Research Article

Optimizing Supply Chains for Cultural Heritage Renovation: An Operational Perspective

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Abstract

This study presents an integrated framework for managing cultural heritage (CH) renovation projects by aligning supply chain operations with project management methodologies. Recognizing the unique challenges posed by heritage restoration, such as limited material suppliers, specialized labor, and regulatory constraints, the paper emphasizes the need for synchronized supply chain planning, procurement, and execution. Drawing on existing literature, the study outlines a supply chain operational model rooted in institutional oversight and resourcefulness, encompassing structural, energy-efficiency, and ornamental interventions. A case study of Riga's Central Market pavilions illustrates the framework's application, focusing on three restoration works: fiber Bragg grating sensor installation, concrete overlay strengthening, and corrosion monitoring system deployment. Using Critical Path Method (CPM) simulations, the study identifies critical tasks and bottlenecks, highlighting how delays in material delivery, equipment availability, and skilled labor can impact project timelines. The analysis reveals that activities such as rebar replacement, overlay casting, and sensor embedment are highly sensitive to supply chain disruptions. The study also maps resource flows (materials, equipment, tools, and labor) underscoring the importance of coordination among stakeholders. Findings suggest that integrating supply chain dynamics into project scheduling enhances responsiveness and reduces hidden delays. The study contributes a novel operational framework that integrates supply chain dynamics with project scheduling, offers empirical evidence of supply chain impacts on restoration timelines, and identifies resource-sensitive activities that influence project duration. It also provides practical guidance for aligning procurement, logistics, and workforce planning with restoration sequencing.

Keywords: cultural heritage; supply chain; operations; critical path method; project management; renovation; institutional oversight; resourcefulness;

Highlights

- The study introduces a novel framework that aligns supply chain operations with project management methodologies to address the unique challenges of cultural heritage renovation, including limited suppliers, specialized labor, and regulatory constraints.
- Through a case study of Riga's Central Market pavilions, the research applies Critical Path Method (CPM) simulations to identify bottlenecks and critical tasks that are highly sensitive to supply chain disruptions.
- The findings underscore the importance of coordinating resource flows and integrating supply chain dynamics into project scheduling, offering practical guidance to improve responsiveness and minimize hidden delays in heritage restoration projects.

1 Introduction

Renovation works for cultural heritage are essential for preserving history, maintaining architectural integrity, and ensuring that future generations can appreciate and learn from the past (Wijesuriya et al., 2013; Zhao et al., 2025). Renovating Cultural Heritage in Europe needs the establishment of robust processes covering the inquiry of the necessary repairs, production of preliminary designs, alignment with legal constraints, obtaining the necessary permits and finally the execution of the works (Wijesuriya et al., 2013). To execute the renovation work supply chains, need to be established, planning the appraisal of materials, equipment and thereby the contracting and booking of skilled workforce (Thomas H. & Ellis, 2017).

Due to the specialized nature of heritage restoration, materials such as historically accurate building components or custom-crafted elements may have limited suppliers, leading to acquisition challenges and potential delays (Artesani et al., 2020; Baglioni et al., 2021). Skilled labour is another critical factor, as restoration often requires expert craftsmen and specialized techniques that typically are scarce and subject to tight scheduled in construction or renovation projects (Arsan et al., 2021; Karakul, 2022). In addition, compliance with heritage protection laws and obtaining permits is highly uncertain and it can affect scheduling, requiring careful planning to align legal approvals with material deliveries and workforce deployment (Divolis et al., 2024; Foster, 2020; Wijesuriya et al., 2013).

Given these constraints, project activities must be carefully sequenced along a critical path to ensure timely execution. Traditional Critical Path Method (CPM) models often focus on task durations and dependencies (Zhao et al., 2025). Without integrating supply chain variables, such as lead times, delivery sequencing, and resource availability there is a risk to overlook hidden delays and misalignments (Balyan et al., 2025; Zhao et al., 2025). Incorporating supply chain dynamics into CPM frameworks allows for more accurate identification of bottlenecks as well as the optimal integration of lean and just-in-time (JIT) practices, which can streamline logistics, reduce inventory costs, and improve coordination among artisans, suppliers, and site managers (Balyan et al., 2025; Sousa et al., 2024).

Previous research has examined the challenges associated with renovation work for cultural heritage. Research has proposed frameworks tailored to assess and improve energy performance and Indoor Environmental Quality (IEQ) in historic buildings (Divolis et al., 2024; Ziozas et al., 2024). Some studies have mapped BIM-based workflow processes, demonstrating how BIM model outputs, eventually integrated with the critical chain method, can support supply chain restoration activities (Pinti & Bonelli, 2022; Tapponi et al., 2015; Zhao et al., 2025). Others have focused on life cycle analysis, assessing energy consumption and emissions in building renovation plans (Fahlstedt et al., 2024). Doukari et al. (2023) propose a BIM-based automation process to assess and simulate renovation works in terms of duration, effort, and costs. Zhao et al. (2025) use of the Critical Chain Project Management (CCPM) method to address resource constraints and scheduling conflicts and integrate the approach in BIM by considering procurement costs. Nonetheless, the integration of supply chain design, planning, and execution in CH renovation remains insufficiently addressed in current research.

This study develops a supply chain operational framework emphasizing the integration of supply chain and project management practices for cultural heritage renovation work. To highlight the implication of supply chain activities, the study proposes a case study approach, integrating both qualitative and quantitative data, to assess the performance of renovation work supply chains in the city of Riga, focusing on one of the central market pavilions.

The structure of this paper is organized as follows: beginning with an introduction that contextualizes the relevance of supply chain management and project management in heritage restoration, the subsequent section develops a supply chain operational framework by synthesizing prior research, with emphasis on institutional oversight and the resourcefulness inherent in cultural heritage practices. This is followed by a detailed presentation of the methodological approach employed in the study, culminating in the empirical analysis of the restoration process at the Riga Central Market pavilion. The final part of the paper engages in a critical discussion of the findings, drawing conclusions that underscore the implications for future heritage restoration initiatives and supply chain optimization.

2 Supply Chain Operational Framework for Heritage Restoration Projects

Previous studies have explored the structure and dynamics of cultural heritage (CH) supply chains (Balyan et al., 2025; Irwan et al., 2025). Key challenges in enhancing supply chain logistics and management include the planning of the interventions in relation to local regulations, the implementation of centralized procurement frameworks, and addressing resource-related aspects (Balyan et al., 2025; Thomas H. & Ellis, 2017). Hence, this section highlights two key aspects of CH supply chains: institutional oversight and resourcefulness. It then introduces the operational framework that supports their implementation.

2.1 Institutional oversight

From a regulatory standpoint, the conservation of cultural heritage structures is subject to multi-tiered governance aimed at safeguarding their historical and cultural significance (Foster, 2020; Wijesuriya et al., 2013). This regulatory framework originates at the international level, notably through the guidelines set forth in the World Heritage Convention and is subsequently tailored to align with the specific legal and cultural frameworks of individual nations. The Convention provides a foundational model for heritage management systems, emphasizing the need for structured approaches to the preservation of cultural assets (Wijesuriya et al., 2013). These assets are inherently vulnerable to degradation, physical damage, and environmental wear caused by atmospheric conditions or natural disasters such as earthquakes and floods. In response, effective heritage management systems should incorporate three essential components (Sousa et al., 2024) (Figure 1):

- Planning: a detailed plan is developed outlining the methods and techniques to be used for preservation and conservation, based on the heritage building, current conditions and potential threats faced.
- Implementation: carrying out necessary actions to preserve, conserve and restore.
- Monitoring: Ensure the heritage structure remains protected over time through routine inspections and evaluation.

