Data Engineering Roadmap for Implementing Business Intelligence in Higher Education

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***Abstract*—This article addresses the implementation of Business Intelligence (BI) systems in Higher Education Institutions (HEIs), focusing on developing an appropriate data architecture that meets the specificities and requirements of this sector. With the rapid advance of information technologies, HEIs face the growing challenge of managing a considerable volume of data, making it essential to implement BI systems that support informed and efficient decision-making. Using the Design Science Research methodology, this study proposes a BI architecture model that aligns technologies with HEIs' academic and administrative needs and facilitates their integration and ongoing maintenance. The model is designed to be flexible and scalable, allowing adaptations as institutional needs evolve. The article describes the architecture development process, from initial planning to implementation, and discusses how this framework can significantly improve data management and the quality of decision-making processes in educational institutions. The research offers practical and theoretical insights for academics and managers seeking to optimize the use of BI in educational contexts.**

Keywords*—*business intelligence, higher education, data engineering, decision-making.

I. INTRODUCTION

Higher Education Institutions (HEIs) face increasing challenges in managing and utilizing the vast amounts of data generated across various academic and administrative functions [1], [2], [3]. Efficient data management and analysis are crucial for informed decision-making, which directly impacts institutional effectiveness and academic outcomes [4], [5], [6]. Traditional Business Intelligence (BI) systems often struggle with scalability, flexibility, and integration, limiting their effectiveness in dynamic educational environments [7], [8], [9].

Previous studies suggest that BI implementations often fail to reach their full potential due to the lack of a data architecture that effectively aligns technologies with the specific needs of HEIs [2], [10], [11], [12]. This article presents a comprehensive BI architecture model tailored for HEIs, designed to optimize data management and enhance decision-making processes. Utilizing the Design Science Research (DSR) methodology, the study develops a flexible, scalable, and secure architecture based on Microsoft Azure technologies. This approach stands out by ensuring seamless integration with existing systems and adaptability to evolving institutional needs, which is a significant improvement over traditional on-premises or non-integrated BI solutions.

Specifically, this study focuses on the University of Trás-os-Montes and Alto Douro (UTAD) to illustrate the practical application of the proposed architecture. The unique requirements and challenges faced by UTAD were carefully analyzed and addressed, ensuring that the BI solution not only meets general standards but also aligns with the specific operational and strategic goals of the institution.

The key contributions of this study include the introduction of a BI architecture model that leverages Microsoft Azure's cloud-based solutions to provide a robust, scalable, and secure framework tailored to the specific requirements of HEIs. The implementation methodology is detailed, providing a step-by-step exposition of the process at UTAD, highlighting practical challenges and the solutions adopted to overcome them. The practical evaluation validates the proposed BI model through a comprehensive case study at UTAD, demonstrating the architecture's effectiveness in improving data management and decision-making in a real-world academic environment. Finally, the study illustrates how the implemented BI architecture significantly improves the quality and efficiency of decision-making processes within HEIs, supporting better strategic planning and operational management.

The study aims to provide a reference model that other HEIs can adopt and adapt to meet their unique data management and decision-making needs, fostering continuous innovation and quality improvement in higher education.

II. RESEARCH METHODOLOGY

This study adopts the DSR methodology, which combines theory and practice in the development and evaluation of innovative technological artefacts. DSR was chosen for its suitability in creating practical solutions to real problems, ensuring relevance and applicability. The DSR methodology encompasses several phases. The first phase, problem identification and motivation, involved conducting semi-structured interviews with data management officials at the UTAD to identify key challenges and needs. Based on these interviews and a comprehensive literature review, the requirements and objectives for the BI architecture were defined in the second phase.

In the design and development phase, a BI architecture was crafted using Microsoft Azure technologies, emphasizing scalability, security, and integration with existing systems. This approach contrasts with traditional BI implementations that often rely on on-premises infrastructure, which can be limited by hardware constraints and lack of flexibility. The Azure-based architecture offers significant advantages, including cost-efficiency, scalability, and the ability to integrate various data sources seamlessly.

The demonstration phase involved implementing the model at UTAD, which included processes for data ingestion, transformation, and presentation through interactive Power BI dashboards. The architecture was specifically designed to address UTAD's unique needs, such as compliance with Portuguese educational regulations and specific data integration requirements.

The evaluation phase consisted of both qualitative and quantitative assessments of the implemented solution, measuring improvements in decision-making efficiency and user satisfaction. The evaluation was conducted with a focus on the practical application within UTAD, ensuring that the proposed solution meets the specific operational and strategic goals of the institution.

