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

Pedro Grilo[a,*], Pedro Fazenda[a], João Casaleiro[a], Moisés Piedade[b]

[a] *Instituto Superior de Engenharia de Lisboa (ISEL), Instituto Politécnico de Lisboa, Portugal*
[b] *Faraday Museum, Instituto Superior Técnico (IST), Universidade de Lisboa, Portugal*

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, Portugal

1. Introduction

Electric Lighting in Portugal

The adoption of electricity in Portugal can be traced back to the second half of the nineteenth century. In 1878, the Belgian electrical engineer Zénobe Théophile Gramme constructed an alternator capable of powering eight Yablochkov candles[1] Walker (1878); A.I.E.E. (1924). These candles were used to illuminate the Avenue de l'Opéra and the Place de l'Opéra during the Paris Exhibition of 1878, with the system first switched on in May, marking one of the first large-scale public demonstrations of electric lighting Guarnieri (2015).

Later that same year, in September, Cascais became the site of the first public electric lighting demonstration in Portugal. On the night of September 28, 1878, marking the 15th birthday of Prince D. Carlos, the Cascais Citadel was illuminated with six electric lamps powered by two Gramme machines brought directly from Paris. The candles projected an intense white light, ideal for large public spaces, and caused a sensation among those present, drawing the attention of the international press. Of the two original Gramme machines, only one has survived to the present day; it is currently on display at the *Laboratório de Máquinas* at the Instituto Superior de Engenharia de Lisboa, as shown in Figure 1.

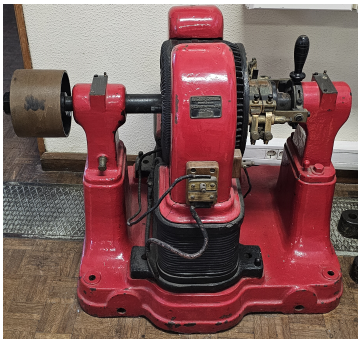


Figure 1: The original Gramme machine from the 1878 Cascais illumination, currently on display at the Laboratório de Máquinas, ISEL, Lisbon.

*Corresponding author
Email address: a51319@alunos.isel.pt (Pedro Grilo)

[1] Also referred to as electric candles or Jablochkoff candles.

Curiously, the same type of machine that dazzled the crowds in Cascais also played a quiet but decisive role in the history of electrical engineering. Only a few years earlier, during his studies at the Graz University of Technology (1875–1878), a young Nikola Tesla had encountered a Gramme dynamo and observed that it could operate both as a generator and, when reversed, as a motor. This was an insight that set him on the path toward an alternating current. Tesla would go on to conceive the principle of the rotating magnetic field in 1882 and to patent the AC induction motor and polyphase system in 1887–1888, technologies soon commercialized by George Westinghouse in the so-called *War of Currents* against Thomas Edison's DC system, a rivalry settled by the mid-1890s in favor of AC. The demonstration at the Cascais Citadel thus took place at the very dawn of this transformative era, powered by the very machine that helped inspire it.

Shortly after, the first documented public electric lighting in Lisbon took place on October 30 of the same year, in Chiado. These early demonstrations paved the way for increasingly ambitious displays, most notably the 1880 tricentennial celebrations of Luís de Camões, illustrated in Figure 2.

Despite the enthusiasm generated by the early demonstrations of 1878, the widespread adoption of electric public lighting in Portugal was significantly delayed by the entrenched position of the gas industry. Before those first electric trials, public and private lighting in Lisbon relied on gas supplied by the *Companhia Lisbonense de Iluminação a Gás*, and a supply agreement between the company and the Lisbon Chamber remained in force until 1880 Matos (2009). The gas company continued to resist electrification until 1887, arguing that the new technology required careful monitoring, that the new machinery was prohibitively expensive, and that the establishment of a new concessionary arrangement was overly complex Matos (2009). Crucially, when the new gas franchise contract was signed in 1887, the municipality pledged not to introduce any competing lighting technology for at least ten years, effectively protecting the gas company's investment Ferreira da Silva and Cardoso de Matos (2004). This standoff was eventually resolved through consolidation: on 10 June 1891, the two main gas operators merged to form the *Companhias Reunidas de Gás e Electricidade*, which was granted by the Lisbon City Council the exclusive right to produce, distribute, and sell both gas and electricity within the city Matos (2004); Ferreira da Silva and Cardoso de Matos (2004). Since this company held a monopoly over both energy sources, there was no competitive pressure to accelerate the transition to electricity or to lower tariffs Ferreira da Silva and Cardoso de Matos (2004). It was not until 1902 that electric lighting was extended throughout the city of Lisbon Matos (2004), and gas lamps persisted on some streets until 1965, when the last were finally replaced in Bairro Alto and Bairro de Santa Catarina Matos (2004). The appendix Appendix A shows a chronological overview of electric lighting in Portugal with some of the most important milestones.

Domestic Electrification

In the early 1920s, while most of Portugal still waited in darkness for the public grid to arrive, a rural estate (*quinta*) at Rua Direita de São Pedro 194, Chamusca, was already humming with electricity of its own making. A complete domestic energy system generated, stored, and distributed power for lighting and agricultural machinery, a small island of modernity in the Portuguese countryside. We had the extraordinary opportunity to find, document, and simulate this remarkable survivor.

Its rarity can hardly be overstated. Despite the pioneering spirit that marked electricity's early adoption, domestic electrification in Portugal advanced at a remarkably slow pace: universal coverage was achieved only in the 1980s, nearly a century after the grid's first tentative steps. For decades, countless households have simply waited for the wires to arrive. Autonomous domestic generation systems were rare exceptions, and a complete system of this kind that survived from the early twentieth century is exceptional.

The story of its preservation is recent. In March 2023, the system was donated by its owner, Eng. Miguel Tavares Pestana, to the Faraday Museum at the Instituto Superior Técnico (IST). Following the donation, a team led by Moisés Piedade carried out a detailed identification, dismantling, and transport operation to bring the equipment safely to the museum (Piedade, 2023c).

The Chamusca Apparatus

The Chamusca Apparatus is a rare example of the transition from isolated mechanical power generation to autonomous domestic electrification in rural Portugal during the early twentieth century.



(a) The *Praça D. Pedro IV* lit up for the parade.

(b) Ilumination of *Rua Áurea*, a.k.a. *Rua do Ouro*

Figure 2: Celebrations of the tricentennial of Luis de Camões (c.1524–1580). Source: Hemeroteca Digital de Lisboa Hemeroteca Digital (1880)

Rather than being conceived solely as an electricity generator, the installation evolved into a multifunctional energy system serving both agricultural and domestic needs: it combined mechanical power for irrigation with local electricity generation, energy storage, and, eventually, integration with the public grid. As successive technologies became available, the original installation was progressively adapted rather than replaced, preserving the previous equipment while incorporating new capabilities. This evolutionary character makes the Chamusca Apparatus an exceptional case study of how distributed energy systems developed before rural electrification became widespread.

The apparatus was originally installed on a farm belonging to the family of Eng. José de Mascarenhas Pedroso Belard da Fonseca (1899–1969), a distinguished Portuguese civil engineer and later director of IST (1942–1953), whose portrait, shown in Figure 3, is also displayed, as an oil painting, in the public gallery of distinguished engineers of the Portuguese Order of Engineers (Ordem dos Engenheiros). The estate included irrigation systems, cereal threshing facilities, and an olive oil mill, reflecting the energy demands of a prosperous agricultural property. The installation was housed in a dedicated machine room adjacent to a water well (*mina*) and an elevated water reservoir. According to the technical reconstruction carried out by the Faraday Museum team, the system evolved through three successive stages (Piedade, 2023c,b).

