A Reference Architecture for AI-Driven Industrial Equipment Life Cycle Boosting Agility, Sustainability and Resilience

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Abstract
This paper presents the Reference Architecture (RA) framework of AIDEAS project and the Machine Passport, aiming to improve European machine manufacturing companies' sustainability, agility, and resilience within the industry 4.0 paradigm. This AIDEAS reference architecture, representing a three-tier pattern of Edge, Platform/Data and Enterprise layers as well as four functional domains, namely Application, Business, Information and Edge, provides a structured view of the infrastructure from the immediate interactions at the edge to the overall management of business processes and data flow and serves as basis for the description of solutions developed in AIDEAS. The Machine Passport, a core element of the AIDEAS ecosystem, is an intelligent platform that facilitates acquiring, managing, and exchanging manufacturing data at various lifecycle stages. This solution ensures traceability, scalability, security, and interoperability, contributing to the comprehensive monitoring of machine conditions throughout the lifecycles of industrial assets. In the context of Industry 4.0, the AIDEAS project presents an innovative approach to industrial data management, fostering sustainability and advancing the capabilities of European machine manufacturing companies.

Keywords
Reference Architecture, IIRA, Digital Passport, Machinery Manufacturing

1. Introduction

Digital and sustainable strategies represent a main goal for EU countries in the coming years. With this medium-term objective in mind, AIDEAS simplifies concepts related to managing the entire product lifecycle and uses digital machine passports to enable circular economy practice. AIDEAS aims to improve European machinery manufacturing companies' sustainability, agility, and resilience by providing solutions for specific problems in the manufacturing machine lifecycle by means of AI technology.

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Planning a good implementation of the AI applications while considering all equipment available in the industrial processes and which the solutions may interact with is challenging. Reference architectures (RA), such as Industrial Internet Consortium [1], Reference Architectural Model Industry 4.0 [2], or GAIA-X [3] to mention some, help us to understand and plan better how to implement these solutions. Therefore, the primary goal of an RA is to improve the efficiency, reliability, and safety of industrial systems by providing a standardised approach for systems design and operation [4]. It must cover various aspects of industrial systems, including hardware and software architecture, communication protocols, data management, and security.

This paper presents the release of the AIDEAS Reference Architecture and the Machine Passport, which are ready to deal with large amounts of data in industrial environments and were developed in the AIDEAs project [5].

2. Methodology

A close collaboration with Solution Providers and Pilots in the definition of use case scenarios and the analysis of requirements and functional specifications paved the way for an in-depth analysis of AIDEAS Solutions to better understand how they fit into the RA. Moreover, a strong connection between the RA and the 16 AIDEAS Solutions was a priority. This connection ensured an inclusive and coherent vision provided by AIDEAS RA. Creating and managing a cohesive Reference Architecture is undeniably intricate due to the involvement of diverse individuals with varying backgrounds who use different notations and express a consistent set of interests and activities to be part of the requirements specification. To facilitate the communication and understanding of the architecture, the RA description is based on standards such as ISO/IEC/IEEE 42010 standard [6] and involved parallel efforts in analysing various stakeholder's perspectives. The AIDEAS RA is built upon the insights gained from widely accepted RA frameworks such as Industrial Internet Reference Architecture (IIRA), and previous research activities and international community versions, such as I4Q RA [7] (REF) and is described from four viewpoints, each providing valuable input to system stakeholders and being influenced by architecture. AIDEAS RA includes:

- **Business Viewpoint** Identification of key business, regulatory, and stakeholder contributions.
- **Usage Viewpoint** identifies tasks, functions, or activities to be carried out by the solution.
- **Functional Viewpoint** decomposes the solutions into domains.
- **Implementation Viewpoint** aims the identification of associated flows, along with the analysis and selection of technologies necessary for their implementation.

Beyond collecting feedback from the different stakeholders from the very early phase, using the value-oriented approach suggested in IIRA, architectural viewpoints were gradually improved, enabling feedback loops from top to bottom (i.e., from the business perspective to the technical implementation perspective) and from bottom to top, organizing meetings to ensure that different viewpoints are consistent. The iterative exchange of feedback between the architecture and user expectations was essential, fostering alignment between different elements of the system. The operational needs that characterize each solution's creation, implementation and use represented a valid contribution and helped to identify a common RA, refining its modules, components, and functionalities.

