Simulation Platform for an Early 20th-Century Domestic Energy Management Apparatus

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Abstract. This paper presents the design of a digital twin for a domestic electrical energy system originally installed in a rural estate in Chamusca (Portugal) around 1920 and donated in 2023 to the Faraday Museum at Instituto Superior Técnico (IST). The system integrates a Crossley internal combustion engine, an ASEA direct-current dynamo, an ASEA three-phase induction motor, and a Tudor open-cell lead-acid battery bank. Based on technical documentation produced by the Faraday Museum during the system's dismantling and restoration, this work outlines a digital preservation platform combining three components: (1) a 3D reconstruction in Blender, (2) an interactive real-time simulation in Unity, and (3) a Retrieval-Augmented Generation (RAG) system for accessing historical data. The project aims to preserve the technological heritage of early domestic electrification in Portugal and provide an educational tool for researchers and museum visitors.

Keywords: Digital cultural heritage · Domestic electrification · Digital twin · Interactive simulation · Lead-acid batteries · Retrieval-Augmented Generation

1 Introduction

The electrification of Portugal followed a markedly uneven trajectory, beginning with spectacular public demonstrations in the late nineteenth century and expanding only gradually into domestic and rural contexts [1–5]. In Lisbon, early installations were closely intertwined with the gas industry and municipal concession regimes: gas remained dominant for decades, and the creation of combined gas–electric utilities reduced competitive pressure to accelerate electricity diffusion or lower tariffs [3, 5]. Long-run energy reconstructions confirm that, even after the turn of the twentieth century, electricity represented only a small share of final energy consumption, while coal, biomass and petroleum products continued to prevail, particularly outside the major urban centres [6, 7]. Universal domestic electrification was only achieved in Portugal in the late 1980s, revealing a persistent gap between technical possibility and household access [4, 6].

Within this broader context, autonomous local systems assembled by estates, small industries and provincial towns played a crucial transitional role. Recent work on energy access and mini-grids emphasises that small isolated systems—often combining mechanical power, electricity generation and limited storage—were central to early electrification pathways, but remain under-documented in comparison with large utilities and national grids [8]. In Portugal, detailed engineering case studies at domestic or estate scale are particularly scarce; most narratives treat non-urban supply via aggregated statistics or generic references to "isolated stations" [6, 7]. This makes surviving examples of early autonomous domestic installations valuable both as historical evidence and as material for technological analysis.

Originally located at a rural estate in Chamusca, the domestic energy installation, now preserved by the Faraday Museum at Instituto Superior Técnico (IST), represents a rare case where hardware, layout and archival documentation have survived together. The preserved apparatus combines a Crossley internal combustion engine, an ASEA direct-current dynamo, an ASEA three-phase induction motor, a Tudor open-cell lead-acid battery bank and a marble control board for charge and discharge regulation [9]. Rather than representing a single static phase, the installation records a layered technological evolution from mechanical pumping, to local DC generation and storage, and finally to hybrid operation following the arrival of three-phase alternating current in Chamusca [9, 10]. As such, it offers a compact but unusually complete example of early twentieth-century domestic energy management in rural Portugal.

This paper presents the design of a digital preservation platform for this installation, conceived as a heritage-oriented digital twin integrating three complementary components: a three-dimensional reconstruction in Blender, an interactive real-time simulation in Unity, and a Retrieval-Augmented Generation (RAG) interface for consulting museum documentation [9, 11, 12]. The project is motivated by both conservation and interpretation. The original machinery is historically valuable but heavy, mechanically complex and unsuitable for continuous operation in a gallery setting. At the same time, the system's significance lies not only in the physical artefacts but also in the interaction between generation, storage, control and use. We therefore argue that interactive simulation provides explanatory value beyond static three-dimensional representation, and that a critically framed RAG layer can broaden access to technical heritage documentation while preserving source visibility and signalling uncertainty.

The contributions of this work are threefold. First, it provides a micro-historical reconstruction of an autonomous domestic energy system in rural Portugal, complementing national and urban-scale histories of electrification with a detailed case study grounded in surviving hardware and documentation. Second, it operationalises digital twin concepts for a compact hybrid mechanical–electrical apparatus by combining geometric reconstruction and physics-based modelling. Third, it prototypes a corpus-specific RAG interface tightly coupled to the digital twin, thereby opening a space to examine how AI-assisted access mediates the interpretation of technical heritage under the ethical and epistemic constraints identified in recent guidelines for AI in memory institutions [12].