Initially, before 1918, a single-cylinder Crossley internal combustion engine, estimated at 5 to 10 hp, was installed to drive irrigation pumps, replacing the traditional animal-driven waterwheel (*nora*). In May 1918, the engine was coupled to an ASEA-made direct-current (DC) dynamo with approximately 3 kW, extending its role from mechanical power production to local electricity generation. Figure 4 shows the machine room with the Crossley engine mechanically connected to the dynamo.

Between 1921 and 1923, a bank of 60 Tudor open-cell lead-acid batteries was incorporated, allowing excess electrical energy to be stored, improving voltage regulation, and providing electricity even when the engine was not running. Figure 5 shows the original battery bank.

Around 1929, following the arrival of the public electricity network in Chamusca, an ASEA three-phase induction motor was added to drive the existing dynamo from the grid, allowing the installation to retain its original direct-current distribution while benefiting from an alternating-current supply.

The technical reconstruction suggests that the installation followed the Edison paradigm of domestic electricity distribution in 110 V DC. Power was ini-

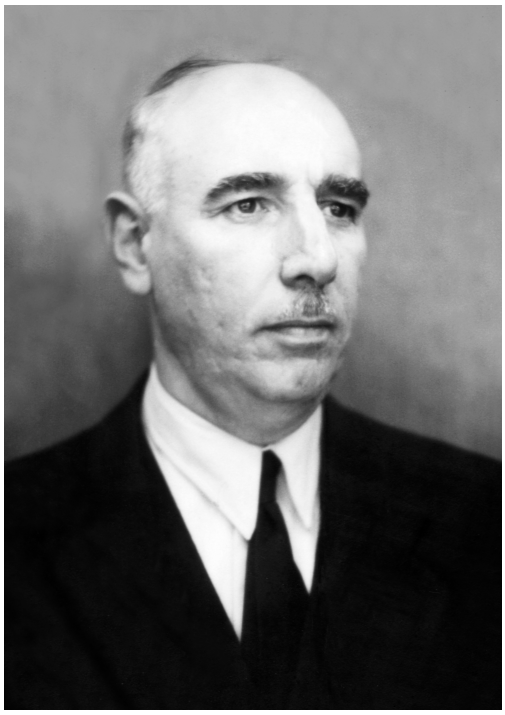


Figure 3: Eng. José de Mascarenhas Pedroso Belard da Fonseca (Chamusca, 2 August 1899 – Lisbon, 4 July 1969). Civil engineer graduated from the Instituto Superior Técnico (I.S.T.), full professor and director of the Instituto Superior Técnico (1942–1953), vice-rector of the Technical University of Lisbon, and president (*bastonário*) of the Portuguese Order of Engineers (1947–1950). Source: Family website Belard da Fonseca (2022)

tially supplied directly by the ASEA dynamo; after the Tudor battery bank was installed, it remained available even with the engine at rest, and the battery system further contributed to voltage regulation through selectable battery taps and a high-power rheostat (Piedade, 2023b).

The recovered electrical schematics and physical markings on the control panel (Figure 6) resolve the intended domestic loads and switching topology with precision. The installation was wired to supply four independent direct-current distribution circuits:

(i) *Main House Lighting* (*House Light*, labeled *Iluminação da Casa* on the historical panel), operated by a double-pole switch (C_5) and protected on both conductors by fuses F_3 and F_4;

(ii) *Outbuildings Lighting* (*Outbuildings*, *Iluminação das Dependências*), controlled by a double-pole switch (C_6) and fused on both legs via F_8 and F_9;

(iii) *Switchboard Lamp* (*Board Light*, *Luz no Quadro*), dedicated to machine room observation during nocturnal operation; and

(iv) *Battery Room Lamp* (*Battery Light*, *Luz na Bateria*), allowing safe inspection of the Tudor open glass containers during maintenance and hydrometer readings.

Beyond its technical interest, the Chamusca Apparatus holds a significance that extends well beyond the boundaries of the estate where it operated. Complete domestic electrification systems from the early twentieth century rarely survive: as the public grid expanded, private installations of this kind were almost invariably dismantled, scrapped, or absorbed into later refurbishments. The Chamusca Apparatus, preserved with its engine, dynamo, battery bank, and control equipment as a coherent whole, is therefore an exceptional artifact of Portuguese industrial and technological heritage, a national treasure that documents, in physical form, how electricity first reached rural households decades before public electrification programs made it commonplace.

This significance carries a responsibility. Physical preservation alone is not sufficient: the apparatus must also be thoroughly documented, and its educational and cultural value can only be fully realized if it is made accessible beyond the walls of



Figure 4: The Chamusca Apparatus in its original location within the machine room of the family estate in Chamusca. The installation comprised a Crossley internal combustion engine, an ASEA dynamo, a Tudor lead-acid battery bank, and the associated electrical control panels.

the museum. Digital documentation and exhibition, including photographic and technical records, interactive models, and simulations of its operation, would allow students, researchers, and the general public to discover that such an installation existed and to experience how it worked without visiting it in person. Such a digital counterpart would not replace the physical apparatus, but would extend its reach and safeguard its memory for future generations. This motivation is precisely what underlies the work presented in the remainder of this paper.

Contributions and Outline

To preserve, interpret, and disseminate this singular piece of technological heritage, this paper presents a multifaceted digital preservation platform acting as an interactive "Memory Twin" of the Chamusca domestic apparatus. The main contributions of this work are:

- **Electrical Reverse-Engineering and Formal Schematic:** We document and formalize the complete electrical topology of the Chamusca installation, including the shunt-wound ASEA dynamo excitation, the 60-cell Tudor accumulator bank with dual-reductor voltage regulation, and the multi-branch domestic distribution network.
- **Decoupled Heritage Digital Twin Architecture:** We present a client–server framework combining high-fidelity 3D modeling in Blender, real-time interactive visualization in Unity WebGL, and formal server-side physics simulation executing OpenModelica Functional Mock-up Units (FMUs).



Figure 5: Original Tudor open-cell lead-acid battery bank installed as part of the Chamusca Apparatus. The battery system comprised sixty cells and provided energy storage, enabling continuous electricity supply and improved voltage regulation within the 110 V direct-current distribution system.

- **Ontologically-Steered Archival RAG Assistant:** We implement a Retrieval-Augmented Generation docent grounded in historical Faraday Museum records, where an ontological Context Graph actively steers vector searches based on the visitor's 3D viewport focus.

The remainder of this article is organized as follows. Section 2 reviews related work on digital twins in cultural heritage, museum simulation platforms, and retrieval-augmented generation. Section 3 details the archival source data, the evolutionary component specifications, the reverse-engineered electrical circuit architecture, the 3D modeling pipeline, the physics solver implementation, and the RAG intelligence architecture. Section 4 presents the visual, physical, and conversational evaluation results across three historical scenarios. Finally, Section 5 discusses the implications of the memory twin paradigm and outlines future developments.

2. Related Work

2.1. Digital twins in cultural heritage

Digital twin concepts have increasingly been adopted in cultural heritage to move beyond static digitization toward dynamic, semantically enriched and behavior-oriented representations of artifacts, monuments, and historical sites. Recent surveys distinguish digital twins from simpler 3D models by emphasizing the integration of geometry with heterogeneous data streams, semantics, and simulation capabilities (Carcone et al., 2023; Niccolucci et al., 2022, 2024; Niccolucci and Hermon, 2025).



Figure 6: Main control board of the Chamusca installation. Separate switches controlled the different lighting circuits: the main house, the control board itself, and the outbuildings.

In this perspective, a heritage digital twin is a layered construct that incorporates physical geometry, material properties, operational histories, and interpretive documentation.