3. AIDEAS Reference Architecture

3.1. Business Viewpoint

The AIDEAS RA provides a portrayal of business operations that can be applied to multiple companies, identifying shared processes and potential opportunities for information sharing and reuse in different manufacturing lifecycle phase. AIDEAS is developing four integrated suites: (i) **Design:** Integrates AI technologies into CAD/CAM/CAE systems, optimizing the design of structural components, mechanisms, and control elements of industrial equipment; (ii) **Manufacturing:**

Focused on leveraging AI technologies, it aims to optimize the production of industrial equipment; (iii) **Use:** Concentrating on AI technologies, it seeks to improve the user experience and optimize the use of industrial equipment; (iv) **Repair-Reuse-Recycle:** Utilizing AI technologies, it extends industrial equipment life through prescriptive maintenance (repair), enables intelligent adaptation for a second life (reuse), and identifies sustainable end-of-life approaches (recycling).

3.2. Usage Viewpoint

The AIDEAS RA usage viewpoint task oversees the definition of how to implement the AIDEAS capabilities and structure. At this point, the task focuses on identifying the four key elements of the usage viewpoint: the tasks, the activities of AIDEAS. Starting from both the human and the solutions point of view. Once the previous elements have been defined, we continue with the development of the functional and implementation map, which will allow us to specify which role executes which task within the activity. Considering the triggers that initiate the activity, the workflows that define the organization within the activity and the effects that the execution of the activity will produce in the system and the restrictions of its execution.

3.3. Functional Viewpoint

Developing partners in charge of architecting the solutions leverage domains, layers, and standard semantics for the Functional Viewpoint (**Figure 1**). Like other IoT architectures [8], AIDEAS RA Functional Viewpoint presents a three-tier architecture pattern facilitating efficient data flow, processing, and application deployment. In the foreground is the edge layer, composed of devices and physical assets. This layer collects, processes, and filters data locally, acting as the first gateway in the information journey. The data/platform layer is in the middle, orchestrating data processing and communication between peripheral devices and the application layer. Beyond its foundational role, this layer provides essential security, authentication, and data validation services. In certain scenarios, the platform layer is deployed at two distinct levels: the fog layer, an embodiment of decentralized computing infrastructure, and the cloud layer, a centralized domain dedicated to data storage, management, and processing. At the top is the Enterprise layer. This layer is responsible for storing application logic, user interface and data presentation, thus providing a cohesive ecosystem where applications and software services come together. The Enterprise Layer serves as a nexus for end users, presenting business information and empowering decision-making through the various business data and services.