Finally, the communication phase involved detailed documentation of the process and results, aimed at serving as a reference for future implementations in other HEIs. This structured approach ensured that the proposed BI architecture was not only theoretically sound but also practically effective, addressing the specific needs and challenges of HEIs in data management and decision-making.

III. RELATED WORK

Several studies describe the architecture of a BI system similarly. According to [13], a BI system consists of several tools, including data warehouses, Online Analytical Processing (OLAP) and dashboards. A data warehouse groups and analyses accurate, clean and detailed data from multiple sources. OLAP supports multidimensional analysis in real-time and allows users to perform various operations such as aggregation, roll-up filtering and drill-down to obtain details. Dashboards are front-end applications that enable data visualization and performance management.

On the other hand, according to [14], a BI system architecture consists of a structure that includes processes, methods and systems designed to extract, transform and analyze data to create meaningful information and support decision-making in managing a HEI [14]. This architecture involves the integration of different data sources to create a central data repository [14], [15]. The architecture includes components for data extraction, transformation, modelling and visualization, using technologies and tools such as data warehouses, Extraction, Transformation and Loading (ETL) processes and dashboards to enable data processing and analysis [16], [17]. The BI system architecture also incorporates data governance and security measures to ensure data quality, privacy and compliance [14], [15].

The BI system architecture is designed to provide access to timely and relevant information that can support informed decision-making. This architecture supports identifying patterns, trends and information in educational data, enabling a HEI to optimize its educational processes, improve student outcomes and increase its operational efficiency [14], [15].

The architecture of a BI system is essential to ensure the operational efficiency of BI tools and processes in HEIs. It enables the appropriate collection, storage, processing and presentation of data and provides the necessary foundation for developing solutions tailored to the institution's needs. A well-defined and implemented architecture offers many benefits, including optimizing the use of data for strategic action. As BI systems have evolved, different architectures have emerged to meet the various needs and objectives of HEIs, each with its specific characteristics and approaches. Some of the most common architectures are described below:

- Centralized architecture: Includes a data repository and centralized control and management of the BI system [18];
- Distributed architecture: Data and processing are distributed across multiple systems or nodes, allowing for scalability and fault tolerance [19];
- Cloud-based architecture: Takes advantage of cloud computing infrastructure to store, process and analyze data, providing scalability, flexibility and cost-effectiveness [20], [21];
- Layered architecture: Involves the separation of different components or layers, such as data storage, processing and presentation layers, to provide BI capabilities [22];
- Hybrid architecture: Combines different architectural approaches, such as a combination of centralized and distributed systems or a combination of on-premises and cloud-based systems [23].

It is essential to choose the BI architecture that best suits the needs of an HEI in terms of data volume, complexity, number of users and performance requirements. The reference architecture of a system is an abstract, conceptual model that describes the components, standards, best practices and typical interactions that make up a particular technology solution. This architecture provides a standardized structure and guidelines for the system's design, development, implementation, and operation, helping an HEI create consistent and effective solutions.

A reference architecture for a BI system, in turn, consists of a generic, abstract, high-level model that serves as a starting point for the design and implementation of a specific BI system, i.e. it is not a concrete architecture for a particular system, but rather a guide that illustrates the main components and interactions that are typically found in BI systems. In the context of BI, the following two reference architectures stand out:

- Gartner Architecture: Provides a comprehensive framework for designing and implementing BI solutions, including components such as data sources, integration, storage, processing, analysis and visualization [24];

- Lambda Architecture: Consists of a hybrid architecture that combines batch and real-time processing to handle large volumes of data. It is often used to analyze large volumes of data and can provide accuracy and fast results [25].

The reference architectures for BI systems provide essential guidelines for designing and implementing these systems in HEIs, enabling them to structure their projects effectively and make informed decisions to improve their processes. Each architecture has specific benefits and applications, and the choice of the most appropriate architecture depends on the needs and objectives of the HEI. Often, a bespoke design combining elements from different architectures may be required to meet the institution's specific needs. Implementing a well-designed BI architecture can significantly improve decision-making, streamline processes and enhance management and teaching quality. This architecture comprises various elements that work together to collect, process, store and present information, ensuring that the transformed data is usable and valuable to end users.

