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Influence of Macroeconomic Factors on Construction Costs: An Analysis of Project Cases

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This study presents the case of a large construction company with five case projects as embedded units of analysis. It explores the hierarchical structure within price categories, diversification of the cost breakdown structure, infrastructure sector, delivery system, construction methods, and type of bid in these five case projects to understand commonalities in relation to cost escalations derived from macroeconomic shocks. The analysis reveals significant variations in the relative influence of these factors across the five case projects, which represent diverse infrastructure types with different unit price categories. Unit price categories located higher in the hierarchical breakdown structure display lower vulnerability to macroeconomic changes due to their unique and group-specific influencing factors. Conversely, price categories influenced by macroeconomic factors or specific group-specific factors are identified when departing at lower values in the

hierarchical structure. Additionally, the study combines the Participation Index and 3-cliques to provide nuanced insights into unit price diversification and risk for various infrastructure sectors. The Education and Airport projects demonstrate the lowest diversification in the cost breakdown structure representing a high concentration of risk in a few materials, which can either mitigate or exacerbate cost increases depending on how these specific materials are affected by a macroeconomic crisis. While the Airport project performed the highest cost escalation due to the heavy reliance on off-site construction methods reliant on materials whose price is determined by global market conditions coupled with delivery systems lacking fixed pricing structures (construction management), the Education project performed a much lower cost escalation due to its reliance on-site construction methods intensive on materials whose prices rely on local factors on a life-cycle bundling delivery system (build-lease-transfer public-private partnership). In contrast, the cases with the lowest cost escalation (Road and Wastewater Treatment) projects exhibited high correlation and limited participation, it does serve as a mitigating factor compared to projects with higher participation in multiple cliques benefiting increasingly from integrated delivery systems (design-build). The contributions derived from the cases analyzed provide key elements for further analysis of decision-makers. Under macroeconomic crisis periods, public entities may consider giving high priority to projects more reliant on materials driven by regional dynamics (e.g., concrete pouring) over those driven by global market conditions (e.g., steel, aluminum) while prioritizing integrated delivery systems (e.g., design-build) that promote enhanced collaboration, proactive risk management, aligned incentives, and adaptability for managing complexities and volatilities. Complementary, for projects with higher reliance on global market-driven materials, the cases analyzed in this study suggest that owners and private contractors should prioritize early procurement and acquisition of highly volatile resources in projects under macroeconomic crises.

Keywords: Stakeholder management; Risk management; Risk Propagation; Integrated management; Public-private partnership; Social network analysis.

Introduction

Construction projects are inherently vulnerable to cost overruns due to their reliance on heterogeneous resources, which are often prone to market fluctuations (Di Maddaloni and Davis 2017). The cost performance of such projects is influenced by complex challenges, requiring

stakeholders to grapple with uncertainties and interconnected socio-technical obstacles (Zheng et al. 2021).

The COVID-19 pandemic's global disruptions intensified the volatility of construction material prices required in infrastructure projects, resulting in project suspensions, decreased productivity, cost overruns, and time delays (Akomea-Frimpong et al. 2022). Moreover, decision-makers and project managers were ill-prepared to deal with these heightened risks in those projects (Ottaviani et al. 2024). The crisis that began in 2020 highlighted the vulnerability of the global construction value chain to global shocks (Yagi and Managi 2021). The pandemic-triggered events, such as disruptions in global supply chains of construction materials and building components, have had a significant impact on prices throughout the construction industry, leading to huge cost inflation and escalation (Santacreu and Labelle 2022). The scarce availability of specific resources, technologies, and components in the construction sector has further exacerbated the cost overruns experienced in infrastructure projects (Allam et al. 2022). The exposure to foreign bottlenecks in the global value chain played a crucial role in transmitting the effects of these disruptions to prices (Santacreu and Labelle 2022). The combination of demand and supply shocks, along with varying exposure to these shocks across industries, has worsened the situation. Shipping costs doubled during the pandemic compared to previous costs, leading to higher product costs and increasing inflation. Western countries have been recently affected by high inflation rates, impacting the development of infrastructure projects globally (Allam et al. 2022). More recently, the war in Ukraine has resulted in intensified inflation and unprecedented price increases in key construction materials, such as steel, leading to increased debt for both the public and private sectors (Allam et al. 2022).

The recent global crisis has prompted project managers to develop more resilient strategies for strategic construction materials like oil derivatives, energy, and steel. Despite these efforts, the outbreak significantly impacted the construction industry, revealing weaknesses in existing strategies to protect infrastructure projects from price increases and uncertainties.