2 Historical and Technical Background

2.1 Electrification and domestic energy in Portugal

Historical studies of electrification in Portugal have mostly concentrated on public lighting, urban utilities and the development of large-scale generation and transmission infrastructure. Matos and collaborators detail the emergence of electricity in Lisbon and Porto, the interplay between public authorities and private concessionaires, and the gradual expansion from lighting into transport and industrial uses [3, 4, 13]. These works show that Lisbon became an early laboratory for electric modernity, with emblematic illuminations and tramway electrification, but also emphasise the persistence of gas lighting and the central role of the Companhias Reunidas de Gás e Electricidade (CRGE) as a combined gas–electric monopoly well into the twentieth century [3, 5].

At the national scale, long-run energy series compiled by Henriques and co-authors reveal that electricity's share in final energy consumption remained modest until the interwar period, with structural constraints and investment choices limiting the pace of electrification [6, 7]. Hydroelectric schemes and, later, the national grid progressively extended supply beyond the major cities, but rural and small-town households often obtained access decades after the technology was technically mature [4, 6]. In this literature, domestic electricity is typically treated as a late and uneven outcome of infrastructure and tariff policy rather than as the result of local technical initiatives.

Recent work on energy access provides a broader comparative lens by emphasising the significance of small isolated systems and mini-grids in early electrification phases [8]. In many countries, estates, mines and small towns implemented autonomous plants that combined mechanical power, dynamos and sometimes storage long before being absorbed into larger networks. Portuguese sources document a similar pattern through references to hundreds of small generating stations in the 1920s, most of them of limited capacity and serving restricted customer bases [4, 6]. However, detailed accounts of how these systems were architected and operated at the domestic or estate scale are rare, and surviving installations are exceptional. It is within this interpretive gap that the Chamusca system acquires particular importance.

2.2 The Chamusca installation and its evolution

The Chamusca installation was originally located at a rural estate (quinta) near Rua Direita de São Pedro in the municipality of Chamusca. According to the owner's testimony and the reconstruction undertaken by the Faraday Museum team, the estate belonged to a family with strong engineering connections: Eng. José de Mascarenhas Pedroso Belard da Fonseca (1889–1969), a civil engineer and future director of IST, had close ties to the property and to technical decision-making about the energy system [9]. The estate comprised agricultural infrastructure for cereal threshing and olive oil production. The initial use of steam power was confirmed by the historical reports from the Faraday Museum

(a) Left view of the machine room.

(b) Right view of the machine room.

(c) Tudor battery rack.

Fig. 1: Historical record of the Chamusca domestic mini-grid prior to dismantling (c. 2023).

[9], which document an olive oil mill driven by a steam engine powered by a dedicated boiler, which was also utilized for the purification of olive oil during production. This was later replaced by internal combustion machinery, and the estate incorporated a dedicated machine room (shown in Fig. 1) [9]. Following its recovery in 2023, the restored components are preserved and exhibited at the Faraday Museum (shown in Fig. 2).

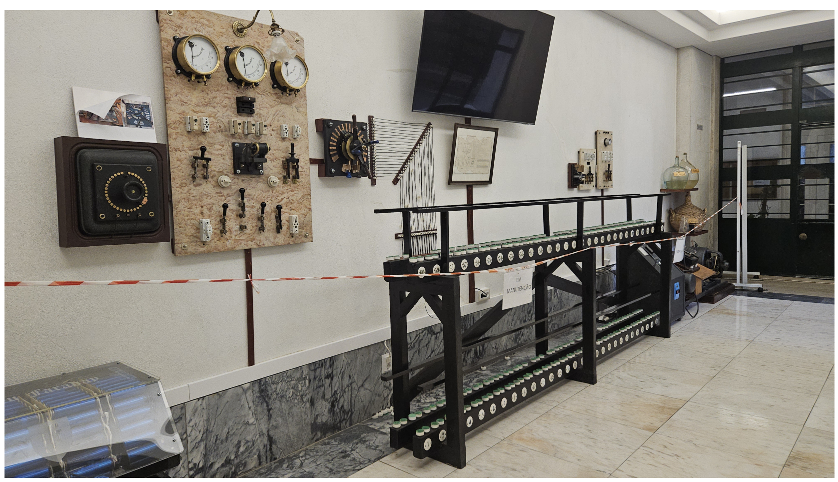

Fig. 2: Restored apparatus as currently exhibited at the Faraday Museum (IST). Note the absence of the Tudor battery cells (only the empty wooden rack is preserved) and the Crossley engine, which could not be transported due to weight and building access constraints.