IV. Architectural Proposal

A BI system architecture proposal describes the structure, components, and processes involved in implementing a BI system in an HEI [14], [16], [26], [27]. To propose an architecture for a BI system in an HEI, it is necessary to take into account the specifics of that institution, such as the different departments, academic and administrative processes, and other peculiarities [8], [28], [29], [30], [31]. This study focuses on the UTAD, detailing a BI architecture that addresses its unique challenges and requirements.

To meet the objectives of a HEI regarding the desired BI platform, a reference architecture based on Microsoft technology and fully supported on the Azure cloud platform is proposed. This architecture consists of a standardized model that defines best practices and guidelines for designing and implementing a system using Microsoft technologies hosted on the Azure cloud. This reference architecture provides a predefined structure for organizing and integrating different Microsoft technologies and services effectively and cohesively, leveraging the capabilities of the Azure platform to create scalable, secure, flexible, and high-performance solutions tailored to the needs of a HEI.

Key components of this architecture for UTAD include:

1) Microsoft Azure cloud platform: Utilized as the basis for hosting and implementing the BI system, ensuring scalability and flexibility [32], [33], [34];
2) Data storage and management: Leveraging Azure Structured Query Language (SQL) Database and Azure Data Lake Storage for efficient data storage and management [32], [35];
3) Apache Spark: Used as a distributed computing framework to process and analyze large amounts of data [33];
4) Octopus Cloud Orchestrator: Employed to automate the deployment and management of the BI system across multiple cloud providers [33], [34];
5) Data integration and ETL: Implemented using Azure Data Factory to extract, transform, and load data from various sources into the data warehouse [33], [34];
6) Reporting and visualization: Utilizing Power BI for creating interactive reports and dashboards to present analyzed data [33], [34];
7) Scalability and Performance: Designed to ensure scalability and performance, taking advantage of Azure's elasticity features [33];
8) Security and Privacy: Implementing Azure's security measures, including access controls, encryption, and compliance standards, to ensure data security and privacy [32], [36];
9) Integration with Other Azure Services: Integrating the BI system with other Azure services like Azure Machine Learning and Azure Internet of Things Platform (IoT) Hub to enhance system capabilities [35], [37];
10) Monitoring and management: Using Azure Monitor and Azure Management Portal to monitor system performance, availability, and health [32].

The proposed architecture is specifically tailored to address the unique challenges and requirements of UTAD, ensuring compliance with local regulations and meeting the institution's strategic goals.

A. Components

Our proposal for implementing the BI solution is based on an Azure Synapse Analytics architecture hosted in a public cloud that is adequately prepared regarding capacity, performance, components, resilience, and security. This system ensures the correct ingestion of internal data residing in a HEI infrastructure and the appropriate processing and enrichment of an analytical model. This model, in turn, feeds a series of reports and dashboards in Power BI that contain indicators, metrics, and Key Performance Indicators (KPIs) essential for managing the HEI. Azure Synapse Analytics is an advanced data analytics platform provided by Microsoft as part of its suite of cloud services known as Microsoft Azure. Formerly known as SQL Data Warehouse, Azure Synapse Analytics is a solution that combines enterprise data warehousing, big data analytics, and data integration into a single platform. This platform is designed to handle various analytical scenarios, from complex queries in traditional data warehouses to real-time big data analytics.

Azure Synapse Analytics is suitable for organizations that want to perform advanced big data analytics in an efficient and scalable way, offering the flexibility of cloud computing to tailor resources to the needs of the moment and providing an integrated platform to handle various data analytics use cases. Azure Synapse Analytics offers significant benefits for implementing BI solutions, making data analysis in an HEI more efficient and powerful, allowing you to streamline your data analysis processes, improve decision-making, and gain a competitive advantage [8], [12], [38], [39], [40].

V. Implementation of the Business Intelligence System Architecture

For this work, the sizing of the reference architecture took into account the information provided by UTAD on data sources, integration cadence, and approximate volumes. The deployment of the solution on the technological platform addresses essential points regarding the resilience of services and components and the security and availability of data through internal replication and distribution processes native to the Azure cloud.

At a conceptual level, the architecture proposed for the BI solution is based on a 'Lambda' BI & Advanced Analytics architecture. One of the fundamental principles of this type of architecture is the ability to integrate data from different information sources through ingestion processes:

- Information sources that provide data of a more static nature, with a predefined ingestion cadence that is more focused on a batch-loading approach;
- Information sources with data ingestion needs that are more focused on real-time consumption or similar, based on data streaming technologies.