Despite the extensive literature on risk analyses in construction (Boateng et al. 2012; Flyvbjerg 2017; Shi et al. 2022) and growing research on the impact of the COVID-19 pandemic on

infrastructure projects (Cepparulo et al. 2023; Eggleton and Gürses 2023), there exists a noticeable gap in understanding the intersection between construction material sourcing risk and global crises within the context of construction projects. More precisely, there is limited research that combines construction material price increases under global crises and case study analysis with embedded multiple projects.

To bridge the gap, this research analyzes the construction price increase and price diversification for multiple infrastructure types in construction projects under macroeconomic shocks. Moreover, this analysis allows identifying the specific construction materials and infrastructure types according to their sensitivity to price increases during global crises. To achieve this goal, three techniques of network science are integrated: the Minimum Spanning Network (MST), the sub-optimal distances, and the Planar Maximally Filtered Graph (PMFG). These techniques have been extensively utilized to explore financial relationships, specifically concerning price fluctuations in the foreign exchange and stock markets (McDonald et al. 2005; Shomroni 2022; Yan et al. 2015). This research extends their application to investigate variations in construction cost prices triggered by global crises to offer a novel perspective on understanding how macroeconomic disruptions impact the financial aspects of construction projects, thereby providing insights into the underlying dynamics of cost fluctuations in the face of economic instability.

To illustrate the process, this study implements an approach to analyze a single case study at the organizational level (an Italian construction company) with embedded cases of analysis at the project level for five construction categories, namely: social, transport, education, and wastewater infrastructure sectors, developed across the Covid-19 pre-pandemic and pandemic periods.

Although these techniques have been widely applied to time series data of stock prices in financial markets and asset prices (de Carvalho and Gupta 2018; Hu et al. 2019; Majapa and Gossel 2016; Memon et al. 2020; Tumminello et al. 2005), this is the first time these are applied within the Project Management field to analyze the impact of price increases and the effects of global crises.

This paper is organized as follows. First, the research gap is introduced, followed by an outline of the pertinent literature. Next, the methodology for the network analysis is detailed. The paper then presents and discusses the findings, while practical implications and theoretical contributions are explained. Lastly, the conclusions, limitations, and potential avenues for future research are presented.

Literature

Risks in Construction Projects

Risk management is a critical aspect of construction projects (Boateng et al. 2012). Extensive research has been devoted to investigating risk in those projects, resulting in a strong body of knowledge (Osei-Kyei et al. 2022). Effective risk management is essential for projects, considering the complexity and uncertainty involved throughout a long project lifecycle (Castelblanco et al. 2024; Kuru and Artan 2020).

To effectively address construction risk management, numerous research articles have delved into multiple processes, encompassing risk assessment (El-Sayegh 2008), mitigation (Albalade et al. 2015), allocation (Nasirzadeh et al. 2013), and identification (Khallaf et al. 2018). This research underscores the pivotal role of risk management in the successful execution of infrastructure projects. Commonly examined risk factors encompass force majeure events, legal and regulatory risks, operational risks, financial risks, and political risks (Biziorek et al. 2023; Khallaf et al. 2024; De Marco et al. 2017).

Among the aforementioned processes, risk mitigation and allocation stand out as critical components for infrastructure projects' effective risk management (Akomea-Frimpong et al. 2021). Scholars have proposed different models for risk allocation based on the principle of transferring risks to the party best-suited for their management and implementing mechanisms for effective risk-sharing (El-Sayegh 2008). Furthermore, researchers have accentuated the significance of contractual provisions, such as insurance and performance guarantees, in safeguarding the financial sustainability and mitigating risks in those projects (Castelblanco and Guevara 2022; Chiara and Kokkaew 2013; Salazar et al. 2024).

Ameyaw and Chan (2015) conducted an in-depth analysis of 40 risk factors within the water supply sector in China. Through expert interviews, they identified critical risk factors, including conflict between the parties, financial risks, wrong demand forecasts, lack of experience, time and cost overruns, political interference, and poor contract design. Economic risks are intricately linked to macroeconomic variables such as economic downturns, interest rates, exchange rates, and inflation (Castelblanco et al. 2022; Guevara et al. 2024; Marcellino et al. 2023; Osei-Kyei and Chan 2017). Variations in macroeconomic conditions can exert significant influence on project financing arrangements, costs, and revenues. Construction risks tend to emerge more predominantly during the project development respecting design or other risk categories (De Marco and Narbaev 2021; Nguyen et al. 2018; Osei-Kyei and Chan 2017). These risks are closely linked to material price increases, which may result in delays in construction and cost overruns. Consequently, the implications of construction materials price increases ripple through project timelines, budgets, and overall quality.