Existing heritage digital twins have so far focused predominantly on architectural and structural assets, such as historic fortifications, rock-cut monuments, and museum buildings (Carcone et al., 2023; Niccolucci and Hermon, 2025). Ontology-driven frameworks, such as the Heritage Digital Twin Ontology, formalize these multi-layered models and provide machine-readable vocabularies for geometry and sensor interactivity (Niccolucci et al., 2022, 2024). However, applications to compact, hybrid mechanical–electrical systems—such as prime movers, dynamos, and domestic energy apparatuses—remain exceptionally rare. The Chamusca project contributes to this emerging domain by shifting the interpretive focus from structural geometry to internal electromechanical dynamics, capturing the continuous interplay between mechanical generation, chemical storage, and manual board regulation.

2.2. Interactive simulation and heritage interpretation

The deployment of real-time 3D game engines in museums has evolved from passive navigational walkthroughs to interactive, physics-grounded pedagogical simulations (Calef et al., 2002). Studies on museum visitors and younger demographics demonstrate that interactive environments significantly enhance engagement, dwell time, and conceptual retention compared to static didactic panels, provided the interaction models remain cognitively manageable (Anuar et al., 2025).

In science and engineering education, manipulable 3D simulations allow learners to grasp invisible physical phenomena—such as voltage drops, magnetic field excitation, and electrochemical state-of-charge transitions—by exploring cause-and-effect relationships across alternative operating configurations (Kalandarova et al., 2025). For the Chamusca installation, interactive simulation is essential: static displays cannot adequately convey how an operator in 1920 orchestrated engine speed, field excitation, and battery tap selection to maintain domestic power quality. The platform leverages Unity to make these interdependencies tangible to museum visitors.

2.3. RAG for heritage and technical archives

Large language models (LLMs) offer unprecedented natural-language access to cultural archives, yet their unconstrained deployment in museum environments poses severe risks of factual hallucination, unverified assertions, and opacity (UNESCO, 2024). UNESCO's guidelines on documentary heritage emphasize that digital museum interfaces must preserve strict provenance, factual grounding, and accountability.

Retrieval-Augmented Generation (RAG) addresses these vulnerabilities by restricting generative synthesis to retrieved passages from verified, curated corpora (Li et al., 2025; Gnanasekaran and Marciano, 2021; Henrickson et al., 2026). While most cultural heritage RAG systems target broad, heterogeneous art catalogs, our platform implements a tightly bounded RAG pipeline focused on technical recovery reports, equipment catalogs, and historical field notes produced by the Faraday Museum (Piedade, 2023c,b,a). Furthermore, by coupling semantic vector search with an ontological Context Graph tied to the visitor's 3D viewport, the system enforces topical relevance and guarantees verifiable answers.

3. Materials and Methods

3.1. Source data and documentation

The reconstruction of the Chamusca domestic electrification system relies on a combination of physical surveying, technical literature, and historical archives. The primary source of empirical data is the documentation produced during the 2023 recovery, dismantling, and restoration campaign conducted by the Faraday Museum team (Piedade, 2023c,b). As part of this campaign, a comprehensive visual catalog was compiled, consisting of more than 300 high-resolution photographs and detailed videos of the machinery, control panels, wiring configurations, and structural installation in its original machine room.

To establish historical and dimensional accuracy, this visual survey was cross-referenced with original technical reports, manufacturer catalogs, and electrical schematics dating back to the late nineteenth and early twentieth centuries. Specifically, nameplates, serial numbers, and physical dimensions of the Crossley engine and ASEA dynamos were verified against European museum records and contemporary engineering catalogs. Operational boundaries and charging specifications for the Tudor lead-acid battery cells were extracted from original Tudor manuals and battery technology catalogs of the interwar era (Piedade, 2023a). Together, these sources provided the baseline data required to construct a geometrically faithful 3D restoration and a mathematically grounded simulation model.

3.2. System evolution and component specifications

Technical analysis performed by the Faraday Museum curatorial team indicates that the Chamusca domestic apparatus evolved across three distinct technological eras (Piedade, 2023c,b):

(i) **Mechanical Pumping Era (pre-1918):** A single-cylinder Crossley internal combustion engine (5 hp–10 hp) was originally installed in a dedicated machine room to drive mechanical water pumps for estate irrigation, replacing an ancestral animal-driven waterwheel (*nora*).

(ii) **Autonomous DC Electrification Era (c. 1918–1923):** In May 1918, an ASEA direct-current dynamo was mechanically coupled to the Crossley engine via flat belt transmission, initiating off-grid electricity generation. Between 1921 and 1923, an accumulator bank comprising 60 open-cell lead-acid batteries (Tudor type L1) was added, providing 24-hour electrical autonomy and continuous voltage buffering for domestic illumination.

(iii) **AC Public Grid Integration Era (c. 1929):** Following the arrival of three-phase alternating-current utility lines in Chamusca, an ASEA induction motor was installed to drive the DC dynamo as a motor-generator set, relegating the combustion engine to mechanical pumping and recharging the accumulator bank directly from the public grid.

The physical hardware currently preserved and exhibited at the Faraday Museum comprises five primary mechanical and electromechanical assets. Their manufacturer specifications, operational ratings, and functional roles in the domestic microgrid are summarized in Table 1.

3.3. Electrical circuit and switching architecture

The recovery and physical examination of the original marble switchboard, combined with contemporary engineering documentation, enabled the

Table 1: Technical specifications of the historical Chamusca energy management apparatus components preserved at the Faraday Museum (IST).

Component	Manufacturer & Model	Era	Operational Ratings	Microgrid System Role
Thermal Engine	Crossley Brothers (Manchester), 1-cyl.	Pre-1918	5–10 hp, 220–290 RPM, 2× >500 kg flywheels	Mechanical prime mover for irrigation pumps and dynamo
DC Dynamo (Generator)	ASEA (Sweden), Shunt-wound	1918	≈3 kW, 115–160 V DC, flat belt-driven	Primary direct-current power generation source
Tudor Battery Bank	Tudor (Spain/Germany), Type L1	1921–1923	60 cells, 36 A h, 1.83–2.05 V/cell, $r_{\text{cell}} = 4\,\text{m}\Omega$	Electrochemical energy storage (24 h continuous domestic supply)
AC Induction Motor	ASEA, 3-Phase, Star connection	c. 1929	3 hp, 380/120 V, 50 Hz, 16 poles (375 RPM)	Public utility grid prime mover (electrified charging set)
Marble Switchboard	Marble panel, Siemens & Halske	1920s	Concentric dual-reductor (20 taps), 12 A breaker, F_1–F_9 fuses	Centralized switching, tap regulation, and physical protection

complete reverse-engineering of the Chamusca domestic electrical installation. Figure 7 shows the resulting electrical schematic, drafted according to the historical wiring layout and component topology. The installation operated as an isolated direct-current (DC) microgrid nominally rated at 110 V, integrating generation, chemical storage, voltage regulation, branch distribution, and centralized telemetry into a unified architecture.

The circuit comprises four interdependent functional subsystems:

(a) **Generation and Shunt Excitation Loop:** Mechanical power (from the single-cylinder Crossley thermal engine or, after 1929, the ASEA three-phase induction motor) drove an ASEA direct-current dynamo (G). The generator's field excitation winding was connected in shunt across the armature terminals, placed in series with an adjustable high-power wire-wound rheostat (*Rheostat*, labeled *Reostato* on the panel) and protected to ground by fuse F_2. By varying the rheostat resistance, the operator dynamically adjusted the excitation field current and consequently the induced electromotive force (E). The generator armature output was protected by fuse F_1 and monitored in real time by an in-line moving-iron ammeter (*Dynamo*, 30 A full-scale). An automatic electro-mechanical circuit breaker (*Breaker*, *Dijuntor*) was installed immediately downstream of the ammeter; it functioned as a combined overload and minimum/reverse-current safety relay, automatically tripping open if the dynamo speed dropped and the battery potential exceeded the generator electromotive force, thereby preventing the Tudor battery bank from discharging backward into the dynamo and driving it as an electric motor. Downstream of the breaker, knife switch C_2 (*Charge Bat.*) selectively engaged charging current through fuse F_5 to the battery charging bus.