The outlined steps are deeply rooted in the established heritage principles of preservation, conservation, and restoration (Wijesuriya et al., 2013) (Figure 1). Preservation emphasizes keeping a site in its current condition, ensuring its integrity remains intact. Conservation builds upon this by incorporating minimal, strategic interventions to halt deterioration, forming a key component of implementation that aligns with the values defined during the planning phase. Restoration, on the other hand, is a more targeted approach. It presumes that the original state of a site or building has been compromised, often due to significant climatic events or other forms of damage. As such, restoration aims to return the site to a documented earlier condition, typically requiring thorough research, precise records, and strong justification (Figure 1).

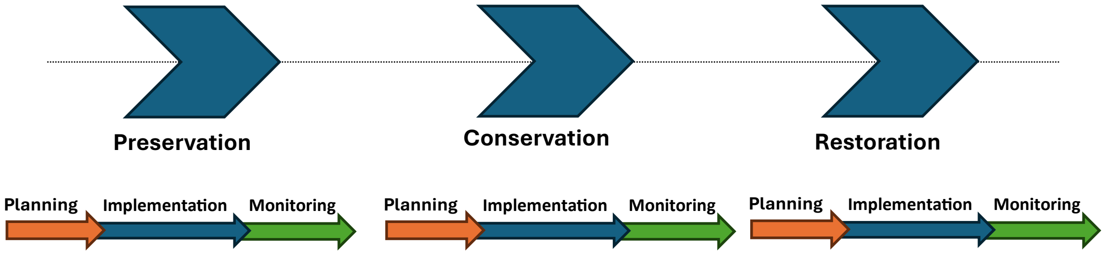

Figure 1. The Heritage Management System for preservation, conservation and restoration (adapted from Wijesuriya (2013)).

The above guidelines are followed by legal frameworks and standards issued at the national level by Member States. For instance, standards on EU level are available (CEN, 2017; Divolis et al., 2024; Sousa et al., 2024):

- EN 16883:2017. Conservation of cultural heritage – Guidelines for improving the energy performance of historic buildings.
- EN 15757:2010. Conservation of Cultural Property - Specifications for temperature and relative humidity to limit climate-induced mechanical damage in organic hygroscopic materials.
- EN 16096:2012. Conservation of cultural property - Condition survey and report of built cultural heritage.
- EN 16853:2017. Conservation of cultural heritage - Conservation process - Decision making, planning and implementation.
- EN 15898:2011. Conservation of cultural property - Main general terms and definitions.
- EN 15759-1:2011. Conservation of cultural property - Indoor climate - Part 1: Guidelines for heating churches, chapels, and other places of worship.

2.2 Resourcefulness of Cultural Heritage

Any preservation, conservation, or restoration work undertaken for cultural heritage involves estimating and allocating resources efficiently to carry out the renovation within a defined timeline. We may distinguish three types of interventions that may be necessary for cultural heritage buildings or infrastructure: *structural, energy efficiency* and *ornamental*.

Structural interventions are necessary to maintain and restore the structural performance of historical building, while respecting their architectural and cultural significance (Revez et al., 2021; Rossi & Bournas, 2023). Interventions often include repairing cracks, reinforcing weakened components, and retrofitting structures to withstand environmental and seismic stress. Modern approaches emphasize minimal intrusion and reversibility, using innovative materials like textile-reinforced composites embedded with fibre optic sensors to simultaneously strengthen and monitor the building (Rossi & Bournas, 2023). Cultural heritage assets are exposed to the risk from natural hazards, climate change, or human impact. Interventions should cover structural stabilization, as well as regular and extraordinary maintenance that take into consideration cost-effectiveness, expert judgements and long-term sustainability (Revez et al., 2021).

Energy efficiency is promoted by the Kyoto Protocol and reinforced through European Directives such as 2009/28/EC and 2010/31/EU, which support the development of renewable energy and the implementation of energy-saving measures across the built environment, including cultural heritage assets (Negro et al., 2016). With over 60% of European buildings constructed before 1980 and 25% classified as cultural heritage, these structures often exhibit poor energy performance in contrast to new technologies and materials available on the market (Divolis et al., 2024; Ziozas et al., 2024). Hence, this underscores the urgent need for targeted energy retrofitting interventions (Ziozas et al., 2024). Energy retrofitting interventions need the specialized labour skills, equipment and materials, e.g. heat pumps, underfloor radiant heating, thermal energy storage systems, rooftop photovoltaics etc. (Negro et al., 2016; Ziozas et al., 2024)

Ornamental restoration consists of architectural intervention that prioritizes the aesthetic and decorative aspects of a historic structure (Dias Martins, 2025). Dias Martins (2025) discusses the ornamental renovations carried out in the Alhambra Palatine City, particularly during the 19th century. The selection of appropriate materials is emphasized as a complex process, avoiding the influence of aesthetic enhancement over historical accuracy. Ornamental restoration can involve the usage of specialized equipment and expertise, such as 3D printing (Tomei et al., 2024). This technology enables the reproduction of missing parts of ancient statues or intricate ornamental architectural components with complex geometries. The supply chain must ensure the availability of suitable raw materials to feed into the printing machines. Additionally, the design process must balance mechanical strength with efficient material usage (Tomei et al., 2024).

Renovating cultural heritage buildings, whether for structural integrity, energy efficiency, or ornamental restoration, demands carefully coordinated supply chains to source specialized materials and skilled labour. These operations must be tailored to respect historical authenticity while integrating modern standards, often involving niche suppliers and conservation experts. A general framework aligned with this scope is proposed by Thomas and Ellis (2017) as the factor-resource model (Figure 2). The model shows the interaction between three main elements: the work content, disruptions and resources. The disruptions are caused by external elements like congestion, weather, or any other unexpected event that could halt or delay operations. The work content is the design of the work to be performed. Finally, the resources consist of physical and workforce assets that are needed to carry out the work (Figure 2):

- Labor. Skilled and unskilled employees that are necessary for the construction project.
- Materials. The construction materials are in different types (e.g. concrete, steel, wood, aggregates etc.) and quantities.
- Equipment. This category includes specialized construction equipment, tools, machinery, vehicles, etc.
- Tools. Basic tools for construction and renovation operations, e.g. hammers, screwdrivers, levels, cutters, brushes, drills etc.
- Information. Information systems are necessary to review the design, BIM models, as well as project management software to monitor and control the construction projects. Finally, communication tools to interact with clients, contractors as well as the human resources in the construction site.
- Support Services. These support services include any type of additional services offered by third parties. These services can be seen as indirect supplies that do not directly affect the main work content, but instead support it, e.g. supply of utilities, water, electricity but also desks, fences, uniforms, helmets, insurances, etc.

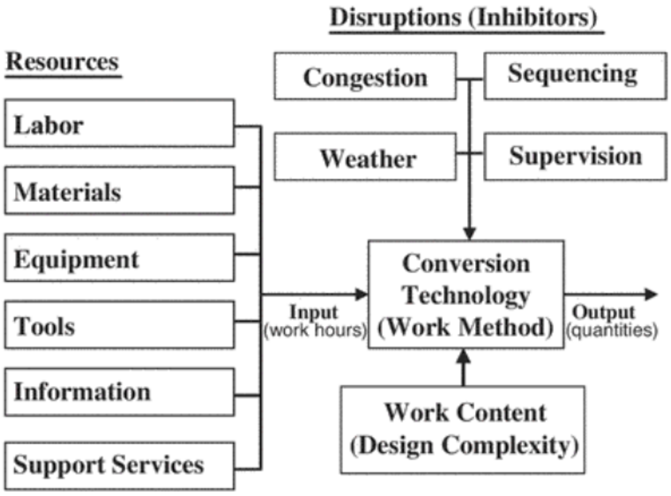

Figure 2 The Factor Resource model (Thomas H. & Ellis, 2017).