Piedade's documentation reconstructs the installation as evolving through at least three main phases [9, 10]. In a first mechanical phase, a single-cylinder

Crossley internal combustion engine replaced an animal-driven nora to raise water and perhaps to drive other agricultural machinery. In a second, "DC electrification" phase (c. 1918–1923), an ASEA direct-current dynamo was coupled to the engine, and a bank of 60 Tudor open-cell lead-acid batteries was installed, providing both domestic lighting and extended availability beyond engine operating hours. In a third, "AC integration" phase (c. 1929 onwards), following the arrival of three-phase alternating current in Chamusca, an ASEA induction motor was installed to drive the dynamo from the grid, transforming the system into a hybrid configuration in which the internal combustion engine was largely relegated to mechanical duties while the public network was used to recharge the battery bank.

Technically, the preserved apparatus is notable for the survival of both its major components and its control logic. The system comprises the Crossley engine, the ASEA DC dynamo, the ASEA three-phase induction motor, a Tudor battery bank consisting of 60 open glass cells, and a marble control board fitted with voltmeters, ammeters, a high-power rheostat and a dual selector switch that accesses taps on the last twenty battery cells [9, 14]. The dynamo uses a Gramme-type armature, consistent with mainstream DC generator practice since the 1870s [15], while the Tudor cells follow open-cell lead-acid designs developed and industrialised by Henri Tudor and licensees, widely employed in stationary installations [14, 16]. Crossley engines of similar configuration are well documented in European museum collections and technical literature, confirming their widespread use in small industrial and agricultural power applications [17].

This configuration effectively realises a domestic-scale mini-grid that integrates generation, storage and control in a single installation. Its survival, together with the detailed photographic and narrative documentation produced during the 2023 dismantling and transport operations, makes it an unusually rich case for studying early domestic energy management, including aspects of operating practice that are rarely accessible in other examples [9, 10].

3 Related Work

3.1 Digital twins in cultural heritage

Digital twin concepts have increasingly been adopted in cultural heritage to move beyond static digitisation toward dynamic, semantically enriched and, in some cases, behaviour-oriented representations of artefacts, buildings and sites. Recent surveys distinguish digital twins from simpler three-dimensional models by emphasising the integration of geometry with heterogeneous data streams, semantics and simulation capabilities [11, 18–20]. In this perspective, a heritage digital twin is a layered construct that can incorporate physical geometry, material properties, environmental data, conservation records, usage histories and interpretive content, potentially updated over time.

Existing heritage digital twins have so far focused predominantly on architectural and structural assets. Case studies include historic gates and fortifications, where detailed 3D models are combined with structural health monitoring and predictive maintenance workflows, and rock-cut sites or caves, where sensor data support risk assessment and emergency planning [11, 20]. Ontology-driven approaches, such as the Heritage Digital Twin Ontology and its subsequent extensions, formalise these multi-layered models and provide vocabularies for describing geometry, sensors and reactivity in a machine-readable way [18, 19]. However, applications to compact technological systems—such as engines, dynamos, machine tools or domestic energy installations—remain relatively uncommon.

The Chamusca project contributes to this emerging area by applying digital twin concepts to a hybrid mechanical–electrical apparatus. In contrast to building-scale examples, the primary interpretive challenge here lies in representing the internal dynamics of the system: how mechanical, electrical and electrochemical processes interact over time, and how the control board mediates these interactions. By combining detailed three-dimensional reconstruction with physics-based modelling, the platform aims to produce a behaviour-oriented heritage digital twin that foregrounds operational logic rather than only spatial form.

3.2 Interactive simulation and heritage interpretation

The use of real-time 3D engines in museums and heritage interpretation has been explored in several projects that adapt game technologies for educational and presentational purposes. Early work demonstrated how game engines such as *Quake* could be repurposed for navigable reconstructions of historic sites, offering users spatial immersion and interaction beyond what static images or physical models can provide [21]. Subsequent research on augmented reality (AR) and virtual reality (VR) in museum contexts has shown that interactive environments can increase visitor engagement, dwell time and perceived learning outcomes when compared with traditional displays, provided that the experiences are carefully designed and evaluated [22].