Recent Global Crises and Risks

Over the last few years, the world has grappled with two outstanding global crises, the Global Financial Crisis and the COVID-19 pandemic that emerged. These crises have left an indelible mark on the construction industry. The pandemic crisis has unleashed unprecedented challenges on a global scale, such as disruptions to the intricate web of global construction supply chains. Simultaneously, other factors, such as the worldwide surge in inflation and the war in Ukraine, have also impacted the construction industry (Castelblanco et al. 2023). Although numerous studies have dissected each of these crises individually, there remains a notable gap in research that systematically analyzes the degree of relationship between the macroeconomic fluctuations derived from these crises and specific construction material prices within infrastructure types.

The pandemic bears striking similarities to the Global Financial Crisis, both characterized by profound global economic ramifications to the 1929 Great Depression. In fact, both crises were instigated by extraordinary exogenous shocks, culminating in unparalleled uncertainty levels that rattled worldwide international supply chains and financial markets linked to all kinds of

construction materials (Santacreu and Labelle, 2022).

The pandemic has presented unparalleled challenges for infrastructure projects on a global scale (Eggleton and Gürses 2023). Research exploring the pandemic's repercussions on project execution has shed light on diverse challenges and risks encountered by project stakeholders (Castelblanco and Guevara 2024; Hasan et al. 2021).

Compounding these challenges during the pandemic are disruptions in global supply chains (Yagi and Managi 2021). Restrictions on trade and displacements have impeded the timely procurement of construction materials, precipitating cost escalations and delays.

Cost Overruns Due to Price Escalation

Countless papers have dealt with project performance and project cost overruns, however, most of them are focused on tracking project cost performance focused on issues in project management or changes in scope contrasting with less research on macroeconomic-related sources of underperformance such as the ripple effect from price escalations in resources and materials on the cost breakdown structure (Flyvbjerg et al. 2018; Hoseini et al. 2020). Moreover, most of the literature focused on the impact of price escalation used to be limited to the analysis of traditional inflationary mechanisms instead of the heterogeneous impact of macroeconomic crises across the cost breakdown structure of projects. Some literature has focused its attention on analyzing contractual mechanisms for addressing cost overruns in specific jurisdictions (Abu Helw and Ezeldin 2022; Choi et al. 2006; Mekonen et al. 2023) or at an international level (Chammout et al. 2024). However, the impact of price escalation on project resources, materials, and labor is heterogeneous and there is required further analysis of the source of this heterogeneity along with strategies for managing this risk tailored to the specific conditions of projects (Marcum 2023).

Cost escalations in construction projects due to resources' price escalation can vary widely depending on several key factors, including the type of infrastructure, the delivery system, the type of bid, the construction method, and the diversification of resources. Each of these elements interacts with macroeconomic conditions and project-

specific circumstances to influence the extent and nature of cost overruns. Different types of infrastructure projects (e.g., roads, wastewater treatment plants, educational buildings, airports, social infrastructure) vary significantly in complexity, scale, and requirements (Bitran et al. 2013). The sensitivity of a project to material price fluctuations depends on the heterogeneous reliance on specific materials such as lumber, steel, or cement, each relying increasingly either on local or international supply chains and pricing (Shiha and El-adaway 2024). A higher reliance on specific construction method also impacts project costs due to the heterogeneous dynamics of on-site and off-site construction in terms of the manufacturing and supply chain logistics complexity (Ekanayake et al. 2021). The delivery system also may potentiate the impact of resources price increases on project cost performance when considering integrated methods (e.g., Design-Build or Build-Lease-Transfer PPP) that promoting collaboration and lifecycle integration as opposed to unbundled methods (e.g., separate Design-Bid-Build) that fragments design and construction into distinct phases and contracts (Papajohn and El Asmar 2020). Lastly, the type of bid may impact the capacity of the contractor on resources management when comparing open bids driven by open best-price bids as opposed to negotiated bids prioritizing quality control and adaptability over lowering initial cost (Zhang et al. 2016).

Method

Research Design

The proposed approach seeks a more comprehensive understanding of construction price increases and price diversification for projects under macroeconomic shocks. Moreover, this analysis allows us to identify construction materials and infrastructure types according to their sensitivity to price increases during global crises. To this end, an embedded design approach was chosen for this investigation, a technique recognized among scholars for its efficacy in exploring complex phenomena within the construction and project management sectors (Narayanan and

Huemann 2021). It is important to highlight that this approach was purposely chosen because this study is focused on analytic generalization (i.e.: facilitating the generalization of theories) rather than statistical generalization (i.e.: quantifying occurrences) (Yin, 2018: 78). In the process of grounding this research, the Italian construction industry was targeted as the test-bed for this analysis. The embedded design approach led us to consider the construction resource (i.e., material, labor, and equipment) price increase in Italy as the main unit of analysis. Once this analysis was done at the country level, the embedded case corresponds to major projects built by one of the top-10 largest construction companies in the country. Ultimately, the company chosen for our study was the one that agreed to provide access of data for research purposes.