2.3 A cultural Heritage supply chain operational framework

Different frameworks that conceptualize cultural heritage (CH) supply chains can be found in the literature. We distinguish two main areas of research. The first area comprises studies that focus on the end-to-end processes enabling heritage assets to be preserved, conserved, and ultimately delivered as products to the tourism sector. One notable approach outlines four key stages: preservation, excavation, conservation, and research, culminating in museum presentation (Zan & Bonini Baraldi, 2013). Within this context, the authors introduce the Heritage Chain Management framework, adapted from supply chain theory and illustrated through the Horse and Chariot case in China. Importantly, actors often perceive themselves as isolated producers rather than as part of an integrated chain. Therefore, competing dynamics must be considered to ensure optimal performance. The same framework is applied in Turkey to demonstrate how bureaucratic centralization and fragmentation affect heritage outcomes (Bonini Baraldi et al., 2013). Similarly, Zan (2014) uses the framework to show how China's cultural heritage system suffers from underinvestment and weak coordination. This results in administrative decentralization, institutional fragmentation, and misaligned incentives, disrupting the flow and coherence of the heritage chain.

The second area includes studies that investigate material acquisition, lean practices, or general supply chain optimization. Most of these papers do not focus specifically on cultural heritage but rather on renovation or construction processes more broadly. A CH supply chain can be viewed as a set of processes that ensure dynamic planning and scheduling of resource deliveries for construction (Purushothaman et al., 2025). Hsu et al. (2020) introduce a multi-stage stochastic programming model that optimizes supply chain decisions related to production and transport planning, as well as inventory management under uncertain site demand and traffic conditions. Golpîra (2020) presents a novel mixed integer linear programming (MILP) model to optimally integrate the vendor managed inventory (VMI) strategy into the multi-project, multi-supplier, multi-resource construction supply chain (CSC) network design and facility location problems.

In this paper, we try to combine these two areas of research into a combined framework, where principles to safeguard physical integrity of cultural heritage have to be coordinated with the economic costs and speed performance of the supply of assets, i.e. materials, labour and tools. Preservation and conservation are implemented through institutional oversight, i.e. the approval process as part of a planning process of the contracted renovation firm, the quality inspections during renovation execution and post-renovation monitoring activities (Figure 3). The design of the intervention involve conservation experts, architects, and engineers who develop restoration strategies and drawings aligned with cultural significance and regulatory frameworks (Wijesuriya et al., 2013; Zan & Bonini Baraldi, 2013). During planning, the procurement department of the appointed contractors or construction firms undertake resource estimation, determining the types and quantities of labour, materials, and equipment required for the restoration activities. Suppliers, including transportation service providers, are invited to submit proposals, initiating a selection process based on predefined criteria (Figure 3).

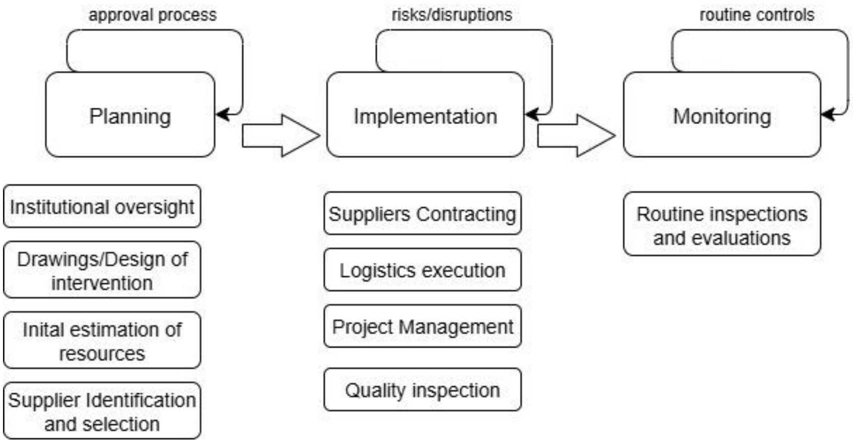

Figure 3. Cultural Heritage supply chain operational framework.

Once restoration begins, contractual agreements are established with contractors or construction firms, which in turn impose obligations on material suppliers and logistics providers responsible for storage and transportation to the construction site (London, 2007; Thomas H. & Ellis, 2017). It is during this phase that materials, skilled labour, and equipment must be efficiently coordinated and delivered (London, 2007; Purushothaman et al., 2025; Thomas H. & Ellis, 2017). Contractual agreements and logistics execution must account for spatial constraints at the construction site, storage layout configurations, and the sequencing of project activities (Figure 3). Project management is typically used to sequence and coordinate the restoration activities; hence, this function is expected to liaise with the supply chain and its logistics execution (Zhao et al., 2025).

Upon completion of the restoration project, a formal quality inspection is conducted to verify adherence to the approved design specifications. Concurrently, financial transactions are initiated to settle payments with contracted professionals and suppliers, ensuring that all obligations are fulfilled. Following this phase, the responsible authority or owner of the cultural heritage asset establishes a protocol for routine inspections and evaluations. These measures are designed to facilitate ongoing monitoring of the site and to maintain readiness for potential damage or deterioration (Figure 3). In this last phase, no supply chain activities are expected.

2.3.1 Resources of cultural heritage supply chains

Building on the previously outlined operational framework for cultural heritage supply chains, which mapped out the key processes and logistical structures, attention should be paid to the underlying resource flows that enable those operations: materials, equipment, tools, and labour.

Materials, equipment and tools

A wide array of materials, equipment, and tools is available on the market to support the restoration and conservation of cultural heritage. From traditional craft-based supplies to cutting-edge technologies, practitioners can select from a diverse range of options tailored to the specific needs of each heritage context. In general, the selection and application of these resources must be guided by principles of authenticity, historical integrity, and technical appropriateness. To support informed decision-making, international bodies such as the International Centre for the Study of the Preservation and Restoration of Cultural Property (ICCROM) and the International Institute for Conservation (IIC) have published comprehensive guidelines (Borrelli, 1999; IIC, n.d.). ICCROM's *ARC Laboratory Handbook* offers practical insights into material analysis and conservation techniques, while IIC curates a repository of global standards and best practices, including environmental protocols and documentation frameworks.

Majority of materials for the renovation of cultural heritage can be classified as cleaning, consolidation and surface protection materials (Baglioni et al., 2021). Examples of materials include synthetic polymers (e.g. acrylic polymers) recommended for coating and protection of painting, nanosols, colloidal silica and alkoxysilane for stone and wood conservation. Tooling include electrochemistry to conserve bronze outdoors, while colloids are part of the restoration tools (Baglioni et al., 2021). To consolidate CH structures (e.g. to improve the connections between 1) walls, 2) walls and floors and 3) walls and roofs) available construction techniques necessitate ties, rings, wooden beams, among others (Modena et al., 2009).

To protect CH surfaces protective coatings should be engineering in order to respond to the following factors: transparency, reversibility, compatibility with the surface, long-term, low-cost and non-toxicity. Examples of materials to protect metals, glass and stones are nanocomposites, fluoropolymers, plasma polymers, organic coatings, acrylic resins etc. (Artesani et al., 2020).