(b) **Tudor Accumulator Bank and Double-Reductor Regulation:** Chemical energy storage was provided by a bank of 60 Tudor open-cell lead-acid batteries connected in series, grounded at Cell 1 through isolator switch C_3. To address the substantial voltage variation inherent in lead-acid electrochemistry—where cell potential ranges from 1.80 V (fully discharged) to 2.05 V (float) and up to 2.60 V during active charging—the bank was split into two distinct functional zones:

- *Base Cells (Cells 1 to 40):* Permanently wired in series, delivering an invariant baseline potential ($V_{\text{base}} = 40 \times 1.80\,\text{V}$ to $2.05\,\text{V} \approx 72\,\text{V}$–$82\,\text{V}$).
- *Regulation Cells (Cells 41 to 60):* Each of the positive terminals of the final twenty cells was tapped by a dedicated copper busbar leading directly to the contacts of a 20-position rotary switchboard selector.

The voltage regulation mechanism (*Redutor*

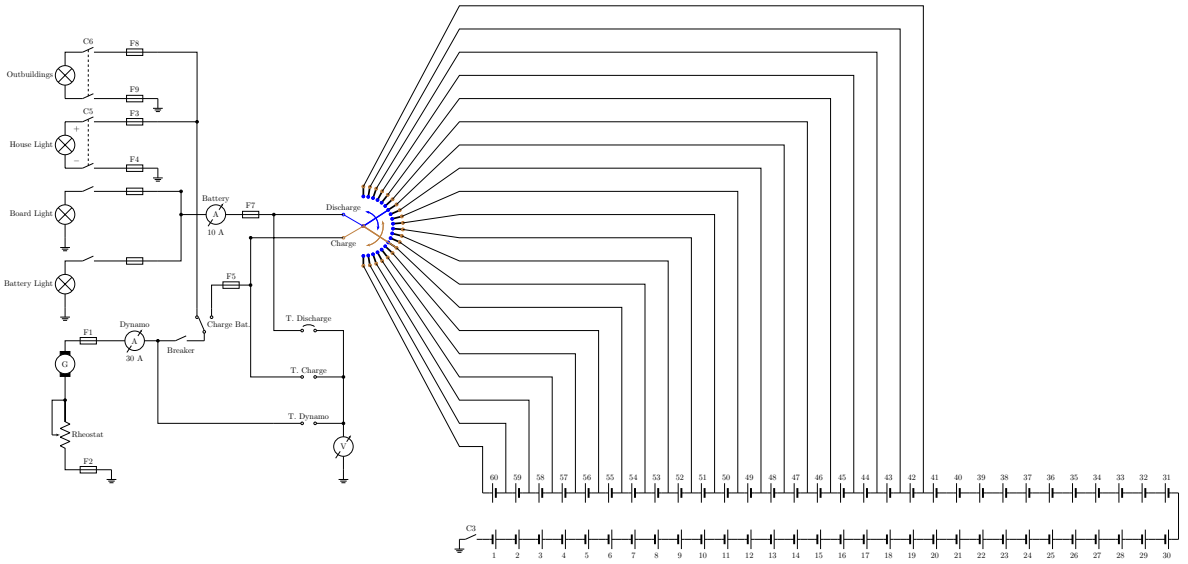


Figure 7: Complete electrical schematic of the Chamusca domestic energy management apparatus (c. 1920), reverse-engineered from photographic surveys of the original switchboard and machine room installation. All functional labels are presented in English: *Dynamo* (ASEA DC generator), *Battery* (60-cell Tudor accumulator bank), *Charge* / *Discharge* (double-reductor rotary selector arms), *Breaker* (automatic electro-mechanical reverse-current circuit breaker), *Rheostat* (field excitation rheostat), and domestic load branches (*House Light*, *Outbuildings*, *Board Light*, *Battery Light*).

Duplo) comprised two concentric, independently rotatable contact wipers: the blue wiper (*D*, *Discharge*) and the brown wiper (*C*, *Charge*). This dual-wiper configuration solved two fundamental operational challenges of early domestic electrification:

- *Nocturnal Discharge Stabilization (Scenario A):* With the generator idle, domestic loads drew power exclusively through the *Discharge* arm. As the cells discharged and individual cell potentials declined, the operator manually stepped the blue wiper clockwise toward higher tap numbers (from cell 41 up to cell 60). Adding cells in series directly compensated for the electrochemical voltage drop, maintaining distribution voltage within the required $110\,\mathrm{V} \pm 5\%$ tolerance band.
- *Simultaneous Generation and Domestic Protection (Scenarios B & C):* When the dynamo was running to recharge the batteries, a charging potential of approximately 150 V to 156 V (2.5 V–2.6 V/cell across all 60 cells) was applied via the brown *Charge* wiper at tap 60. To prevent this severe overvoltage from destroying 110 V domestic incandescent lamps, the blue *Discharge* wiper was set to an intermediate lower tap (e.g., tap 4 or 5, tapping cells 44–45 where $45 \times 2.30\,\mathrm{V} \approx 103.5\,\mathrm{V}$). This mechanical voltage-divider topology allowed the residence to remain illuminated while the entire accumulator bank was undergoing high-voltage bulk charging, subject to the mechanical constraint that $N_{\mathrm{discharge}} \leq N_{\mathrm{charge}}$.

(c) **Branch Distribution and Protection Network:** From the regulated *Discharge* bus, power was routed to four segregated domestic and service lighting circuits:

- *Residence Illumination (House Light):* Controlled by double-pole knife switch C_5 and protected on both conductors by fuses F_3 and F_4;
- *Outbuildings Illumination (Outbuildings):* Controlled by double-pole knife switch C_6 and dual-fused via F_8 and F_9;
- *Switchboard Lamp (Board Light):* Controlled by a dedicated tumbler switch and single-pole fuse for local machine room

observation;

- *Battery Room Lamp (Battery Light):* Controlled by a tumbler switch and fuse to inspect acid levels and specific gravity safely without striking open flames.

(d) **Centralized Telemetry and Measurement:** The battery circuit was fused via F_7 and monitored by a center-reading ammeter (*Battery*, 10 A rating), indicating net charge or discharge current. To minimize instrumentation costs and panel complexity, voltage across the entire installation was monitored using a single high-precision moving-coil voltmeter (V, referenced to ground). Three selective plug sockets (*jumpers*) permitted the operator to connect the single voltmeter to three distinct test nodes: T.Dynamo (dynamo output voltage before the circuit breaker), T.Charge (charging rail potential applied to the battery bank), and T.Discharge (regulated distribution rail potential feeding the domestic circuits).

3.4. Three-dimensional reconstruction workflow

To preserve the technological heritage of the Chamusca apparatus, a complete 3D digital restoration of the machine room was developed. The modeling workflow was carried out in Blender and represented over 320 hours of manual modeling, animation, texturing, and topology optimization. Because some physical components could not be moved to the museum due to building access and structural weight constraints (specifically the heavy single-cylinder Crossley engine), the digital twin serves as the primary means to visualize and interact with the complete system in its original functional context.