In parallel, studies in science and engineering education have investigated the didactic potential of three-dimensional modelling and simulation for teaching complex physical phenomena. These works argue that dynamic, manipulable models can support conceptual understanding by allowing learners to observe system responses to parameter changes, explore multiple scenarios and form mental models of underlying mechanisms [23]. They also caution that realism must be balanced with cognitive load: overly detailed simulations may overwhelm users, while overly abstract ones may fail to convey crucial aspects of system behaviour.

For the Chamusca installation, these findings support treating interactive simulation not as an optional embellishment but as an interpretive necessity. The historical and technical significance of the system lies in the orchestration of engine, dynamo, battery bank and loads under varying operating modes and constraints. A Unity-based simulation that allows users to adjust rheostat and selector positions, and observe their effect on voltages, currents and battery state of charge can make these interdependencies explicit in ways that static models cannot. At the same time, design decisions must be made to align underlying physics with visitor expectations and attention spans.

3.3 RAG for heritage and technical archives

Large language models (LLMs) have recently been explored as interfaces to digital collections and archives, but their use raises concerns about trustworthiness, hallucination and the opacity of generated narratives. UNESCO's guidance on artificial intelligence and documentary heritage emphasises that memory institutions must carefully evaluate AI systems in light of principles such as transparency, provenance, accountability and respect for archival integrity [12]. In this context, Retrieval-Augmented Generation (RAG) has emerged as a promising paradigm, as it constrains generation by grounding answers in retrieved passages from a curated corpus.

Several projects in the cultural heritage domain illustrate how RAG can mediate access to complex datasets while maintaining links to underlying records [24–26]. These developments demonstrate that RAG can serve as a powerful mediator between non-expert users and complex heritage datasets, but they also underline that retrieval quality, corpus coverage and interface design remain critical determinants of trustworthiness [12, 25]. The Chamusca project adopts RAG in a more focused configuration: the corpus is limited to a small, high-quality set of Faraday Museum reports and related technical documentation about a single installation [9, 10, 14]. This setting reduces some of the retrieval challenges seen in large heterogeneous collections, and offers an opportunity to examine, in a controlled scenario, how RAG-mediated explanations handle contested interpretations, missing data and explicit uncertainty in the underlying documents.

4 Materials and Methods

4.1 Source data and documentation

The primary sources for reconstructing the Chamusca installation are internal reports produced by Piedade and collaborators at the Faraday Museum, together with photographic and video documentation recorded during the dismantling and transport operations [9, 10, 14]. These documents are complemented by external technical sources describing comparable Crossley engines and Gramme-type dynamos [15–17]. Together, these sources support both the reconstruction of the physical configuration of the system and the estimation of plausible operating parameters.

4.2 Three-dimensional reconstruction workflow

The three-dimensional reconstruction of the installation is being developed in Blender, based on photographic surveys and video footage. The modelling process focuses on the core apparatus components. The room is modeled as a representation of the machine room, but it is not intended to be a 1-to-1 fidelity reconstruction of the original environment.

Every component, including the complex geometries of the Crossley engine and the ASEA dynamos, was hand-modeled to ensure technical accuracy. This high-fidelity master model was subsequently optimized for the Unity WebGL environment. Given that WebGL applications are primarily accessed on mobile devices or hardware with lower compute power, the geometry and textures were refined to balance visual quality with runtime performance. Modelling decisions aimed to "refurbish" the assets to their presumed original state, with assumptions and uncertainties addressed through analogy where primary sources were limited.

4.3 Interactive simulation design

The runtime environment is implemented in Unity, which serves as the host for physical models of the installation. The platform utilizes Functional Mock-up Units (FMU) generated via OpenModelica to simulate the system's electrical and mechanical behavior. This approach ensures that the simulation is grounded in formal mathematical modeling rather than simple approximations. Visual feedback is provided through animated instruments on the control board (voltmeters and ammeters), dynamic labels and optional overlays that show energy flows and numerical values. The simulation time-step and numerical integration schemes are chosen to ensure stability and responsiveness without requiring specialised hardware.

4.4 RAG system architecture

The RAG component is designed as a corpus-specific interface to the Faraday Museum documentation. The pipeline consists of document preprocessing, semantic indexing and answer generation using a large language model. For each user query, the system retrieves the top-k most relevant passages and requests a structured response grounded in the retrieved content, preserving source uncertainty where present.

5 Results

The implementation of the platform has resulted in a functional prototype that integrates hand-modeled 3D assets and an AI-driven archival interface.