Finally, 3D printing is recommended as an equipment for ornamental renovations (Tomei et al., 2024). In addition, there are diverse instruments that are known and used for CH interventions, e.g. scalpels, brushes, thermohygrometers, tweezers and needles, ultraviolet (UV) devices, knives/cutters, magnifying lenses etc. (PEL, 2024). Additionally, lab equipment, that is not necessarily made available at the construction site where the interventions are taking place include microscopes, fume hoods and ultrasonic cleaners.

Energy retrofitting interventions require specialized labor, equipment, and materials. In the city of Sassi, Italy, a historic site was adapted using aerogel insulation, low-emissivity gas-filled windows with wooden frames matching the building's original finishes, and sustainable systems like condensing boilers, reversible heat pumps, and underfloor radiant heating (Negro et al., 2016). In Trento, Italy, optimal energy savings were achieved through the installation of a heat pump coupled with a borehole thermal energy storage system, along with upgrades to the electrical systems using rooftop photovoltaics, innovative building-integrated photovoltaic shingles, and an LED lighting system (Ziozas et al., 2024).

Labour

Labour skills for the renovation of cultural heritage require a blend of diverse technical expertise, but a common strong historical sensitivity as well as a commitment to preserving cultural heritage. Labour skills are essential for the diverse range of interventions required in the conservation and restoration of cultural heritage (Arsan et al., 2021; Karakul, 2022; Waked et al., 2019). These skills range from general support roles, usage of special equipment, to highly specialized craftsmanship. High levels of specialization are particularly critical in ornamental restoration, where precision and historical accuracy are paramount. Existing studies have identified and categorized the various types of craftsmanship available, highlighting the distinct competencies needed for different restoration tasks (Sousa et al., 2024):

- Traditional Stonemasonry: Proficiency in working with stone, including cutting, shaping, and joining stones to restore or replicate historical structures.
- Brick Masonry: Skill in laying bricks using traditional techniques, such as Flemish bond or English bond, to match existing patterns.
- Plasterwork: Expertise in applying lime-based plaster, decorative stucco, and ornamental mouldings.
- Woodwork: Ability to repair or recreate wooden elements like doors, windows, and intricate carvings.
- Metalwork: Knowledge of forging, welding, and blacksmithing for restoring iron gates, railings, and decorative metal features.
- Glasswork: Handling stained glass repair, leaded glass restoration, and glazing techniques.

Craftsmanship involves working with various materials and techniques to preserve or recreate their original features. Craftsmen need to be proficient in traditional stonemasonry, which requires cutting, shaping, and joining stones to match the historical structures. They also need to be skilled in brick masonry, using traditional local patterns. Plasterwork is another important skill, as it involves applying lime-based plaster, decorative stucco, and ornamental mouldings to the walls and ceilings. Woodwork is essential for repairing or recreating wooden elements, such as doors, windows, and carvings, that add character to the buildings. Metalwork involves forging, welding, and blacksmithing to restore iron gates, railings, and metal features. Finally, glasswork requires handling-stained glass repair, leaded glass restoration, and glazing techniques to maintain the beauty and functionality of the windows.

3 Method

This research employs a mixed-methods approach to investigate the integration of supply chain dynamics into cultural heritage project management. The study is grounded in a case study conducted in Riga, Latvia, focusing on three restoration projects at the historic Central Market pavilions. The pavilions were constructed between 1924 and 1930, by repurposing metal frameworks from German Zeppelin hangars, which were dismantled and transported to Riga. These pavilions serve as a representative context for examining the operational and logistical complexities inherent in heritage conservation efforts.

Several damages have been identified in the pavilions which require some renovation works to prevent further degradation that may compromise the strength and stability of the building (Peredistijs, 2024). In the basement, moisture-related deterioration was observed, likely resulting from defective or absent waterproofing, allowing water to infiltrate through the foundation structure. As a result of this moisture exposure, structural elements such as the reinforced concrete (RC) basement slab exhibit corrosion, leading to spalling of the protective concrete layer. Moreover, signs of corrosion were also observed in the steel beams that provide load-bearing support to the RC slab. These conditions are critical considering that the load-bearing capacity of the basement slab is near its full capacity under the current loads. Therefore, the renovation works considered to mitigate the moisture exposure and ensure long-term durability are the following:

- **FBG-OSG Sensor Installation with Structural Reinforcement.** Sensors are installed to enable continuous monitoring of the steel beams' deformation, by means of local strains. Moreover, steel beams that exhibit slight corrosion but maintain overall structural integrity can be effectively reinforced using Carbon Fiber Reinforced Polymers (CFRP). This technique provides not only an increase in load-bearing capacity but also serves as a protective barrier against moisture ingress, thereby mitigating future corrosion.
- **Concrete overlay installation on the Riga Pavilion basement slab.** Strengthening the reinforced concrete basement slab of the Riga Central Market with concrete overlays. This renovation work includes the replacement of the corroded reinforcement to meet the structural demands of the basement slab.
- **Corrosion monitoring System.** Implementing a structural health monitoring (SHM) system based on FBG embedded in a concrete layer bonded to the reinforcing rebar that requires replacement. The implementation of this SHM system will inform timely maintenance of the basement slab by analysing structural changes such as cracks.

The qualitative component involves an in-depth analysis of project documentation, stakeholder interviews, a site visit, and archival records consisting of a technical inspection report of the Riga Central Market, Dairy Pavilion (Peredistijs, 2024). This enabled an improved understanding of the restoration processes, the technical specifications and the stakeholder roles. Interviews were conducted during a site visit in Riga with contractors, and municipal authorities to capture diverse perspectives on the energy and technical specifications of the site to renovate, institutional oversight function, and local supply chains. A recurring theme raised during discussions was the coordination challenge specific to cultural heritage renovation, where interventions must satisfy both engineering requirements and regulatory conditions for preservation. The case also revealed procurement and logistics issues that commonly arise in this type of project, such as long lead times for specialized materials and the need for carefully timed deliveries in urban settings. These challenges frequently contribute to delays and underline the importance of effective coordination across institutions and project partners.

The quantitative component applies the Critical Path Method (CPM) to model project performance in presence of supply chain constraints. Specifically, the analysis focuses on the total project duration, identification of bottlenecks, and thereby discuss processes criticalities. The activity and resource data for the CPM were collected from municipal representatives and consultants involved in the renovation works. These interactions provided practical insight into task durations, equipment requirements, material quantities, and workforce allocation, complementing available technical documentation.

To determine the critical paths of the three renovation works, the following assumptions have been undertaken:

- **FBG-OSG Sensor Installation:** a representative size of ~30 sensors (≤50 per fibre chain), medium cable/run distances (using typical values), and task durations expressed in working days (1 day = 8 hours; shorter tasks shown in decimals). A conservative repair sequence is assumed, with structural repairs (B-series) completed before corrosion sensor installation and final commissioning. Commissioning occurs only after all DAQs (Data AQuisition) and sensor types are connected and tested.
- **Concrete overlay installation:** the project operates on a baseline area of 100 m^2, aligning with many quantity estimates, and follows a strict work calendar of 8-hour weekdays with no weekend activity. Temporary shoring is essential for safety during open substrate phases and is included in the schedule for erection, though its removal is contingent on the overlay reaching

at least 70% strength and is not separately modelled. While full concrete strength is achieved after 28 days, the schedule relies on a 7-day strength checkpoint to determine progress. Curing durations assume typical ambient conditions, with no significant weather-related delays anticipated.

- **Corrosion Monitoring system.** The study assumes a working area of 100 m^2, consistent with earlier examples, and follows a standard schedule of 8-hour weekdays with no weekend work. All necessary permits, scaffolding, shoring access, and temporary power are in place from the outset, ensuring uninterrupted progress. Sensor installation is planned at a density of approximately one probe per 20 m^2. Rebar replacement is considered extensive, warranting a 14-day duration in the schedule. The overlay process is divided into two distinct phases: a one-day casting operation (A8a) followed by a seven-day curing period (A8b), reflecting the need for proper material setting and strength development.