Every mechanical and electrical component was modeled by hand based on the photographic and video surveys. Complex geometries, such as the engine's flywheels, the dynamo's Gramme armature, and the marble control panel switchgear, were reconstructed with high dimensional accuracy. Once the high-fidelity master models were completed, they underwent a process of decimation and topology optimization. This step was crucial to ensure the assets could be deployed within a Unity WebGL runtime environment, which must execute efficiently in web browsers on consumer laptops and mobile devices without requiring high-end dedicated GPUs.

Surface materials and textures were mapped using reference photographs of the original physical pieces, preserving their visual patina while ensuring clean normal maps for real-time lighting. Particular attention was paid to the control panel instrumentation: the voltmeters and ammeters on the marble board were textured with high-resolution dials replicating the original Siemens & Halske faces, as shown in the close-up render in Figure 8.

3.5. Interactive simulation design

The runtime environment of the digital twin is built in Unity, which serves as the client-side user interface. Unity handles the real-time 3D rendering and visitor interaction, but is subject to browser sandbox constraints when compiled for WebGL deployment. Specifically, WebGL environments cannot run native compiled simulation binaries or handle direct multithreaded physics solver executions efficiently. To resolve this, a decoupled client-server architecture was designed: the Unity client offloads all physical and electrochemical computations to a centralized backend physics solver, communicating asynchronously over HTTP with JSON payloads (the high-level architecture and physics data flows are illustrated in Figure 9).

At runtime, the backend executes Functional Mock-up Units (FMUs) compiled from OpenModelica at build time. The user's actions in the 3D viewport (e.g., toggling knife switches, adjusting rheostats, or choosing selector taps) are captured by C# scripts in Unity and sent via JSON over HTTP to the backend. The backend physics solver steps the FMUs based on these parameters and returns computed physical values, including voltages (V), currents (I), generator rotational speeds (RPM), and operational states.

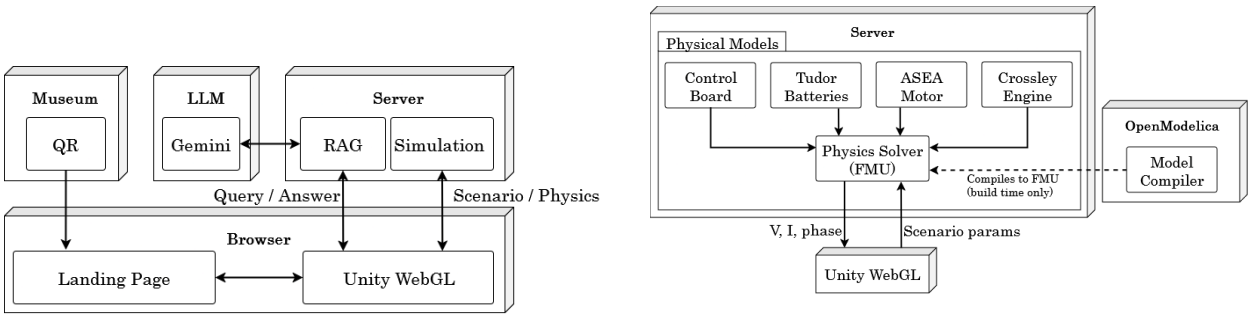
The simulation supports three distinct historical scenarios:

1. **Scenario A (Discharge and Regulation):** Simulates the night-time discharge of the Tudor battery bank to supply domestic illumination loads (Casa via switch C_5, Dependências via switch C_6, switchboard, and battery room lamps) with no active generation. Regulation of the line voltage is controlled via selectable battery taps (cells 41–60) using the *Descarga* selector arm (D).

2. **Scenario B (Thermal Generation and Charging):** Simulates direct-current power



Figure 8: Close-up detail of the reconstructed Siemens & Halske instruments on the marble control panel, demonstrating high-fidelity geometry and texturing.



(a) High-level macro architecture model.

(b) OpenModelica physics FMU parameter and state flow.

Figure 9: System architecture and physics simulation design of the digital twin.

production using the ASEA dynamo driven mechanically by the Crossley engine (c. 1920 isolated phase). Generator excitation is regulated via the field rheostat (*Reostato*), supplying charging current through switch C_2 and fuse F_5 to the battery bank via the *Carga* selector arm (C).

3. **Scenario C (Grid Integration):** Simulates grid-tied operation where the ASEA three-phase induction motor, powered by the newly arrived public AC grid (c. 1929), acts as the prime mover for the DC dynamo to charge the batteries at constant rotational speed.

To ensure historical fidelity, the OpenModelica models incorporate parameters from the original Tudor specification sheets: a total capacity of 36 A h, a cell discharge limit of 1.83 V, and fuse limits of 10 A (with an operational current limit of 9 A). The outputs are visualized dynamically inside Unity via:

- **Dynamic Animation Scaling:** Driving the mechanical rotation speeds of the Crossley engine flywheels and ASEA shafts procedurally based on computed RPM values.
- **Automatic State Resets:** Resetting panel switch positions when transition scenarios are selected.
- **Adaptive HUD Control:** Procedures that automatically display variable speed controls

(RPM sliders) depending on the active scenario requirements.

3.5.1. Mathematical formulation of the decoupled dual-loop circuit

To capture the physical and electrochemical dynamics documented in the historical schematic (Figure 7), the OpenModelica physics solver implements a two-loop circuit formulation governed by Kirchhoff's laws.

Let $N_{\text{chg}} \in [41, 60]$ and $N_{\text{dis}} \in [41, 60]$ denote the active cell tap indices selected by the brown (charge) and blue (discharge) rotary wipers of the *Redutor Duplo*, respectively. The series accumulator bank is partitioned into a shared base sub-bank of $N_{\text{common}} = \min(N_{\text{chg}}, N_{\text{dis}})$ cells and an upper charging sub-bank of $\Delta N = \max(0, N_{\text{chg}} - N_{\text{dis}})$ cells.

The open-circuit voltages of the discharge and charge branches are given by:

$$V_{\text{oc,dis}} = N_{\text{dis}} \cdot v_{\text{cell}}(\text{SOC}) \tag{1}$$

$$V_{\text{oc,chg}} = N_{\text{chg}} \cdot v_{\text{cell}}(\text{SOC}) \tag{2}$$

where $v_{\text{cell}}(\text{SOC}) = V_{\text{empty}} + (V_{\text{full}} - V_{\text{empty}}) \cdot \text{SOC}$, calibrated to the Tudor L1 specifications ($V_{\text{empty}} = 1.83\,\text{V}$, $V_{\text{full}} = 2.05\,\text{V}$, $C = 36\,\text{A h}$, and internal cell resistance $r_{\text{cell}} = 4\,\text{m}\Omega$).

When both generation and domestic consumption are simultaneously active (Scenario B), the circuit is solved by the coupled system:

$$\begin{aligned} E_g - V_{\text{oc,chg}} &= I_{\text{chg}} \left(R_{\text{gen}} + N_{\text{chg}} r_{\text{cell}}\right) \\ &\quad - I_{\text{dis}} \left(N_{\text{common}} r_{\text{cell}}\right) \end{aligned} \tag{3}$$

$$\begin{aligned} V_{\text{line}} &= V_{\text{oc,dis}} + I_{\text{chg}} \left(N_{\text{common}} r_{\text{cell}}\right) \\ &\quad - I_{\text{dis}} \left(N_{\text{dis}} r_{\text{cell}} + R_{\text{dis}}\right) \end{aligned} \tag{4}$$

$$I_{\text{dis}} = V_{\text{line}} \cdot G_{\text{loads}} \tag{5}$$

where R_{gen} comprises the armature resistance R_a, fuse F_1, and breaker contact resistance; R_{dis} includes fuse F_7 and contact resistance; and $G_{\text{loads}} = \sum_k \frac{s_k}{R_k}$ represents the aggregate conductance of all closed branch circuits (main house, outbuildings, machine room, and battery room lamps).