5.1 Digital reconstruction

The 3D assets represent the complete technological suite of the 1920s installation (depicted in Fig. 3). Hand-modeling ensured that mechanical relationships (e.g., belt alignments between the Crossley engine and ASEA dynamo) are accurately preserved. The optimization process successfully reduced the polygon count for efficient delivery through the WebGL environment without sacrificing the identifiable "patina" and character of the original artifacts.

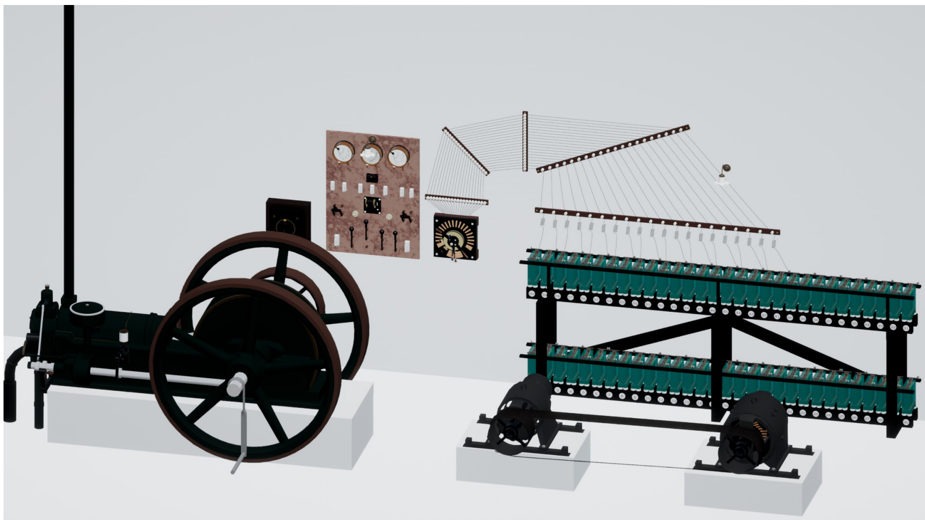

Fig. 3: Ongoing digital reconstruction in Blender optimized for real-time WebGL interaction, showing the Crossley engine, induction motor, ASEA generator, and Tudor batteries running inside the Unity simulator.

5.2 System Implementation and API

The backend is implemented in Python using the FastAPI framework, providing a low-latency interface for the Unity client. The simulation service manages FMU sessions, allowing real-time parameter updates for the engine and dynamo.

5.3 Context Graph-Augmented RAG Performance

The system utilizes a formal domain ontology (implemented via NetworkX) to actively steer semantic retrieval. Validation achieved a 100% pass rate across functional tests, confirming that the graph-based context prelude effectively guides the AI while preventing technical hallucinations.

5.4 Archival interaction layer

The interaction platform is fully realized through a web interface (`webgl/-index.html`) that embeds the Unity build alongside a generative chat system (shown in Fig. 4). This platform allows users to query the RAG backend through multiple modalities: direct chat, selecting specific components within the WebGL view to steer the context, or selecting text directly from the landing page to initiate detailed inquiries.