Finally, a sensitivity analysis was performed to understand the impacts on the critical path of selected supplies, i.e. the procurement and supply of sensors and cables. These were selected in the analysis as they are critical components for energy monitoring and technical infrastructure as well as the related activities are time sensitive for the renovation schedule. Interviews with a consultant with experience in purchasing these materials unveiled occasionally longer lead times and defects for the following activities

- Supply and embedding of sensors, can extend in case of shortage. A 8–12 week availability window should be considered in case of a disruption (converted to 56–84 days, with a most-likely value near 70 days).
- Rebars availability, 1–2 days delay.
- A delay risk for fixing the cabling and terminations. Shipment delays can reach 5-10 days lead time uncertainty.

The sensitivity analysis consists of three complementary analyses. First, a Monte Carlo simulation (10,000 samples) using triangular distributions was performed to capture joint uncertainty and generate a distribution of possible project finish times. Second, a sensitivity ranking was carried out to assess how three key activities contribute to finish time variability. In this step, Spearman's rank correlation coefficient (ρ) was used to quantify the strength of the monotonic relationship between each activity's duration and the overall project completion time. Finally, a deterministic sweep was performed on the most influential activity by iteratively varying its lead time from 0 to 90 days. This analysis helped identify critical threshold values at which lead time extensions trigger a shift in the critical path.

4 Case Study: analysis of Riga Renovation work

4.1 Overview of Riga Restoration Project

FBG-OSG Sensor Installation with Structural Reinforcement

The installation of the fiber-based sensors, FBG and OSG, consists of 18-day sequence of specialized tasks for structural health monitoring, sensor integration, and corrosion protection within a construction project. It begins with SHM design (F1), followed by a tightly coordinated series of operations (B1–B6) including surface prep, CFRP installation, and sensor setup. Short-duration corrosion monitoring tasks (C2–C4) add diagnostic capability, culminating in final system commissioning (D1) (Table 1).

Concrete overlay installation on the Riga Pavilion basement slab

The installation of a concrete overlay consists of a 29-days sequence of activities (Table 2). It begins with a condition assessment (C1) over two days to evaluate the existing structure. This is followed by surface preparation using hydrodemolition (C2), a four-day process that removes deteriorated concrete. Next, reinforcement cleaning to Sa2 standard (C3) ensures the steel is free of rust and contaminants. Damaged bars are then removed and replaced (C4) over four days, after which shear connectors are installed (C5) in a three-day phase to improve structural integrity.

Table 1. Activities to install FBG and OSG components.

ID	Activity (short)	Duration (days)
F1	SHM design & sensor layout	5.0
B1	Surface prep (frame elements)	2.0
B2	Beam cleaning (blast)	2.0
B3	Primer application	1.0
B4	CFRP laminate/fabric application	3.0
B5	Bonding of FBG sensors to CFRP	1.0
B6	Cable routing & DAQ hookup (CFRP sensors)	1.0
C2	Admixed corrosion inhibitor in overlay concrete	0.5
C3	Install electrochemical corrosion sensors	1.0
C4	Cabling & datalogger setup (corrosion sensors)	1.0
D1	Final system commissioning & baseline (all DAQs)	0.5
—	**TOTAL**	**18.0**

The overlay casting and curing (C6), the longest activity at eight days, involves placing a new concrete layer and allowing it to reach 70% strength. A brief quality control and inspection (C7) follow to verify compliance. Temporary shoring (C8) is erected over two days to support the structure during work. The final touches include sealing expansion joints (C9) and managing and disposing of waste (C10), each taking one to two days to complete. Together, these steps form a comprehensive sequence for structural rehabilitation (Table 2).

Table 2. Activities to install the concrete overlay on the Pavilion basement slab.

ID	Activity (short)	Duration (days)
C1	Condition assessment	2.0
C2	Surface preparation (hydrodemolition)	4.0
C3	Reinforcement cleaning (Sa2)	2.0
C4	Removal & replacement of bars	4.0
C5	Connector installation (shear connectors)	3.0
C6	Overlay casting & curing (50 mm → 70% ≈ 5d)	8.0
C7	Quality control & inspection (7-day checks)	1.0
C8	Temporary shoring (erect)	2.0
C9	Expansion joint sealing	1.0
C10	Waste management & disposal (final)	2.0
	TOTAL:	**29**

Corrosion Monitoring System

The sequence of activities to install the corrosion-monitoring system requires a total of 51.5 days. The project begins with mobilisation and site setup (A1), followed by substrate preparation using hydro-jetting (A2) and abrasive blasting (A3). Temporary shoring (A12) is erected for safety. As a preparatory operation prior to rebar works, FBG strain sensors are mounted to the reinforcement (A9) so that sensors are fixed to the rebars before the reinforcement is placed. Extensive rebar removal and replacement (A4) then proceeds (14 days). After the new reinforcement is positioned, a corrosion-inhibitor coating is applied (A5) and mechanical connectors are installed (A7). The overlay process is prepared by batching an admixed inhibitor mix (A6), followed by a one-day casting operation (A8a) and a seven-day wet-curing period (A8b). During casting and curing the already-installed sensors remain embedded to monitor structural health. Electrical works for data acquisition cabling and terminations follow (A10), and the project concludes with quality control inspections (A11) and ongoing waste management and disposal (A13). Each step is scheduled to ensure structural integrity and compliance with engineering standards (Table 3).

Table 3. Activities to install a Corrosion Monitoring System.

ID	Activity (short)	Duration (days)
A1	Mobilisation & site setup	1.0
A2	Surface cleaning & prep (hydro-jet)	3.0
A3	Abrasive blasting / profile work	2.0
A12	Temporary shoring erection (initial)	2.0
A9	Sensor embedment (probes)	0.5
A4	Rebar removal & replacement	14.0
A5	Corrosion-inhibitor coating (to rebar)	5.0
A7	Mechanical connector installation	3.0
A6	Admixed inhibitor overlay batching (mixing)	7.0
A8a	Overlay - casting (pour day)	1.0
A8b	Overlay - curing (wet curing / 7 days)	7.0
A10	DAQ / cabling & terminations	2.0
A11	QC & inspection (post-cure checks)	1.0
A13	Waste management & disposal (ongoing)	3.0
	TOTAL:	**51.5**

4.2 Critical Path Method (CPM) Simulations

Simulations are performed to analyse the project execution of the three mentioned restoration works. The model simulation results provide a comprehensive overview of the project's planned execution timeline, highlighting the sequence of activities, their interdependencies, and critical path method metrics for performing the three restoration projects (Table 4).

Table 4. joint projects activity for three restoration projects in Riga (Dur. = duration, Pred. = predecessor, ES = Early Start, EF= Early Finish, LS = Late Start, LF = Late Finish).