Main Unit of Analysis – Italian Resource Construction Market

The primary focus of our analysis is the comprehensive pricing within the Italian construction market. There were identified 28 macro-categories of resources that are the constituents of the cost breakdown structure of construction projects. In order to establish the price change on these constituents, a triangulation of multiple sources was made for each macro-category including stock market indices, the National Builders' Association (Associazione Nazionale dei Costruttori Edili - ANCE), National Institute of Statistics (Istituto Nazionale di Statistica – ISTAT), Energy Markets Operator (Gestore dei Mercati Energetici – GME), Italian Ministry of Ecological Transition (Ministero della Transizione Ecologica Italiano), Ministry of Infrastructure and Sustainable Mobility (Ministero delle Infrastrutture e della Mobilità Sostenibili), and the Italian Association of Electrical Cables and Conductors Industries (Associazione Italiana Industrie Cavi e Conduttori Elettrici – AICE).

The Case Company

To examine price diversification and the heterogenous impact of resource price increases across different types of infrastructure, our embedded case study is one of Italy's top-10 largest construction companies, notable for its major international projects across diverse infrastructure sectors. The company is headquartered in Northern Italy and it operates in various regions across

the world mainly in the Arabic peninsula, Brazil, Botswana, Denmark, France, Italy, Romania, Sweden, and the USA, with operations specialized in the development of transport infrastructure such as roads, motorways, railways, subways, bridges, viaducts, and tunnels, as well as civil and social facility construction projects including hospitals, major shopping centers, and airports.

The Analysed Case Projects

To categorize the cost breakdown structures of various infrastructure types and assess the impact of resource price increases, we selected for analysis the firm's projects that were under construction across the COVID-19 pandemic period. Five projects and their consistent detailed dataset on the project's construction costs, which constitute the necessary input parameters, were available for that purpose. Two of the authors acted as consultants to the General Contractor of these projects and could collect first-hand data from the main contract documents.

The five projects are about the construction of a major road, a waste-water treatment plant, an educational facility, an airport terminal, and a social infrastructure facility in the Center, North, North-West, and North-East regions of Italy, as shown in Table 1 and described below.

Table 1. Projects Analysed

Infrastructure Type	Bid Cost (Mil €)	Delivery System and contract	Type of bid	Number of bidders		Cost Escalation per year
Road	75.3	Separated Design-Bid-Build (Sole construction)	Open bid - best price	23		14%
Airport	49.9	Construction Manager	Negotiation	4	23%	
Social Infrastructure	33.0	Design-Bid-Build (Sole construction)	Open bid best price	3	18%	
Wastewater Treatment	118.6	Integrated Design-Build	Open bid - best price and basic design	2		6%

Education	114.7	PPP (Build Lease and Transfer)	Negotiation	1	15%
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The road project is a significant infrastructure development aimed at enhancing the transportation network between the Tyrrhenian coast and the Adriatic Sea, facilitating trade and movement of goods across central Italy. It links important economic hubs, promoting regional development and integration. This corridor is part of the broader European transport network, contributing to the Trans-European Transport Network (TEN-T). It is a crucial link in the north-south and east-west corridors, enhancing Italy's role in the European transportation system. The project is divided into multiple segments, some of them requiring greenfield road development while others involving upgrading the road to a two-lane highway. The project entails multiple stages and involves various engineering tasks such as constructing new road segments, upgrading existing ones, and integrating advanced safety and environmental monitoring systems. Three alternatives for the road alignment were analyzed, with the final decision favoring a combination of new constructions and upgrades to the existing infrastructure. The scope of the project incorporates the construction of two major rotaries, four tunnels, seven bridges, and viaducts. The road safety and environmental measures include continuous monitoring of environmental impacts and strict adherence to safety protocols throughout the construction. The project involves extensive use of various construction materials and techniques, involves various types of asphalt layers including bituminous mixture for base layers, binder layers, and wearing courses, split-mastic asphalt for the topmost layer to enhance skid resistance and improve road safety, and bituminous binder layer for ensuring structural integrity and durability. Additionally, the project is also intensive on using concrete and steel to construct tunnels, bridges, and other road structures such as geotextiles and reinforced earth for stabilizing slopes and ensuring the integrity of embankments.