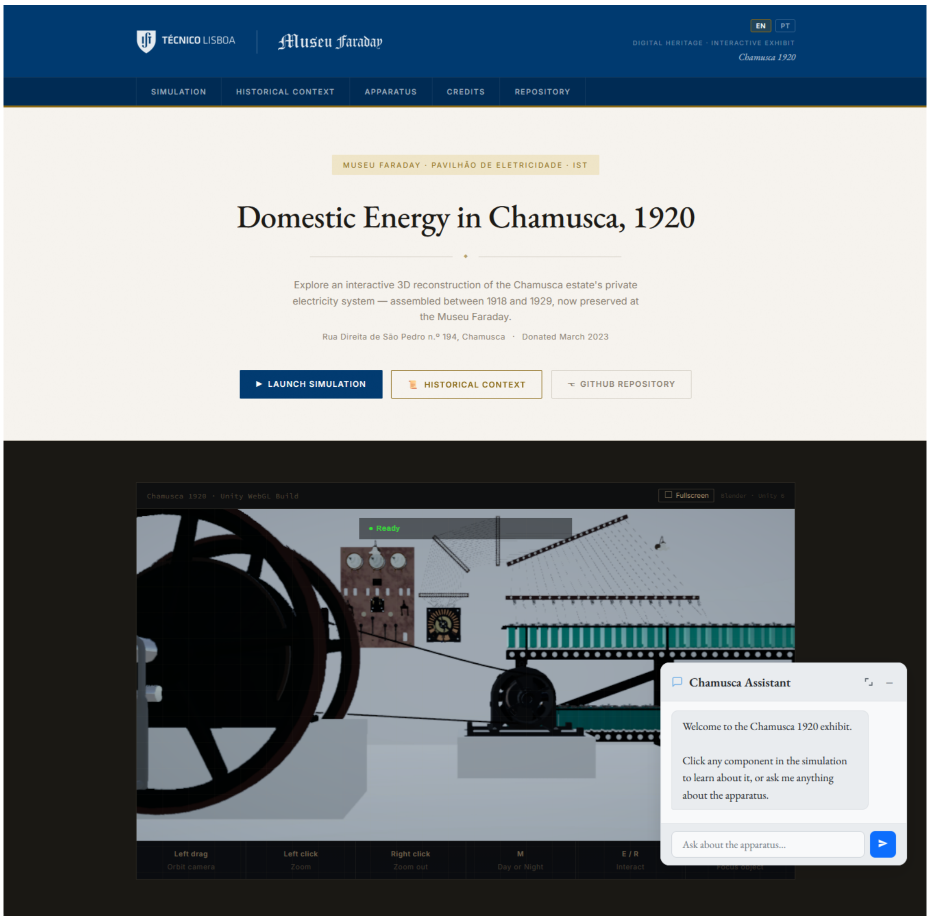

Fig. 4: Integrated landing page portal combining real-time simulation and the ontological RAG assistant.

6 Discussion and Conclusions

The results demonstrate that offloading high-fidelity physics (via OpenModelica FMUs) to the backend is a viable solution for the digital preservation of heritage systems on restricted platforms like WebGL. This architectural choice maintains historically plausible behavior while ensuring accessibility across a wide range of devices.

Furthermore, the platform transcends simple visualization. By integrating component-aware chat and text-selection queries, it creates a "Memory Twin" that explains the technical decisions of the 1920s. While the 3D model shows *what* the system was, the RAG interface explains *why* specific decisions were made, fulfilling goals of museum-based dissemination.

6.1 Declaration of AI Assistance and Statement of Contributions

In compliance with the project guidelines, the author explicitly declares the support of Generative AI tools and details individual contributions to ensure transparency and highlight critical engineering oversight:

- **AI-Assisted Support:** Generative AI tools (Antigravity CLI powered by Gemini models) were utilized to assist extensively in code generation, particularly in developing the FastAPI RAG backend architecture, ChromaDB indexing scripts, and the C# interactive simulation scripts for Unity.
- **Developer Ownership & Critical Thinking:** All architectural choices, system designs, physical equations, and integration schemes were conceptualized, directed, and evaluated by the author. AI outputs were reviewed, debugged, and validated to ensure compliance with Faraday Museum historical records.
- **Evidences of Individual Contribution:** (1) *3D assets:* Manual visual inspection and low-polygon 3D modeling and animation in Blender (representing over 320 hours of individual development). (2) *Physics Modeling:* Formulation of the OpenModelica equations for the Tudor battery (modeling 1.93V–2.11V curves) and the ASEA dynamo. (3) *System Orchestration:* Designing the integration and communication logic between the WebGL frontend, physics server, and the ontological context graph.

Part 2: Technical Evidence

This part presents the technical artefacts and architectural decisions that support the *Simulation Platform for an Early 20th-Century Domestic Energy Management Apparatus*. It documents the system's distributed nature, the physics-based simulation workflow, the retrieval-augmented intelligence layer, and the overall visitor experience.

6.2 High-Level System Architecture

The platform is designed as a distributed ecosystem that bridges the physical museum environment with cloud-based intelligence and server-side physics. Figure 5 illustrates the macro-components and their interactions. The workflow begins with a visitor scanning a QR code at the museum, which opens the Landing Page in a mobile browser. This client layer hosts both the interaction UI and the Unity WebGL instance. These components communicate with a central FastAPI Server, which orchestrates RAG queries (via Gemini) and simulation steps (via the FMU execution engine). The complete schema models, high-level deployment layouts, and the ontology schema structure are available in the supplementary Architecture and Design report in the project deliverables under `02_Desenho/02_Desenho.pdf`.