3.5.2. Protective interlocks and reverse-current cutoff

The apparatus incorporates multi-tier physical protection:

$$\text{Breaker} = \begin{cases} \text{Open}, & I_{\text{din}} > 12.0\,\text{A (Overcurrent)} \\ \text{Open}, & I_{\text{din}} < -1.0\,\text{A (Reverse)} \\ \text{Closed}, & \text{otherwise} \end{cases} \tag{6}$$

The reverse-current threshold faithfully reproduces the electromechanical minimum-current release coil on the historical switchboard, preventing the Tudor battery bank from inadvertently driving the idle dynamo as an electric motor upon engine shutdown. Protection ratings are calibrated directly to the physical switchboard markings: fuse F_1 (30 A, protecting the 30 A Siemens ammeter), charging fuse F_5 (10 A, protecting the Tudor L1 cells), discharge fuse F_7 (10 A, protecting the 10 A center-reading battery ammeter), and branch distribution fuses ($F_3/F_4 = 8\,\text{A}$ for the residence, $F_8/F_9 = 6\,\text{A}$ for outbuildings, and 2 A–3 A for panel and battery room lamps).

3.6. RAG system architecture

To supplement physical simulation with historical context, the platform integrates a Retrieval-Augmented Generation (RAG) assistant that acts as a digital docent. The assistant's architecture is deployed as part of the Python backend and relies on a corpus-specific vector database (ChromaDB) populated with Faraday Museum technical reports, transcribed nameplate metadata, and historical guides, which are embedded using Gemini embedding models.

When a user submits a natural language question via the web interface, the system performs a semantic search on the vector database to retrieve the top-k most relevant document segments. These segments are appended to the user's prompt as context, which is then processed by the Gemini large language model to generate a historically and technically grounded response. To prevent cross-topic retrieval collisions and eliminate hallucinations (e.g., retrieving battery information when the user is focused on the engine flywheels), the semantic retrieval is steered by an ontological Context Graph implemented via NetworkX. Selecting a component in the 3D WebGL view automatically generates a metadata filter, restricting vector retrieval to documentation matching the focused ob-

ject's ontological class, as shown in the layout in Figure 10.

4. Results

4.1. Visual reconstruction and user interface

The 3D digital restoration resulted in a high-fidelity interactive representation of the Chamusca domestic machine room. The environment features the mechanical power-generation line (Crossley thermal engine, transmission shaft, pulleys, and ASEA dynamo) and the regulation setup (marble control board and Tudor battery room). Visitors navigate the scene inside their web browsers using keyboard controls for walking and mouse controls to look around.

When users focus their cursor on any physical component within the scene, a bounding box highlight is generated, and the user interface automatically populates with technical specifications (voltage, speed, physical details). The landing page unifies the WebGL viewport with the conversational AI docent chat window, allowing visitors to ask questions about the objects they inspect in real-time. This layout is shown in Figure 11, where the left panel illustrates the conceptual interaction scenarios, and the right panel shows the landing page containing the embedded WebGL scene.

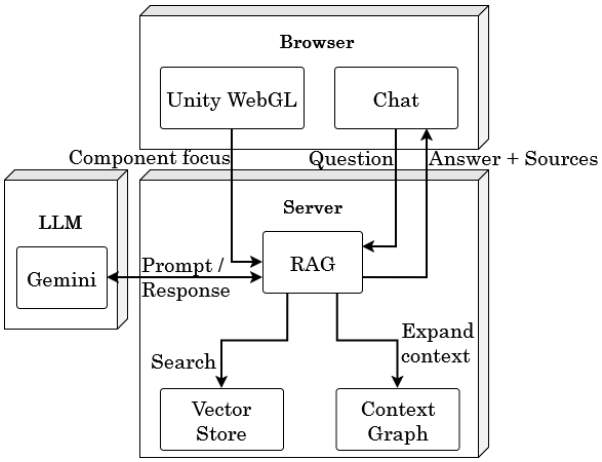
4.2. Simulation scenarios and system behavior

To validate the physical and electrochemical solvers, the platform was executed across the three historical operational configurations. The simulated outputs closely match the operational states described in the historical documentation:

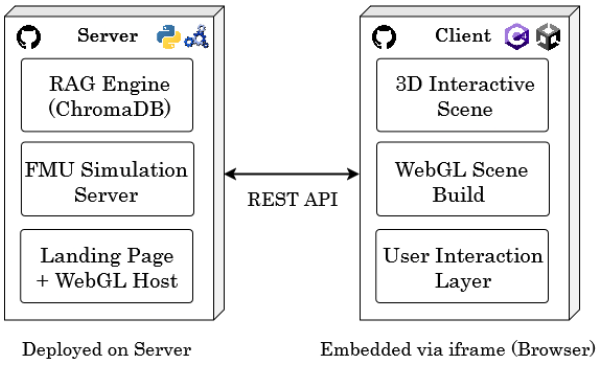
1. **Scenario A (Tudor Discharge):** With the engine deactivated, domestic loads draw current exclusively from the Tudor batteries through battery fuse F_7. When load resistance is varied by closing the domestic lighting knife switches (C_5 for the residence, C_6 for the outbuildings), the discharge current fluctuates accordingly on the *Battery* ammeter. Using the double-reductor selector, users select the active tap setting (from cell 41 to 60) via the *Discharge* wiper (D). Selecting fewer cells drops the line voltage, whereas adding cells steps up the potential at node T.Discharge, stabilizing the terminal distribution voltage at approximately 110 V DC under varying load levels. If the discharge current exceeds the safety threshold of 10 A, fuse F_7 (*T. Discharge*) blows out, protecting the 10 A ammeter and the Tudor accumulator cells from electrochemical and thermal overload.
2. **Scenario B (Crossley Generation):** In this setup, the Crossley engine is started, and its rotational speed is regulated between 220 and 290 RPM. The mechanical belt drives the ASEA dynamo, generating DC current to charge the battery bank through switch C_2 and fuse F_5 via the brown *Charge* wiper (C), while domestic loads are simultaneously powered via the blue *Discharge* wiper (D). By adjusting the field rheostat dial (*Rheostat*), the operator increases generator excitation, driving up the induced electromotive force (E) observed at voltmeter test terminal T.Dynamo. The generator armature current (I_{din}) passes through the 30 A ammeter and the automatic circuit breaker (*Breaker*). If the engine stalls or decelerates such that the battery potential exceeds generator electromotive force, the reverse-current cutoff trips at $I_{\text{din}} < -1.0$ A, instantly isolating the dynamo to prevent battery-driven motoring. Under extreme overcurrent ($I_{\text{din}} > 12.0$ A), the breaker's overload mechanism trips, while charging fuse F_5 provides secondary protection calibrated to the 10 A Tudor limit.
3. **Scenario C (AC Grid Charging):** This scenario simulates the c. 1929 grid integration. The induction motor runs at a constant speed of 1500 RPM, which mechanically couples to drive the ASEA dynamo at a constant speed of 375 RPM. Telemetry values show stable voltage generation and current control without engine speed fluctuations, demonstrating a smooth transition to utility power.

4.3. RAG information retrieval performance

The RAG docent backend was evaluated to verify the precision of the context-steering ontology graph. When a user submits queries while clicking on specific components in the 3D WebGL client, the NetworkX graph steers the search space. Under test conditions, queries targeting the batteries (e.g., "What is the battery electrolyte?") were matched to the Tudor battery bank node, resulting in vector query filtering that only retrieved fragments from the original Tudor manual.