The Airport project involves the expansion and upgrading of a departure terminal to modernize and enhance the terminal facilities to meet growing passenger demands and improve overall airport efficiency. This airport serves as a major gateway for the Northern Italy region and

provides critical connectivity for both domestic and international travel. The project encompasses an expansion of approximately 11,500 square meters and the requalification of an additional 12,300 square meters. The project faced relevant technical challenges derived from the integration of new systems with existing infrastructure, and the necessity to maintain airport operations throughout the construction phase. The project required careful phasing to minimize disruptions to airport operations, including demolitions, foundation work, and the construction of new facilities and systems. The scope of the project involved extensive excavation, foundation construction, and the erection of new floors and structures after demolitions and provisional works. Civil works included the construction of new walls, partitions, and finishes for both the exterior and interior spaces and, installation of modern roofing and insulation systems. In addition, the project implemented a photovoltaic system to enhance energy efficiency and upgrade electrical systems for enhanced control and monitoring. The project also incorporated advanced systems for passenger security screening and baggage handling. The scope of the project was significantly reliant on glass and aluminum utilized in the modern facade designs and interior partitioning, photovoltaic panels, in addition to concrete and steel for foundational works, structural frames, and other load-bearing elements.

The Social Infrastructure project focuses on the expansion and upgrading of the Wholesale Market in one of the largest cities in Italy, specifically targeting the enhancement of infrastructure and services to meet modern standards and accommodate future growth. The project encompasses a substantial area, including various market facilities and logistical platforms covering several hundred thousand square meters. The project required integrating new construction with existing market facilities in multiple phases, ensuring minimal disruption to ongoing operations while adhering to regional and municipal regulations, particularly those related to public health, safety, and environmental standards. The scope of the project was significantly reliant on roofing and insulation to enhance energy efficiency and protect against weather elements, mechanical and electrical systems including energy-efficient lighting and power distribution, and advanced HVAC systems to ensure optimal climate control within the market facilities, fire systems including alarms, and sprinklers. Complementary, the project also

incorporated the demolition of outdated structures and the removal of obsolete facilities, the erection of modern buildings and logistical platforms to support enhanced market operations with extensive groundwork to ensure the stability and durability of new constructions, and the enhancement of access roads.

The Education project focuses on the development of a new university campus. This initiative aims to address the reorganization needs of educational and research activities and alleviate congestion at current scientific training facilities of one public university in one of the largest cities in Turin. The campus will house the Departments of Chemistry, Earth Sciences, Life Sciences, and Systems Biology. The project includes the construction of new buildings, infrastructure, and associated facilities necessary to support these departments. The scope of the project relied significantly on extensive groundwork, including excavation and foundation construction to support the new buildings; erection of vertical and horizontal structures, utilizing advanced construction techniques and materials to ensure durability and functionality; utility systems, including electrical, thermal, and water systems, and energy-efficient solutions like trigeneration and photovoltaic systems; while incorporating sustainable features such as the creation of extensive green areas and university parks, including irrigation and lighting systems.

The Wastewater project is an infrastructure development aimed at improving the wastewater management system in the metropolitan area of one of the largest cities in Italy. This large-scale project involves constructing a main collector tunnel to enhance the efficiency and capacity of the existing sewer system. The entire project spans approximately 14,400 meters, impacting the territories of the major city along with 20 neighboring municipalities within its metropolitan area. The main collector tunnel will have an internal diameter of 3.2 meters and will be constructed using a Tunnel Boring Machine (TBM) with a cutting head diameter of 4.1 meters. The tunnel construction will involve the installation of 23,000 prefabricated concrete segments. The excavation will generate approximately 250,000 cubic meters of material, which will be transported to disposal sites. Technical challenges involved utilizing advanced TBM technology to construct the tunnel under densely populated urban areas, ensuring minimal disruption to the surface activities and the construction site occupying around 13,000 square meters. To mitigate

traffic interference, an automated transfer system for the prefabricated segments was employed, utilizing rail cars along a 9 km gallery. Additionally, it was required constructing access shafts with a diameter of 25 meters and a height of 20 meters, comparable to a 4-5 story building.

The projects' initial construction costs ranged from 49.9 to 118.6 million euros and the construction phase started from 2018 to 2021. The projects' cost increases reported by the contractor closely due to price material increases ranging between 12.2% and 79.3% up to 2022 when considered all the resources involved in the cost breakdown structure.

The case projects are representative of different infrastructure types with defining characteristics embracing various delivery systems, bid process and market competition (as shown in Table 1), but also varied construction methods, and materials used, which make them suitable test beds for the proposed cost-escalation network analysis. In particular, in terms of construction methods, the Airport, Social Facility, and Wastewater projects rely on off-site prefabricated construction such as the above ground structures for the airport, prefabricated building structures and sandwich panels for the food market, and the concrete rings for the underground tunneling. On the contrary, projects like the Road and the Education ones use more on-site construction operations for concrete pouring, wall bricking, and finishes.