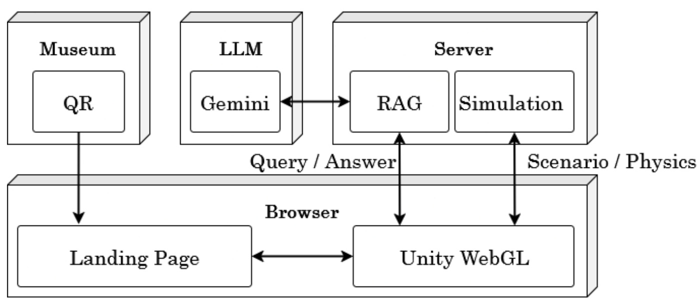

Fig. 5: High-level architecture: From the physical Museum QR entry point to the LLM-cloud integration.

6.3 Software Deployment and Communication

The project is structured into two main repositories, ensuring a separation of concerns between the frontend experience and the backend intelligence. Figure 6 details the deployment strategy.

The `backend-repo` handles the RAG engine (ChromaDB), the FMU simulation server, and hosts the static files for both the landing page and the WebGL build. The unity-repo contains the 3D interactive scene and the user interaction layer, which is embedded into the platform via an iframe and communicates with the server through a dedicated REST API. Detailed codebase scripts, WebGL compression headers configuration, and FastAPI coroutines are fully documented in the supplementary Implementation report under 03_Implementacao/03_Implementacao.pdf.

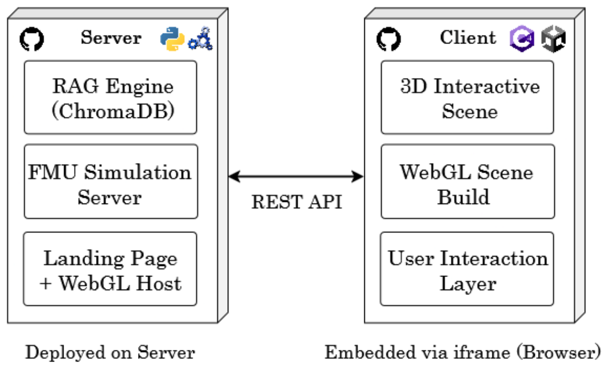

Fig. 6: Deployment and repository structure: Backend services and Browser-based client integration.

6.4 Physical Models and Simulation Workflow

To ensure high-fidelity electrical behavior, the platform utilizes Functional Mock-up Units (FMU) compiled from OpenModelica. This architectural choice addresses the inability of WebGL to execute native binaries. Figure 7 shows the simulation pipeline.

During development (Build Time), the models are compiled in OpenModelica. At Runtime, the Server acts as a Physics Solver, receiving scenario parameters from Unity and returning calculated values for voltage (V), current (I), and operational phases. This ensures that the digital twin's behavior is grounded in formal engineering models.

The system incorporates three distinct operational setups, corresponding to the scenarios modeled in OpenModelica:

1. **Scenario A (Discharge and Regulation):** Models the night-time discharge of the Tudor battery bank to supply the domestic loads (Casa, Dependências, Panel, and Battery Room lamps) without active generation. The battery configuration is regulated using a single discharge selector arm.
2. **Scenario B (Thermal Generation and Charging):** Models the generation of DC power by the ASEA Dynamo driven mechanically by the single-cylinder Crossley internal combustion engine (representing the c. 1920 isolated mechanical-electrical grid phase).

3. **Scenario C (AC Grid Integration / Three-Phase Phase):** Models the generation phase driven by the ASEA three-phase induction motor connected to the newly arrived public AC grid (c. 1929 onwards), which acts as the prime mover for the DC dynamo to charge the Tudor battery bank.

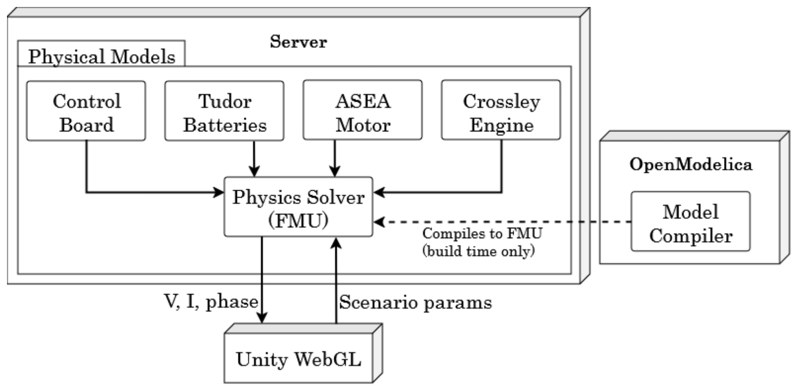

Fig. 7: Simulation architecture: Integration of OpenModelica FMU models for the Crossley engine, ASEA components, and Tudor batteries.