ID	Activity (short)	Dur. (days)	Pred.	ES	EF	LS	LF	Float	Critical?
A1	Mobilisation & site setup	1	—	0	1	0	1	0	Yes
A2	Surface cleaning & prep (hydro-jet)	3	A1	1	4	1	4	0	Yes
A3	Abrasive blasting / profile work	2	A2	4	6	4	6	0	Yes
A12	Temporary shoring erection (initial)	2	A2	4	6	30	32	26	No
A9	Sensor embedment (probes)	0,5	A3	6	6,5	6	6,5	0	Yes
A4	Rebar removal & replacement	14	A9	6,5	20,5	6,5	20,5	0	Yes
A5	Corrosion-inhibitor coating (to rebar)	5	A4	20,5	25,5	20,5	25,5	0	Yes
A7	Mechanical connector installation	3	A4	20,5	23,5	22,5	25,5	2	No
A6	Admixed inhibitor overlay batching (mixing)	7	A5, A7	25,5	32,5	25,5	32,5	0	Yes
C1	Condition assessment	2	—	2	0	17	19	15	No
C2	Surface preparation (hydrodemolition)	4	C1	4	2	19	23	15	No
C3	Reinforcement cleaning (Sa2)	2	C2	2	6	23	25	21	No

C4	Removal & replacement of bars	4	C3	4	8	25	29	21	No
C5	Connector installation (shear connectors)	3	C4	6	10	29	32	23	No
C6	Overlay casting & curing (50 mm → 70% ≈ 5d)	8	C5,B6,A6	32,5	40,5	32,5	40,5	0	Yes
F1	SHM design & sensor layout	5	—	0	5	17	22	17	No
B1	Surface prep (frame elements)	2	F1	5	7	22	24	17	No
B2	Beam cleaning (blast)	2	B1	7	9	24	26	17	No
B3	Primer application	1	B2	9	10	26	27	17	No
B4	CFRP laminate/fabric application	3	B3	10	13	27	30	17	No
B5	Bonding of FBG sensors to CFRP	1	B4	13	14	30	31	17	No
B6	Cable routing & DAQ hookup (CFRP sensors)	1	B5	14	15	31	32	17	No
A8a	Overlay — casting (pour day)	1	A6, A12	32,5	33,5	39,5	40,5	0	Yes
A8b	Overlay — curing (wet curing / 7 days)	7	A8a, C6	40,5	47,5	40,5	47,5	0	Yes
A10	DAQ / cabling & terminations	2	A8b	33,5	35,5	47,5	49,5	14	Yes
A11	QC & inspection (post-cure checks)	1	A10	49,5	50,5	49,5	50,5	0	Yes
A13	Waste management & disposal (ongoing)	3	A11	50,5	53,5	50,5	53,5	0	Yes

The activity network diagram maps out the logical flow of tasks, clearly identifying the critical path and dependencies that drive the overall project duration (Figure 4). Complementing the network diagram map in Figure 4, Table 4 presents detailed scheduling data, including early and late start/finish times, float values, and criticality status, for each activity. Based on these values, the total project duration is 48.5 days. The analysis of the float values reveals that several tasks in the project have zero float, meaning they are on the critical path and cannot be delayed without impacting the overall schedule. However, a few non-critical tasks, such as A7 (Mechanical connector installation) and A10 (DAQ terminations), have minimal float (2 and 5 days respectively), making them vulnerable to delays that could reduce slack and shift them onto the critical path (Table 4). If these tasks experience supply chain or resource delays, the project's flexibility narrows, increasing the risk of bottlenecks. Key bottlenecks include A6 (overlay batching), A8a (casting), A9 (sensor embedment), and A11 (QC inspection), all of which have zero float and are tightly sequenced.

Considering the activities of the supply chain aiming to deliver materials, equipment and workforce reaching the construction site, further critical tasks and bottlenecks can be identified and discussed. Examining Table 5, it can be noticed that activities A4/C4 have the longest duration (up to 14 days), but at the same time high labour (14 person-days), and material-intensive. Activities A6/C6 related to overlay batching and casting necessitate the delivery of concrete which is time-sensitive and adds logistics complexity. This could have significant ripple effects across the project. A5 requires 100L corrosion inhibitor coating which must be in place before performing the overlay, which is a critical activity (gatekeeper role). Finally, the installation of mechanical connector, requires specialized equipment and labour. Its criticality increases due to the potential delays and impacts on safety and progress stall.

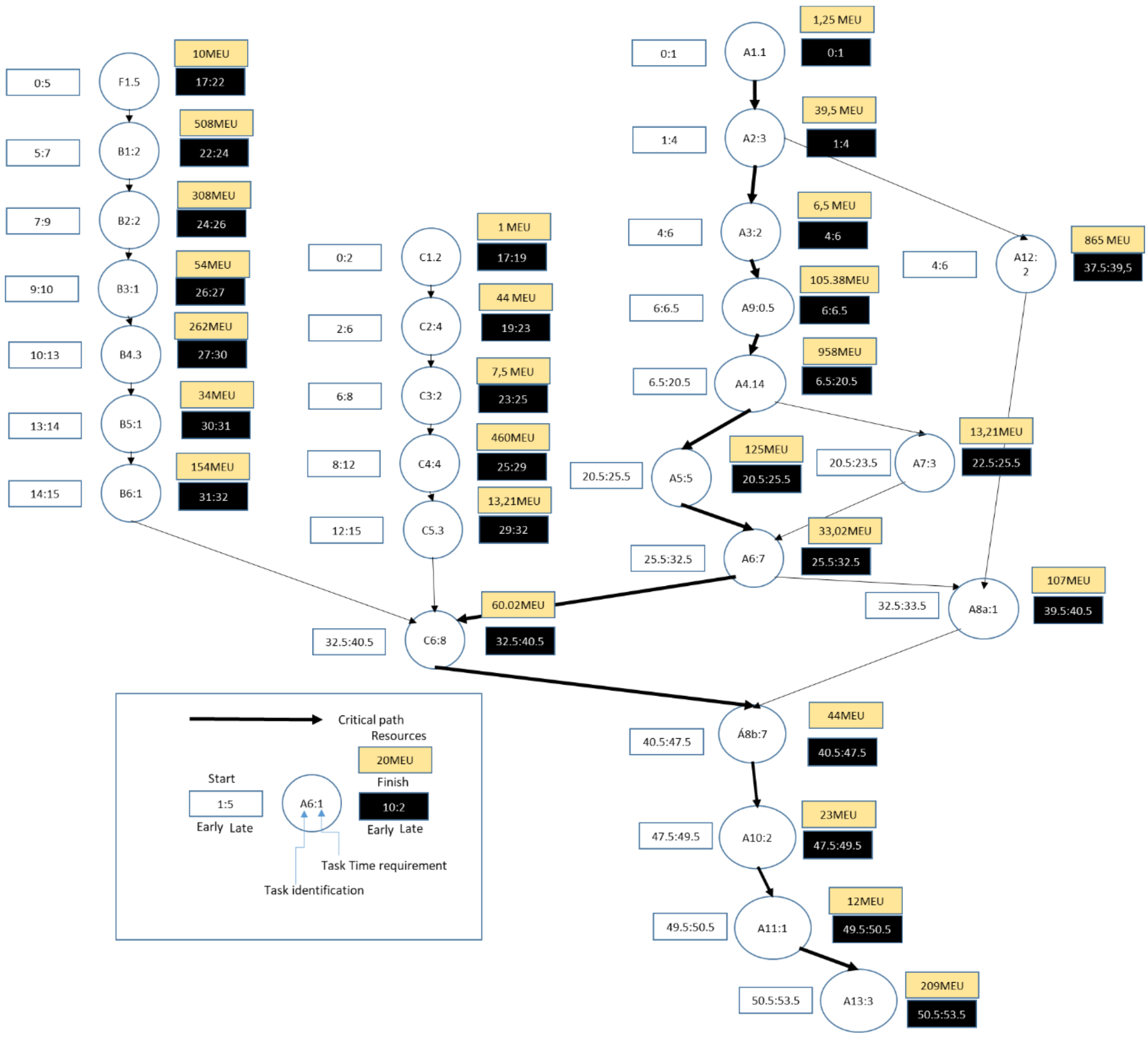

Figure 4. Network Diagram of Project Activities and Dependencies Illustrating time indicators.