As for the construction materials, the Road, Social Infrastructure and Wastewater Treatment projects are highly dependent on asphalt and concrete-based materials and precast concrete components. Instead, the Airport and Education projects largely use steel carpentry and metal-composed materials such as steel metal structures, facade systems, and window walls.

Data Collection: Breakdown Structure and Construction Material Price Increases

To gather the relevant project information, a triangulation of diverse data sources was employed. These sources were carefully selected to ensure a comprehensive and accurate understanding of the projects, encompassing both the breakdown structure and construction material price increases. At the Italian construction market level, relevant legislation was retrieved to obtain the cost breakdown structure according to the national public works standards specified in the

adjudication of such projects. This included the Italian regulation (legislazione normativa D.M. 11-12-1978), which contains the incidence rates for the main categories of works. Complementary, the Regional Price List for Public Works (Prezzario Regionale delle Opere Pubbliche), and the list of prices for the analysis of underground works (Elenco nuovi prezzi su specifiche caratteristiche del cantiere in oggetto per l'analisi dei lavori in sotterraneo Italia) were also retrieved.

The aforementioned sources were complemented by the information from the embedded case (major projects), encompassing the official construction budget for each of the projects. The triangulation of diverse data sources facilitated a comprehensive and accurate analysis of the project. The utilization of multiple data sources at the national level and project' level allowed for a more nuanced and robust evaluation in this embedded design, making a significant contribution to the project management literature.

Data Analysis

The data analysis consists of five distinct stages (Fig. 1). The first stage is focused on the calculation of the variation of construction costs in the Italian market over the pre-pandemic (2018 and 2019) and pandemic (2020 and 2021) periods. Subsequently, the network analysis of the Italian market integrates the construction of the Minimum Spanning Tree (MST) network and definition of the sub-dominant ultrametric space. Lastly, the construction of the Planar Maximally Filtered Graph (PMFG) is focused on analyzed the embedded case (projects). Specifically, Stage 1 introduces a meticulous calculation of the percentage price variation for both the resources and the overall macro-categories at a national level. Stage 2 delves into graph theory and network analysis is integrated to construct a Minimum Spanning Tree network to connect cost categories based on their annual percentage price increases. In Stage 3, the sub-optimal ultrametric distance matrix is calculated, enabling the development of a dendrogram that elucidates hierarchical structures within cost categories. Lastly, Stage 4 introduces the Planar Maximally Filtered Graph construction to analyze the embedded case (projects), emphasizing 4-cliques as fundamental network structures and introducing the Participation Index adapted for the PMFG, offering

insights into price diversification and risk management. These stages collectively form a comprehensive framework for evaluating construction cost variations and risk management strategies in infrastructure projects, enhancing our understanding of their cost resilience and responses to economic shocks.

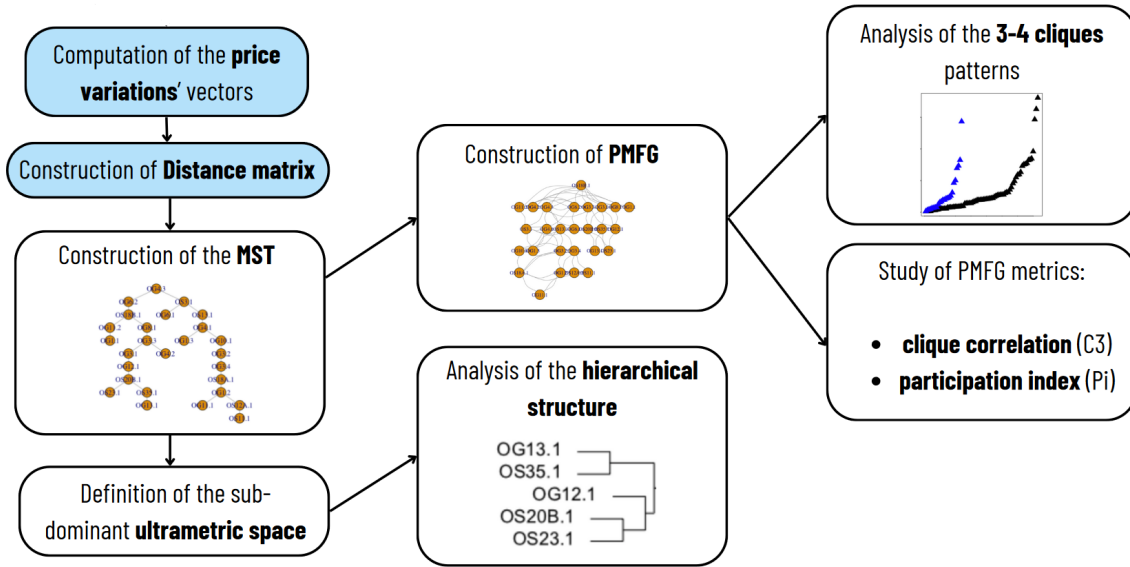


Fig. 1. Data Analysis. Displaying the multiple-stage data analysis.