All three scenarios (A, B, and C) are modeled using the factual historical parameters verified from the original Tudor specification sheet: a capacity of 36 A h, a cell discharge limit of 1.83 V, and fuse limits set to 10 A (corresponding to the historical maximum current rating of 9 A).

To translate these physical outputs into dynamic visual feedback in the 3D viewport, three integration systems are implemented:

- **Dynamic Animation Scaling:** The visual playback speed of the Crossley engine flywheels, generator rotor, and ASEA induction motor are continuously scaled at runtime based on the simulated generator RPM outputs.
- **Automatic State Resets:** Changing scenarios resets all knife switches, indicators, selectors, and circuit breakers back to their OFF/rearmed positions, matching the fresh FMU state.
- **Adaptive HUD Control:** An interactive RPM slider is procedurally injected into the debug HUD canvas and configured to display only during Scenario B, where variable thermal engine speed operations are active.

6.5 Context Graph and RAG Intelligence Layer

The archival interaction layer utilizes a Context Graph-Augmented RAG system. This allows the platform to provide contextually relevant answers based on the user's focus within the 3D simulation. Figure 8 details the retrieval logic.

When a user questions the system, the RAG module performs a dual lookup: it searches the ChromaDB Vector Store for relevant text fragments and consults the Context Graph to expand the relational context (e.g., linked components or specific risks). The result is a grounded prompt sent to the LLM (Gemini), which returns an answer supported by historical sources.

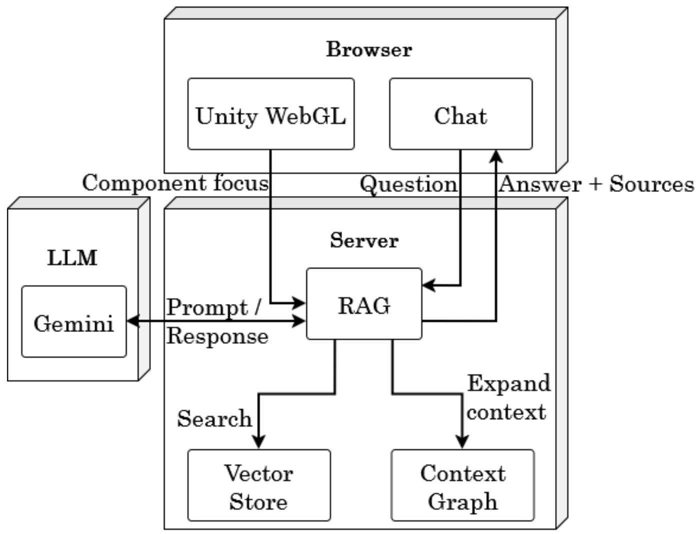

Fig. 8: Intelligence layer: Synergistic interaction between the semantic Vector Store and the ontological Context Graph.

6.6 Visitor Experience and Use Cases

The platform serves two primary user archetypes: the Museum Visitor and the Researcher/Curator. The core functionalities available to each are outlined below.

Visitors focus on accessing the simulation via QR codes, interacting with 3D components, and viewing live electrical data. Researchers utilize the Shared Knowledge Layer to query technical documentation and review source contexts and citations provided by the RAG system. The detailed system functional requirements (FR), non-functional requirements (NFR), and complete use case specifications are available in the supplementary System Requirements Specification report under `01_Analise/01_Analise.pdf`.

6.7 Individual Contribution and Oversight

The development focused on architectural design, high-level orchestration, and the integration of heterogeneous modules. Key responsibilities included:

– **System Integration:** Defining the communication protocol between Unity and FastAPI.
– **Simulation Orchestration:** Managing the execution of simulation FMUs on the backend.
– **Platform Customization:** Refining the RAG logic and landing page interactions to meet museum standards.

The project development chronology, milestones table, Gantt chart timeline, and advisory meetings are fully documented in the supplementary Planning and Chronology report in the project deliverables under `00_Planeamento/00_Planeamento.pdf`.

6.8 Testing and Validation

Validation combined automated tests with integration checks. The RAG module achieved a 100% pass rate across functional tests (Health, Querying, and Error Handling), with an average execution time of 24.89s for the complete suite. For a comprehensive overview of the testing cases, pytest code execution logs, and detailed descriptions of the graphical FMU test harness, the reader is referred to the supplementary Testing and Validation report in the deliverables directory under `04_Teste/04_Teste.pdf`.

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