Several key pieces of equipment in the restoration project can be seen as potential bottlenecks due to their specialized nature and shared usage across tasks. The HP jetting system used in surface preparation (A2 / C2) is highly specialized and likely in demand across multiple activities; if it's unavailable at the required time, delays in surface cleaning can ripple through subsequent tasks. Similarly, the mixer and pump essential for overlay batching and casting (A6 / C6) are critical to maintaining the concrete schedule, any issues with availability or maintenance can stall casting and disrupt curing timelines. Additionally, fiber-optic tools required for sensor bonding and routing (B5, B6) are niche and not easily substitutable (the suppliers' landscape can be limited and force single-sourcing). Hence, delays in their delivery or readiness directly impact the installation of monitoring systems, potentially pushing back quality control and final inspection stages.

Table 5. Key equipment, materials and human resources split on activities.

ID	Activity (short)	Dur. (days)	Equipment (key items)	Key Materials	Human Resources (Person per days)
A1	Mobilisation & site setup	1	Cover-meter / Pachometer, Half-cell meter,	–	2.5

			Rebound hammer, Calipers, Inspection cam, Core drill		
A2 / C2	Surface cleaning & prep (hydro-jet / hydrodemolition)	3–4	HP jetting system (300 L/min @ high pressure), hoses & nozzles, generator, containment, settling tank / filter unit	Water 32,000 L	5
A3 / C3	Abrasive blasting / reinforcement cleaning (Sa2)	2	Blast pot / blasting rig, compressor (185 cfm @ 7 bar), dust extractor, containment panels	Abrasive 2,500 kg	4
A12	Temporary shoring erection (initial)	2	Saw, hammer drill, injection pump, rebar bender/cutter, hand tools	Rebar 410 kg + tie-wire 150 kg + grout ≈ 300 kg	5
A9	Sensor embedment (probes)	0.5 day	Cable drum, tester, handtools	Cables/conduits/sealant (~30 kg)	6
A4 / C4	Rebar removal & replacement	14 (detailed) / 4 (top sheet)	Reciprocating saw / mini jackhammer, rotary hammer, injection pump, rebar bender/cutter	Similar to A12 (≈560 kg + grout)	14
A5	Corrosion-inhibitor coating (to rebar)	5	Mortar mixer, scales, brushes/rollers	100 L liquid (≈110 kg, density ≈1.1 kg/L)	6
A7 /C5	Mechanical connector installation (shear connectors)	3	Percussion drill Ø20 mm, vacuum system, grout pump, proof-load rig, jigs	500 shear connectors pcs (~0.5 kg ea = 250 kg) + grout 400 L (~960 kg)	8
A6 / C6	Admixed inhibitor overlay batching & overlay casting	7 (batching) / 8 (casting & curing)	Mixer / pump (or volumetric truck), vibrators, formwork, hoist, finishing tools, curing sprayers	5.0 m^3 concrete (≈12,000 kg) + admixtures (~20 kg)	6

A8a / A8b	Overlay — casting (pour day) & curing (wet cure)	1 / 7 (monitoring)	Hand tools, small drill, concrete test molds, curing equipment	5 probes (~5 kg total) + curing water (~100 kg est.)	1
A10	DAQ / cabling & terminations	2	Data logger kit, pull-off tester, ultrasonic gauge, compression machine	Consumables small (~20 kg)	5
A11	QC & inspection (post-cure checks)	1	Laser level, spreaders, props, measuring tape	Small tags/labels (<10 kg)	15
F1	SHM design & sensor layout	5	Computer/CAD, instrumentation tools	None	8
B1	Surface prep (frame elements)	2	Hydro-jet operators, hand tools	Water small (≈500 L = 500 kg)	12
B2	Beam cleaning (blast)	2	Hydro-demolition / blasting equipment	Water + abrasive (≈300 kg total)	4
B3	Primer application	1	Spray / roller equipment	Primer/degreaser (≈50 kg)	8
B4	CFRP laminate/fabric application	3	Composite tools, rollers, curing aids	CFRP plies (≈200 kg total) + resin (~50 kg)	8
B5	Bonding of FBG sensors to CFRP	1	Fiber-optic bonding tools, applicators	Adhesives (≈30 kg)	8
B6	Cable routing & DAQ hookup (CFRP sensors)	1	Fiber-optic technicians' kit, electrician tools	Laminate plies (~100 kg) + conduits (~50 kg)	8
A13	Waste management & disposal (ongoing)	ongoing (3 days active)	Skip bins, slurry tank/treatment unit, wheelbarrow, labels	Bags, bins, filters (≈200 kg equivalent)	8

Units: cfm = cubic feet per minute (air flow rate of compressor), ea / pcs = each / pieces., L = liters (volume)., kg = kilograms (mass)., m^3 = cubic meter (volume)., Ø = diameter., hp jetting 300 L/min = water flow rate in liters per minute at high pressure., Person-days = number of workers × days.

Several activities in the restoration project demand significant labour and specialized skills, making workforce planning a critical factor in avoiding delays. Tasks like rebar removal and replacement (A4 / C4), post-cure inspection (A11), and surface preparation of frame elements (B1) require high labour inputs, ranging from 12 to 15 person-days, which, if not carefully scheduled, can strain available manpower and lead to bottlenecks. Additionally, roles such as fiber-optic technicians for sensor bonding and routing (B5, B6), and hydro-jet operators for surface cleaning (B1, B2), involve niche expertise that cannot be easily substituted. If these specialists are unavailable when needed, the affected tasks stall, disrupting the overall project timeline and potentially causing cascading delays across dependent activities.

4.3 Sensitivity Analysis

When considering the expected time delays for A9 (supply and embedding sensors), A4 (short assembly/availability risk for the rebar works) and A10 (supply and installation of DAQ cabling and terminations), the Monte-Carlo distribution of project finish reaches an average of 117.4 days, median ≈ 117.3 days, standard deviation around 5.8 days, with the 5th / 25th / 50th / 75th / 95th percentiles 107.8 / 113.3 / 117.3 / 121.6 / 127.1 days (Figure 5). This is more than twice the original baseline (53.5 days). The distribution shows a relatively tight spread (standard deviation ≈ 5.8 days), but even the lowest 5th percentile outcome is 107.8 days, confirming that nearly all simulated scenarios result in a project duration well over double the initial estimate.

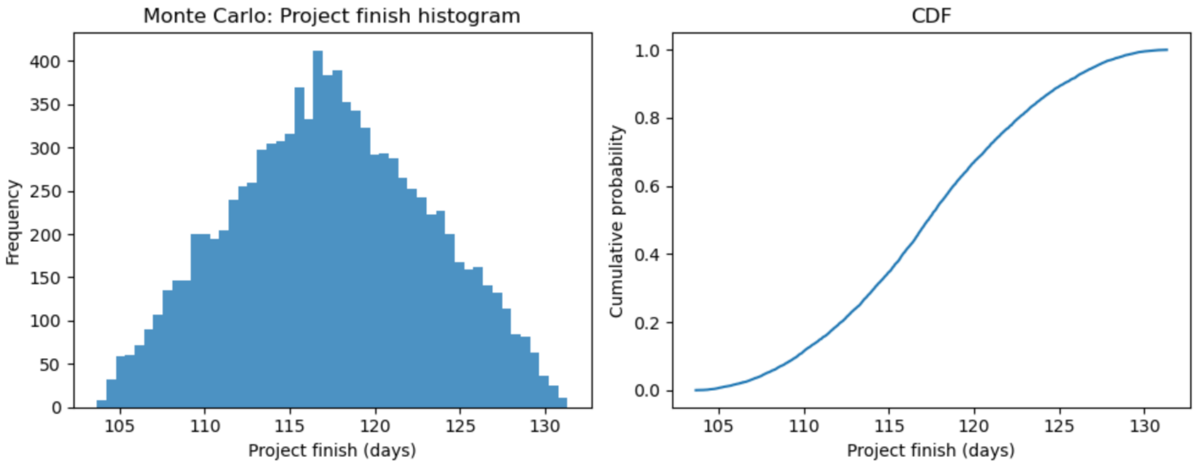

Figure 5. Project finish variability analysed through Monte Carlo simulation (left diagram) and its corresponding Cumulative Distribution Function (right diagram).