The first stage was the calculation of the price variation of the macro-categories constituent of the Italian construction market prices. Initially, the yearly price variation for the resources were calculated as the average of the price increases of the multiple data sources at a national level. Subsequently, the increment of the macro-categories was computed as a weighted average based on the Percentage Incidence Share of the Cost for each resource in the work category, as follows:

$$Increase\ since\ year\ X = \sum_1^n (Percentage\ Incidence\ Share\ of\ the\ Cost\ Resource\ i * Increase\ since\ year\ X\ Resource\ i) \quad (1)$$

The second stage pertains to the construction of the Distance matrix and MST. The distance, measured as the Euclidean distance between the time series vectors of each category, determines the strength of the connections. The MST is rooted in graph theory and network analysis and refers to a tree-like subgraph that connects all the vertices of a weighted graph with the minimum possible total edge weight. To build the MST network, it was calculated a vector

representing the time series of annual percentage increases of the price of each cost category. Next, the distance between two cost categories (nodes) was defined as the Euclidean distance between the time series vectors of each category. To do so, it was required the standardization of the time series of every category. Given the vector of its time series, $v_1 = (x_{2018}, x_{2019}, x_{2020}, x_{2021})$, (where x_i is the increase in year i) the standardized vector is given by:

$$v_1 = \left(\frac{x_{2018} - \bar{v}_1}{\sigma_{v_1}}, \frac{x_{2019} - \bar{v}_1}{\sigma_{v_1}}, \frac{x_{2020} - \bar{v}_1}{\sigma_{v_1}}, \frac{x_{2021} - \bar{v}_1}{\sigma_{v_1}} \right) \quad (2)$$

where $\bar{v}_1$ is the average of v_1 , and σ_{v_1} is its standard deviation. Given two standardized vectors v_1 and v_2 , the distance between nodes r_1 and r_2 is given by their Euclidean distance $\|v_1 - v_2\|$.

Note that this is equal to:

$$\|v_1 - v_2\| = \sqrt{2(1 - \rho(v_1, v_2))} \quad (3)$$

where $\rho(v_1, v_2)$ is the Pearson correlation coefficient between v_1 and v_2 .

The third stage calculated the sub-optimal ultrametric distance matrix $D_{<}$ derived from the MST. This ultrametric matrix is obtained by defining the subdominant ultrametric distance $d_{<}(i, j)$ between categories i and j as the maximum value of any Euclidean distance $d(k, l)$ detected by moving in single steps from i to j through the shortest path connecting i and j in the MST. Next, a dendrogram representing the hierarchical structure of the categories is built, starting from the ultrametric distance matrix $D_{<}$.

The last stage involved the construction of the PMFG is constructed by connecting elements with the largest similarity under the topological constraint of fixed genus $g = k$, in direct analogy with the construction of the MST. The genus of a network is the smallest non-negative integer g such that the network can be embedded onto a surface with g "handles" without any edge crossings. It is defined as the minimum number of "cuts" needed to transform the network into a planar graph, where a planar graph is one that can be drawn on a two-dimensional plane without any edges crossing. Following the ordered list starting from a couple of categories with larger similarity (whose Euclidean distance is smaller), one adds an edge between category i and category j if and only if the resulting graph can still be embedded on a surface of genus $g = 0$

after such edge insertion (to check the planarity, the boyer-Myrvol algorithm was used). This algorithm generates simple, undirected, connected planar graphs and it can be shown that the MST is a sub-graph of the PMFG.

The PMFG allows for identifying 4-cliques. Moreover, during the formation of the PMFG, these 4-cliques cluster together locally at similar correlation values and then connect to each other, forming the skeleton structure of the MST. PMFG heavily relies on the concept of cliques, which are complete subgraphs connecting all within them. This graph is composed of interconnected 4-cliques arranged based on their correlation values. The concept of 4-cliques can be understood intuitively as follows: Consider three elements in a correlation-based network, let's say A, B, and C. If A is strongly correlated with B, and B is strongly correlated with C, then it is highly likely that a strong correlation between A and C should also be detected, forming a triangular clique. Now, if one of these three elements is strongly correlated with a fourth element, let's say D, then it is also likely that the other two elements have a strong correlation with D, resulting in the formation of a 4-clique, resembling a tetrahedron. Due to the topological constraint of planarity, the next most correlated element can only be connected to a maximum of three out of the four elements in such a tetrahedron. Connecting a new element to three elements of the 4-clique generates another 4-clique, forming a new tetrahedron that shares a face with the previous one. Following this reasoning, it can be expected that the fundamental structures in the resulting graph are the 4-cliques.