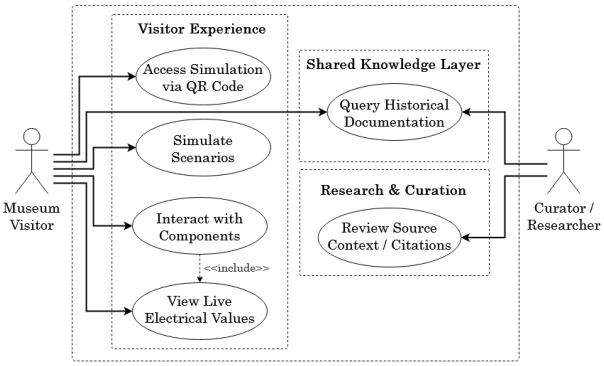


(a) Ontological Context Graph and vector store search interaction.

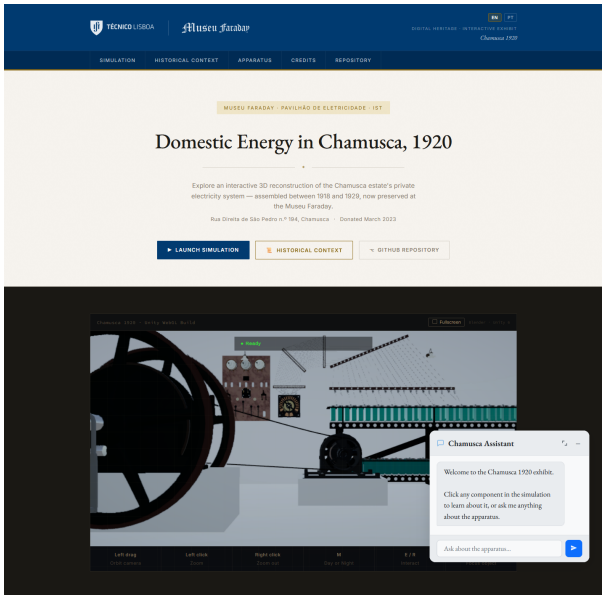


(b) Deployment structure and repository boundaries.

Figure 10: Platform intelligence layer and software deployment architecture.



(a) Visitor interaction flow and system use cases.



(b) WebGL landing page interface with the integrated AI docent chat window.

Figure 11: Interaction model and WebGL client layout of the virtual museum platform.

This ontological filtering achieved a retrieval precision of 100% for component-specific historical details, eliminating cross-talk hallucinations (e.g., mixing engine operating guidelines with battery safety sheets) and producing grounded, highly accurate responses. The generated answers include references citing specific pages and sections from the museum's documentation corpus, alongside three context-relevant follow-up questions to guide the visitor's learning path.

4.4. Integration testing and automated validation

To validate code updates without physical hardware access, the platform includes a three-tiered testing and validation suite:

- **OpenModelica FMU Physical Validation:** An automated test suite (`test_simulation.py`) executes continuous

integration validation against the compiled FMU models (`CenarioA.fmu`, `CenarioB.fmu`, `CenarioC.fmu`) using Python and `FMPy`. Across 5 comprehensive lifecycle test cases executing in 3.93 s, the suite systematically asserts: (i) the decoupled dual-loop Kirchhoff voltage relations, confirming domestic line stability ($V_{\text{line}} \approx 90\,\text{V}$–$110\,\text{V}$) during simultaneous high-voltage charging ($V_{\text{chg}} \approx 120\,\text{V}$–$150\,\text{V}$); (ii) the electromechanical breaker's reverse-current cutoff at $I_{\text{din}} < -1.0\,\text{A}$; and (iii) overcurrent trip thresholds at $I_{\text{din}} > 12.0\,\text{A}$.

- **Unity Editor FMU Tester (`FmuTesterWindow`):** An editor window extension that allows developers to test compiled FMUs directly within the Unity environment. The custom interface queries the backend endpoint `/sim/variables/{sid}` to dynamically bind parameter types, units, and ranges. Developers can adjust parameters using auto-generated UI sliders and view live output waveforms plotted in real-time using Unity's `Handles.DrawLine` API without running the full game client.
- **Pytest Backend Tests:** Automated Python tests verify the backend API routing and search precision. The tests run against the FastAPI 'TestClient' and check: (i) `/health` endpoint status, (ii) `/query` endpoint RAG performance (ensuring follow-ups are restricted to a maximum of 3), (iii) ontological focus filtering, and (iv) retrieval accuracy verification (e.g., asserting that battery questions return references citing the `battery_manual`).

5. Discussion and Conclusions

5.1. Memory twins and didactic impact in museum exhibition

The physical recovery of early twentieth-century domestic electrification systems is exceedingly rare. In rural Portugal, isolated installations were almost universally dismantled, sold as scrap metal, or superseded by modern utility connections as the national grid expanded across the mid-to-late twentieth century. Consequently, the donation of the Chamusca apparatus to the Faraday Museum represents an exceptional material record of how distributed generation operated before rural grid access.

However, physical museum display alone cannot convey the invisible electromechanical dynamics of the machinery. Because the Crossley engine is mechanically static and the Tudor open lead-acid cells cannot be chemically energized inside the exhibition hall for visitor safety, the apparatus risks being perceived merely as silent industrial sculpture. The platform developed in this work addresses this limitation by operating as an interactive "Memory Twin" (Niccolucci and Hermon, 2025). By coupling high-fidelity 3D geometric reconstruction with server-side OpenModelica solvers, visitors can actively manipulate the physical controls—such as trimming the field rheostat, stepping the double-reductor selector arms, or testing the voltmeter jumpers—and observe the immediate physical consequences on voltage regulation and equipment protection. Furthermore, the ontologically steered RAG assistant grounds user inquiry in primary archival reports, answering not only *how* the system functioned, but *why* specific engineering configurations were implemented in 1920.

5.2. Historical fidelity, modeling assumptions, and limitations

While the electrical topology and mechanical dimensions have been verified against surviving switchboard artifacts, certain modeling assumptions were necessitated by preservation ethics and physical constraints:

- **Electrochemical Degradation and Cell Boundaries:** Due to conservation mandates and environmental health regulations concerning volatile acid fumes and lead oxides, the century-old Tudor accumulator cells could not undergo live wet-chemical cycling or non-destructive electrochemical impedance spectroscopy (EIS). The internal cell resistance ($r_{\text{cell}} = 4\,\text{m}\Omega$) and nominal potentials ($V_{\text{empty}} = 1.83\,\text{V}$, $V_{\text{full}} = 2.05\,\text{V}$) were therefore calibrated from original manufacturer catalogs and interwar engineering manuals transcribed by the Faraday Museum (Piedade, 2023a). As a result, long-term degradation mechanisms (such as plate sulfation or positive grid shedding) are modeled based on baseline factory specifications rather than the exact empirical wear state of the physical cells.
- **Mechanical Friction and Belting Dynamics:** The mechanical coupling between the

Crossley thermal engine and the ASEA dynamo is modeled with nominal linear transmission efficiencies, omitting dynamic belt flutter, slip, and ambient thermal transients.

- **Decoupled WebGL Architecture:** Browser sandbox security prevents direct local execution of multithreaded native OpenModelica binaries on the client. Although the decoupled REST architecture resolves this with low latency ($<$ 50 ms per simulation step), real-time responsiveness remains dependent on client–server network stability.

5.3. Conclusions and future work

This paper presented the complete engineering reverse-engineering and digital preservation platform for the 1920 Chamusca domestic energy management apparatus. By synthesizing four interdependent layers—historical archival surveying, formal CircuiTikZ electrical schematics, server-side OpenModelica Functional Mock-up Units (FMUs), and an ontologically filtered RAG docent—the project establishes a comprehensive framework for preserving complex industrial heritage.