The Spearman ranking shows that A9 overwhelmingly dominates the finish variability ($\rho \approx 1.00$), while A4 and A10 are essentially uncorrelated with finish in the current parametrisation ($\rho \approx 0$). This implies that the schedule is robust to the small rebar and DAQ uncertainties reported, but extremely sensitive to sensor procurement and defects. In practice this means that unless A9 is ordered well before site start or spare units are planned, the project finish can shift from ~54 days to ~117 days on average under the assumed procurement uncertainty.

The deterministic sweep analysis, using a sweep increment of A9 (sensors order lead time) from 0 to 90 days, reveals a sharp structural shift (Figure 6): up to a small threshold, the baseline supply chain governs project completion. However, once A9 lead time surpasses the critical lead time of 7 days, the schedule becomes dominated by A9, and the project finish date begins to increase almost linearly, approximately 1:1, with each additional day of A9 lead time. Beyond the lead time of 7 days, the critical path becomes A9 → A4 → A5 → A6 → C6 → A8b → A10 → A11 → A13 and the project finish rises rapidly as A9's availability is delayed.

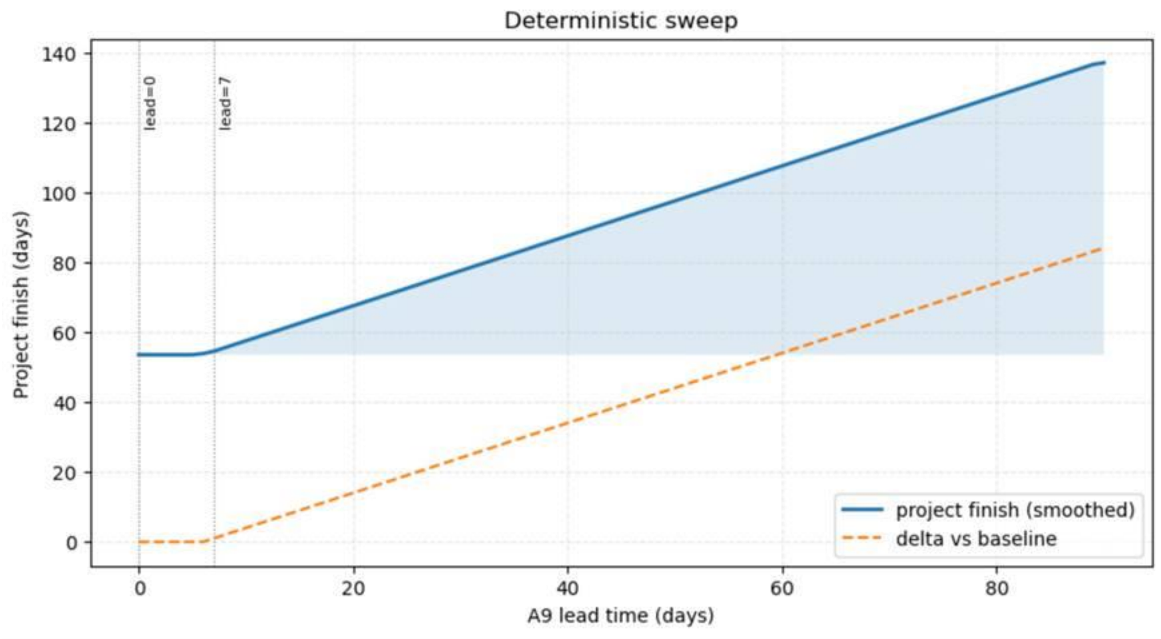

Figure 6. Sensitivity analysis with deterministic sweep, order lead time of sensors 0-90 days (Delta vs baseline= change in total project duration).

5 Discussion and Conclusions

This paper has demonstrated that integrating supply chain aspects into cultural heritage restoration projects reveals a network of critical tasks and potential bottlenecks that can significantly impact project outcomes. Based on data collected and analysed from a case study in Riga, related to renovation interventions in the central market pavilions, activities such as rebar replacement, overlay casting, and mechanical connector installation emerged as critical due to their reliance on timely delivery of heavy materials, specialized equipment, and skilled labour. Simultaneously, bottlenecks were identified in the availability of niche tools like jetting systems and fiber-optic kits, as well as in labour-intensive and specialist-dependent tasks. These constraints underscore the importance of aligning procurement, logistics, and workforce planning with the unique sequencing and sensitivities of heritage interventions.

The findings of this study align closely with as well as contribute to emerging research that emphasizes the importance of integrating supply chain dynamics into project planning frameworks, particularly in the context of cultural heritage restoration. As demonstrated through the identification of critical tasks and bottlenecks, such as delays in rebar replacement, overlay casting, and the availability of specialized equipment and labour, this project reinforces the argument made by Purushothaman et al. (2025) that conventional Critical Path Method (CPM) simulations often overlook supplier timelines and operational constraints, thereby missing hidden delays. The importance of managing and controlling operational constraints have been also highlighted by Thomas H. And Ellis (2017) by means of the resourcefulness model. The need for lean practices involving the coordination of complex workflows including stakeholders like artisans, suppliers, and logistics operators is also found in literature. For instance, Balyan et al. (2025) and Sousa et al. (2024) advocate for lean practices to enhance coordination, reduce waste, and ensure the timely delivery of high-quality materials without overwhelming site logistics. Furthermore, the importance of synchronizing procurement with replenishment policies during execution highlights the value of BIM (Zhao et al., 2025) as well as realtime data sharing and transparency, an area where blockchain technology has been proposed to improve traceability and accountability in handling historical artifacts (Deng, 2024; Irwan et al., 2025).

The practical contribution of this study lies in its demonstration of how supply chain dynamics, specifically material flow, labour/artisan availability, and site-specific logistical constraints, directly influence the critical path and overall timelines of cultural heritage restoration projects. By mapping these dependencies and identifying bottlenecks, the research provides actionable guidance for practitioners seeking to enhance project reliability and responsiveness. Crucially, it recommends that coordination among diverse stakeholders, procurement processes, and logistical planning be integrated into the core of scheduling and sequencing models such as CPM, rather than treated as peripheral concerns.

Future research should focus on simulating the effects of supply chain disruptions, such as fluctuating lead times, delivery sequencing issues, and site logistics, on project duration and critical task dependencies in cultural heritage restoration. These disruptions also impact replenishment policies and spatial constraints at construction sites, which merit further exploration. Additionally, there is a pressing need to develop integrated planning tools that merge supply chain considerations with design and project management systems (e.g. Business Information Modelling, BIM), enabling more responsive and coordinated execution across all phases of restoration.

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Data Availability Statement
The data supporting the findings of this study are available from the corresponding author upon reasonable request. Restrictions may apply to the availability of certain datasets due to confidentiality or third-party agreements.

Conflicts of Interest
The authors declare no conflict of interest.

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