From a global perspective, this architecture takes shape in the modularity of integrating new components that enable these different ingestion methodologies. Starting from the 'Lambda' architecture that serves as the basis for the proposal to implement the BI solution, the focus of this work at this stage is directed towards building the processes for ingesting, correlating, and making information available without neglecting its characteristics of high modularity and scalability potential, which allow a HEI to consume and exploit information while providing a solid basis for expanding its use for other purposes. Fig. 1 shows a schematic representation of the processes for ingesting, correlating, and making available information.

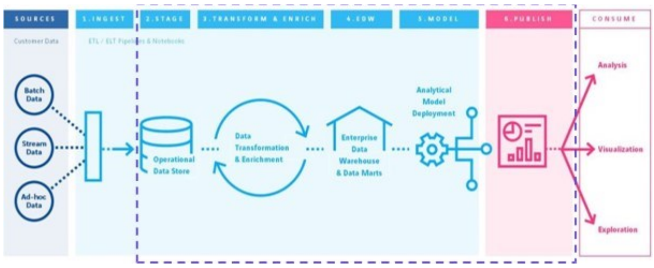

Fig. 1. Schematic representation of the processes of ingesting, correlating and making information available.

Conceptually, a high-level view of the data architecture that embodies this approach to the business analytics process implemented at the HEI is shown in Fig. 2. This figure shows, as an example, different data marts dedicated to other reports and dashboards that can be segmented by organizational unit and target users. These data marts provide smaller models focused on specific dimensions and perspectives regarding information consumption, analysis, and visualization.

Technologically, the solution presented consists of components and services in Microsoft Azure. This ensures the native capacity of cloud components and services in terms of their elasticity and flexibility, making it possible to adapt their capacity and performance to processing needs at any time. In terms of security, reliability, and robustness, all these components and services will be under the purview of well-defined Role Based Access Control (RBAC) processes and under the protection of the multiple layers of security that the Azure cloud service provides at both the logical and physical levels of its data centres.

It should be emphasized that the proposed platform is governed by Microsoft's fundamental principles and best practices for this type of project. The architecture for the proposed platform, shown in Fig. 2, reflects our vision for the production environment. It includes a development environment and a test environment with identical configurations, located in a segregated environment, with specific permissions and capacity models appropriate to the workloads required.

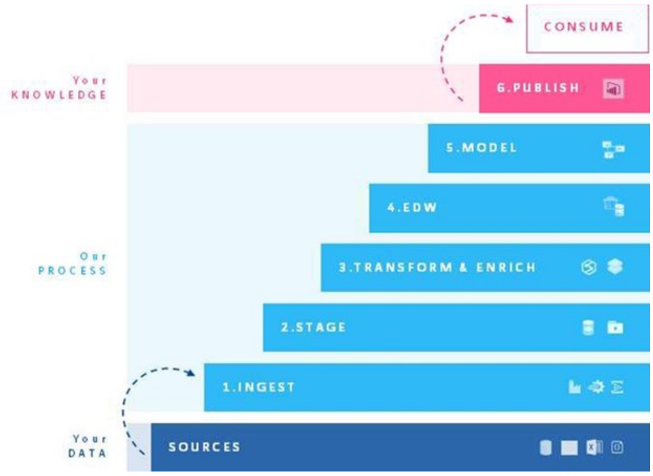

Fig. 2. Architecture for the proposed platform.

To translate this into a more technological vision that guarantees integration with the current technological infrastructure of the HEI, namely the data sources and their characteristics, Fig. 3 shows the mapping of the Azure components and their respective zones. The architecture shown in this figure should be considered as a reference, and any of its components or services can be replaced or added to subsequently without altering the overall principle of the solution.

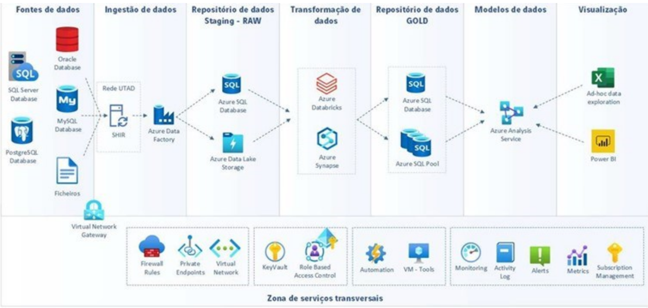

Fig. 3. Mapping Azure components and their zones.