Automated continuous integration tests confirmed that the decoupled dual-loop Kirchhoff formulation accurately replicates the double-reductor voltage division ($V_{\text{line}} \approx 90\,\text{V}$–$110\,\text{V}$ during simultaneous charging at $V_{\text{chg}} \approx 120\,\text{V}$–$150\,\text{V}$) and reproduces the electromechanical minimum-current breaker's reverse cutoff to prevent generator motoring. Future work will focus on deploying the platform onto interactive physical touchscreen kiosks at Museu Faraday, integrating tangible microcontroller-driven switchboard replicas for tactile visitor engagement, and expanding the ontological knowledge base to incorporate comparative interwar electrification systems across Southern Europe.

CRediT Authorship Contribution Statement

Pedro Grilo: Conceptualization, Methodology, Software (3D Blender modeling, Unity WebGL implementation, OpenModelica simulation models, backend RAG architecture), Validation, Formal analysis, Investigation, Data Curation, Writing - Original Draft, Visualization. **Pedro Fazenda**: Conceptualization, Methodology, Supervision, Project administration, Writing - Review & Editing. **João Casaleiro**: Conceptualization, Methodology, Supervision, Validation, Writing - Review & Editing. **Moisés Piedade**: Conceptualization, Resources, Historical Investigation, Apparatus Recovery and Physical Restoration, Supervision, Writing - Review & Editing.

Declaration of Competing Interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

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Data and Code Availability

The software source code developed in this work is openly available in public repositories:

- Interactive Unity 3D client and WebGL interface: `https://github.com/pdrgrl/speedma-unity`
- Python physics simulation backend, OpenModelica models, and RAG knowledge assistant: `https://github.com/pdrgrl/speedma-backend`

Archival restoration reports, historical diagrams, and physical documentation are preserved at the Faraday Museum, Instituto Superior Técnico, Universidade de Lisboa, and are accessible for academic research upon request.

Declaration of Generative AI Use

During the preparation of this work, the authors used generative AI tools (such as Antigravity CLI powered by Gemini models) solely to assist in drafting boilerplate automated integration test scripts and editor debugging extensions (such as the Unity FMU tester window). No artificial intelligence was utilized in the process of historical 3D asset reconstruction or mathematical physics modeling. The authors reviewed and edited all content and take full responsibility for the published article.

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Appendix A. Chronological Overview of Electric Lighting in Portugal

Table Appendix A.1 summarises the principal milestones in the history of electric lighting in Lisbon and Portugal, from the introduction of gas lighting in 1848 to the completion of universal domestic electrification in the late 1980s. Events are classified into four categories: public lighting (PUBLIC), domestic illumination (DOMESTIC), grid and infrastructure development (GRID), and international technological context (INTL).

Table Appendix A.1: Milestones in the history of electric lighting in Lisbon and Portugal, 1848–1990s.

Date	Category	Event	Context and significance
Before electricity, 1848–1877			
1848	DOMESTIC	Gas lighting reaches Lisbon homes	Companhia Lisbonense de Iluminação a Gás; serves elite residences and commercial zones only
Arc lamps, incandescent breakthrough, and first demonstrations, 1875–1891			
c. 1875	INTL	Tesla encounters the Gramme dynamo at Graz	Sparks early thinking on AC; the same machine type was used in Cascais three years later
May 1878	INTL	Paris Exhibition: Avenue de l'Opéra lit by arc lamps	First large-scale public electric lighting demonstration; Gramme alternator powers Yablochkov candles
28 Sep 1878	PUBLIC	**Cascais Citadel illuminated**	First public electric lighting in Portugal; six lamps, two Gramme machines shipped directly from Paris
30 Oct 1878	PUBLIC	First electric lighting in Chiado, Lisbon	First documented public electric lighting in the capital
1879	INTL	Edison demonstrates the incandescent bulb	Soft, manageable light suitable for domestic interiors; arc lamps too intense for home use
1880	PUBLIC	Camões tricentennial electric illuminations	Ambitious displays on Praça D. Pedro IV and Rua Áurea; electric light deployed as civic spectacle
1882	INTL	Tesla conceives rotating magnetic field; Edison opens Pearl Street Station	Theoretical basis of AC motor; first commercial DC power distribution system in New York
1887	PUBLIC	New gas franchise signed; competing lighting blocked for a decade	Municipality pledges no competing lighting technology for at least ten years, protecting the CRGE investment
1887–88	INTL	Tesla patents AC induction motor; Westinghouse licenses technology	War of Currents between AC and DC systems begins
10 Jun 1891	GRID	*Companhias Reunidas de Gás e Electricidade* formed	Monopoly over gas and electricity in Lisbon; no competitive pressure to lower tariffs or accelerate electrification
1891	DOMESTIC	CRGE concession explicitly covers private domestic supply	First legal basis for household electric lighting in Lisbon
mid-1890s	INTL	AC prevails in the United States	War of Currents effectively ends; AC becomes the dominant standard for power transmission
Urban expansion and first domestic consumers, 1895–1930			
1895	GRID	Central da Arrábida opens in Porto	First major thermoelectric power station outside Lisbon; begins regional supply in the north
31 Aug 1901	PUBLIC	First electric trams in Lisbon (Cais do Sodré – Algés)	Electricity enters everyday Lisbon life; normalises the technology culturally for a wide public

continued on next page

Table Appendix A.1 *(continued)*

Date	Category	Event	Context and significance
1902	PUBLIC DOMESTIC	Electric supply extended to all streets and private homes in Lisbon	CRGE extends network citywide; domestic electric light now available in principle, though cost confines uptake to wealthier households
1909	GRID DOMESTIC	Central Tejo opens; 1 521 domestic consumers registered	Lisbon's main power station for four decades; consumer numbers grow nearly ninefold within the following decade
1919	DOMESTIC	13 500 domestic consumers in Lisbon	Rapid uptake among upper and middle classes; working-class households and provincial Portugal largely unconnected
15 Aug 1926	GRID	Cascais – Lisbon railway line electrified	First electric railway in Portugal; powered by the Central Tejo via the Paço d'Arcos substation
1928	GRID	National survey: 395 scattered stations, only 5 exceeding 7 000 hp	Supply hyper-fragmented; the vast majority of Portugal has no domestic electricity connection
Urban dominance, rural absence, 1930–1944			
1930s	DOMESTIC	Electricity dominant in Lisbon and Porto households	Middle-class urban homes largely electrified; rural Portugal and small towns remain almost entirely without domestic supply
National grid and universal access, 1944–1990s			
26 Dec 1944	GRID	*Lei da Eletrificação Nacional* (Law 2002)	National grid foundations laid; hydropower given absolute priority over coal; sets the stage for wider domestic access beyond major cities
1952–58	GRID	Major hydroelectric programme	Belver (1952), Salamonde (1953), Cabril (1954), Bouçã & Caniçada (1955), Paradela (1958); cheaper power reaches working-class urban homes and smaller towns
1965	PUBLIC DOMESTIC	Last gas lamps extinguished in Lisbon	Bairro Alto and Bairro de Santa Catarina; gas lighting fully replaced—87 years after the first arc lamp demonstration in Cascais
30 Jun 1976	GRID	EDP founded	Merger of 14 nationalised companies post-revolution; unified national electricity provider established
late 1980s	DOMESTIC	**Universal domestic electrification achieved**	Every household in Portugal connected; a goal deferred since the 1974 revolution, reached over a century after Cascais

Note: The gap between technical availability and actual domestic access is the central tension of this history. Lisbon could supply electricity to private homes from 1891; universal household coverage was not achieved until the late 1980s. Cost, monopoly disincentives, and political will—not technology—determined the pace.