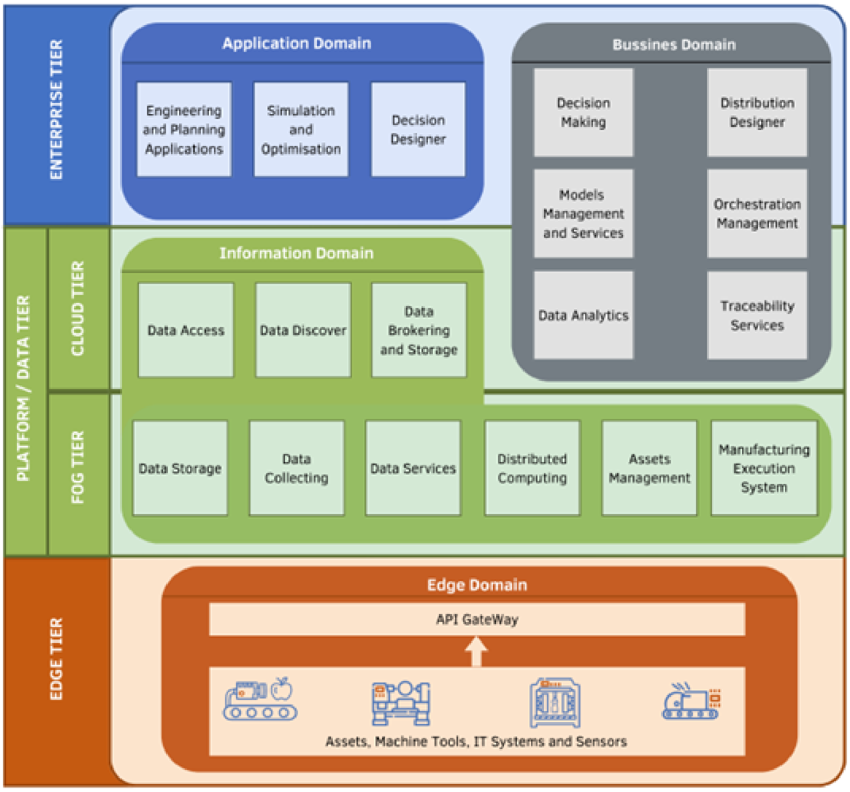

Figure 1. AIDEAS Reference Architecture

This comprehensive architecture facilitates efficient data flow and processing and ensures scalability and adaptability in various scenarios, making AIDEAS RA a robust framework for advanced data-centric applications. Going deeper into the reference architecture, we find the domains. These domains are a functional representation within an end-to-end computing infrastructure, providing a structured view of the applications that interact with data management, business processes and application functionalities.

The first domain encountered is the application domain, located at the network's edge, near the devices and sensors that generate data. As an intermediate layer, this domain, hosted at the edge layer, is key in facilitating seamless communication between devices and other domains. The next domain is the central business domain, dedicated to overseeing the business processes within the system. From planning and scheduling to resource management and performance monitoring, this domain emerges as the orchestrator of operational efficiency and strategic decision-making.

The information domain is responsible for managing the data flow within the system. Typically located under the Platform/Data level, it encompasses functions ranging from data acquisition and processing to storage and communication. The AIDEAS domain is adapted to data management. Finally, there is the edge domain, which echoes the essence of the application domain but emphasizes its role as a distinct functional layer below the edge level. Located at the network's edge, this domain encapsulates the infrastructure for real-time data generation, acting as a link between devices and other operational domains. Together, these domains form a cohesive framework that encapsulates the various facets of the computing infrastructure, from the immediate edge to the overall management of business processes and information flow within the system.

3.4.Implementation Viewpoint

Finally, the implementation viewpoint describes, technically, the different components of the AIDEAS Framework, how they are interconnected and perform a selection of technologies that are required for its proper implementation. Among other things, this task will use as inputs the results of the business viewpoint and the set of activities identified in the usage viewpoint, providing implementation maps for the associated implementation components.

4. Machine Passport

In the era of Industry 4.0, the lifecycle of industrial machines is undergoing a transformation thanks to the integration of new technologies. Data plays a key role in shaping industrial machinery's efficiency, productivity, and decision-making processes from the initial design phase to decommissioning.

The ability to acquire data continuously and in real-time from industrial equipment, production processes and other assets is necessary for decision-making. In this context, the implementation of the "digital passport" concept represents a significant innovation [9]. This approach involves the creation of digital profiles for each physical industrial asset, providing detailed tracking of its performance, maintenance history, usage, and other relevant data. This approach provides greater visibility and traceability of industrial assets, resulting in more effective management and optimization of resources throughout all phases of their lifecycle. The introduction of the digital passport adds value to the development of industrial machinery. IoT devices deployed in the factory feed the digital passport, following standards focused on interoperability [10], and leading to improved data reliability. Data interoperability ensures that systems and devices can communicate and share information effectively.

A significant contribution to the AIDEAS framework is the definition of digital trusted datasets. This aspect is crucial for developing the Machine Passport, a key solution facilitating communication and data exchange across various industrial equipment life cycle phases. The reference model analysis conducted during the reference architecture definition served as the foundation for the mapping activity, determining the most suitable datasets for each architectural tier. This meticulous consideration ensures the effectiveness and coherence of the AIDEAS RA in addressing the complex challenges of the industrial equipment life cycle. AIDEAS Machine Passport acts as an intelligent platform dedicated to acquiring, managing, and sharing data collected from various sources through devices or sensors. Designed specifically to store and share manufacturing data across distinct phases of the physical asset or industrial machinery, including design, manufacturing, use and repair-reuse-recycle stages, the MP aims to establish data exchange protocols, standards, and interfaces. These elements facilitate the integration, sharing and seamless exchange of intelligent and reliable data between different computer-aided systems and manufacturing stages. The use of an intelligent platform enables the acquisition, management and sharing of large-scale manufacturing data from various sources, accessible through various devices and dashboard interfaces.