According to our proposal, the information is extracted from different sources and modelled according to the organization's standards (data types, nomenclatures, codes, among others). Once all the data had been modelled, it was mapped from the sources to the HEI data warehouse. Once the data had been uploaded to the data warehouse, work began on building the dashboards to visualize the KPIs. Azure Synapse Analytics was found to be the most suitable solution for this work, as it included all the components originally envisaged in the reference architecture in a unified way:

- The data ingestion area will consist of the Azure Data Factory component, which will provide all the connectors, dataset configuration, and pipeline management required for the ETL / Extraction, Loading, and Transformation (ELT) processes. The Data Gateway component is deployed on the HEI's internal network;

- The data storage zones, whether in their RAW data staging (landing zones) or already transformed data, consist of Azure Data Lake Storage gen2 and Azure SQL Databases components (in their standalone, elastic pool, or SQL dedicated pool versions, depending on the storage and performance requirements assessed during the survey and implementation);
- The data transformation area can benefit from specific features at the level of the different components, such as Azure Databricks or Azure Synapse at the level of the Spark clusters invoked at the level of the running notebooks for data transformation (they are identical in terms of operation and each can be more advantageous depending on the use cases and workloads implemented). It should be noted that Spark clusters are the choice for training machine learning models using specific libraries.

The area for making semantic models available for analysis comprises a component that guarantees the capacity to make tabular models available in memory or in Massive Parallel Processing (MPP), which ensures the necessary data presentation performance. These semantic models are the source of privileged information, already transformed and integrated into the context of the HEI, which meets the challenges of the HEI in terms of its 360° vision of the institution, in its teaching and management aspects, and improving the decision-making aspect.

It is important to emphasize that this platform can also act as a repository for machine learning models, which are then made available for consumption via specific Application Programming Interfaces (APIs). The visualization domain consists of configuring and publishing reports and dashboards in Power BI. It is also the privileged domain for providing the endpoints and/or REST APIs needed to consume the Enterprise Data Warehouse (EDW) data and the potentially trained models. Our work uses Power BI Pro, a paid Power BI licence that offers advanced features and additional capabilities compared to the free version known as Power BI Desktop and Power BI Free.

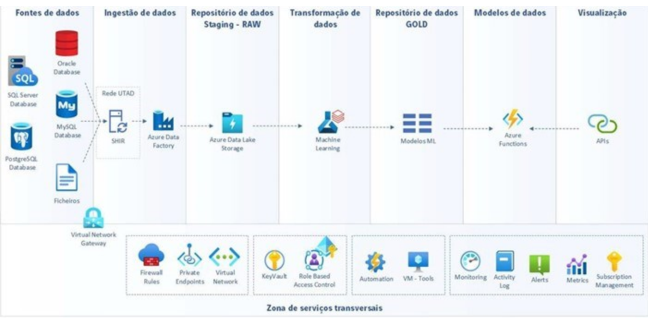

Fig. 4. Proposed architecture for the BI solution.

The transversal services logical zone includes components and services that operate at the infrastructure level of the solution on a global scale and are not restricted to a specific logical zone. It includes services such as VPN gateway, endpoints, KeyVault, automation, RBAC, and platform monitoring. The proposed architecture for the BI solution, shown in Fig. 4, is prepared to include components that could address potential machine learning use cases if required.

VI. Conclusions

This study aimed to enhance the understanding of implementing BI systems in HEIs and demonstrate how a well-designed data architecture can significantly improve these institutions' management and academic performance. Using the DSR methodology, a BI architecture tailored to the specific needs of higher education was developed and implemented.

The proposed architecture, built on the Microsoft Azure platform and technologies such as Azure Synapse Analytics, was designed to be flexible, scalable, and efficient. This design facilitates the integration and analysis of large volumes of data, addressing the complexity of implementation in HEIs with limited IT resources. The Azure-based solution contrasts with traditional on-premises BI systems by offering enhanced scalability, cost-efficiency, and integration capabilities.

The validation of the proposed architecture through a case study at the UTAD confirmed its practical applicability and effectiveness. The implementation led to significant improvements in the quality and efficiency of decision-making processes within the institution.

Future research should explore alternative data integration methodologies to simplify the implementation process in HEIs with fewer resources. Additionally, evaluating the impact of BI implementation on decision-making practices and academic outcomes across a larger sample of HEIs will be crucial. Such evaluations should be conducted after practical validation of the proposed architecture in diverse educational contexts.

In conclusion, this study presents a reference model that can serve as a guide for other HEIs aiming to transform data into strategic insights for more effective management. The proposed BI architecture strategically positions HEIs to meet modern educational challenges and optimize their management processes, thereby laying a solid foundation for continuous innovation and quality improvement in higher education.

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