Unified standard service modelling techniques ensure data compatibility, interoperability, consistency, and quality. Consequently, MP ensures traceability throughout the machines' entire life cycle. This traceability makes it possible to identify the phases in which machines experience the greatest stress. Recognizing the point at which a machine's performance decreases makes it possible to formulate plans to improve its design, manufacture, or use, based on accurate and reliable information. Using artificial intelligence algorithms, the MP guides the orchestration of large-scale data flow and knowledge management throughout the manufacturing phase of the physical asset. By manipulating machine learning knowledge, the MP facilitates asset-related decision-making processes, guiding optimal configuration strategies for repairing, reusing, and recycling industrial equipment.

The Machine Passport describes the stages of the machine life cycle and is responsible for collecting and integrating dynamic and static data. Dynamic data encompasses real-time sensor data, while static data includes predefined data sets from Excel or CSV files.

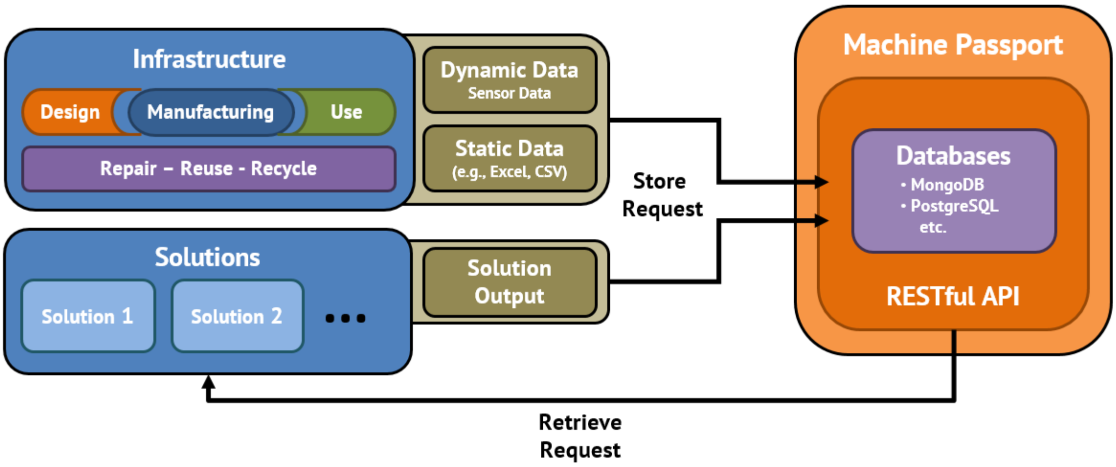

Figure 2. Infrastructure of Machine Passport

The processed data manifests as Solution Outputs, which are tailored responses to specific industrial challenges, such as predictive maintenance, efficiency optimization or resource allocation. The core of the Machine Passport is powered by robust databases such as MongoDB and PostgreSQL. These databases interact with Machine Passport through RESTful APIs, ensuring scalability, security, and interoperability. RESTful APIs facilitate storing and retrieving requests, enabling seamless data flow and integration within Machine Passport. APIs are designed to be stateless and cacheable and have a uniform interface, which simplifies and decouples the interaction between client and server (**Figure 2**). The introduction of MP makes it possible to comprehensively track machine conditions throughout their life cycle, providing insights into the stages at which machines experience the most stress. This information is critical for refining practices at those stages, anticipating potential problems at earlier stages through improved designs, eliminating inefficiencies, or adopting alternative materials. As a result, it minimizes wear and contributes to extending the life cycle of machines.

5. Conclusions

In this paper, the AIDEAS RA has been presented to provide a guideline for implementing the different aspects of the AIDEAS framework. The AIDEAS RA has been defined following the analysis of different viewpoints, which has ensured the description of certain system concerns. Specifically, these viewpoints target the stakeholders and cover system usages, functional components, and technical specifications within the AIDEAS framework. The AIDEAS RA also facilitates the management of the industrial equipment lifecycle. This has enriched the AIDEAS framework and has been achieved through the integration of the Machine Passport, which ensures seamless and efficient data flows within the AIDEAS framework. Through these data flows, the Machine Passport facilitates secure inter-phase communication (i.e., data exchange) between different supply chain actors (manufacturers, suppliers, customers etc.) across the industrial equipment lifecycle to support and ensure circularity in supply chains. The provision of this industrial equipment lifecycle data (i.e., industrial equipment footprint including customer usage data) could also form the basis for decision-making regarding recycling or remanufacturing, thereby enhancing sustainability, agility, and circularity. Within this setup, industrial data traceability and interoperability is achieved throughout the phases of industrial equipment lifecycles.

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Declaration on Generative AI

The author(s) have not employed any Generative AI tools.

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