In classic networks, the participation index measures how equally distributed the connections of a node i are among all communities of the network. It is computed in the following way:

$$p_i = 1 - \frac{\sum_{j=1}^c e_j^2}{k_i^2} \quad (4)$$

Here, e_j is the number of links from node i to community j , while k_i is the degree of node i . $p_i = 0$ indicates that i is only connected to nodes in its community, while $p_i = 1$ shows that its edges are uniformly distributed among all communities. This concept is expanded for the PMFG because in this case, instead of considering communities, cliques are taken into account.

Therefore, while based on the definition of a community, a node can participate in only one community, in the PMFG, a node can be involved in multiple cliques simultaneously. To address this divergence, the normalization k is replaced in the previous formula with the sum of the link multiplicities of node i , where the multiplicity refers to how many cliques that particular link is connected to. Therefore, the new definition of the participation index is as follows:

$$PI_i = 1 - \frac{\sum_{j=1}^c e_j^2}{(\sum_w m_w)^2}. \quad (5)$$

Here, e_j is the number of links from node i to clique j , and can be either 0 (no participation in that clique) or 3 (participation in that clique, hence connecting to all the other 3 nodes of the clique). m_w is the number of cliques that the w -th link of node i involves. When $pi = 0$, it means that node i participates in only one clique, while, if $pi = 1$, it means that node j participates in all cliques serving as a bridge between all the cliques in the network.

In order to present an analytic generalization on the heterogenous impact of the analysis conducted according to the breakdown structure in different infrastructure sectors, the major projects analyzed were used to identify the specific work categories typically involved in their cost breakdown structures. In this way, the work categories used in each major project are presented, and the aggregated participation index and C3 are shown for each project.

Findings

Main Unit of Analysis –Italian Resource Construction Market

To ensure a consistent and standardized approach in analyzing the selected projects, a unified cost breakdown structure was adopted, aligned with the established public work categories in Italy for infrastructure projects. The cost breakdown structure is organized into two types of macro-categories, namely, General Works (OG) and Specialized Works (OS), as outlined in Table 2, further decomposed into categories.

Table 2. Work categories

ID	CATEGORY
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OG1	Civil and Industrial Buildings
OG1.1	Building works
OG1.2	Elevator and hoist installations
OG1.3	Concrete works for buildings
OG3	Roads, Highways, Bridges, Viaducts, Railways, and Subways
OG3.1	Earthworks
OG3.2	Artworks [Viaducts, tunnels, walls]
OG3.3	Road superstructure
OG3.4	Metal Structures for Transportation Projects
OG4	Underground Art Works
OG4.1	Underground works
OG4.2	TBM tunneling
OG4.3	Precast concrete blocks
OG6	Aqueducts, Gas Pipelines, Oil Pipelines, Irrigation Works
OG6.1	Aqueducts, including pipe supply
OG6.2	Sewers
OG6.3	Mechanical and hydraulic systems
OG8	River Engineering, Flood Defenses, Hydraulic Systems
OG8.1	Hydraulic works
OG10	Public Lighting
OG10.1	Electrical supply and lighting installations
OG11	Technological Systems
OG11.1	Electrical installations
OG11.2	Mechanical installations
OG12	Environmental Works
OG12.1	Asbestos Disposal and Landfill
OG13	Environmental Engineering Works
OG13.1	Environmental mitigation, green works
OS3	Water and Sanitary Systems
OS3.1	Sanitary installations
OS4	Electromechanical Conveying Systems
OS4.1	Elevator and Hoist Installations [BHS, Elevators, Escalators]
OS11	Special Structural Components
OS11.1	Supports, joints, and restraints
OS12A	Road Safety
OS12A.1	Road safety barriers
OS13	Precast Reinforced Concrete
OS13.1	Precast concrete structures (slabs, tanks, walls)
OS18A	Metal Structures
OS18A.1	Structural Steel Components
OS18B	Façade Components
OS18B.1	Continuous Glass Façade
OS20B	Geotechnical
OS20B.1	Geotechnical and Field Tests, Laboratory Analysis
OS21	Special Structural Works
OS21.1	Special foundations
OS21.2	Foundations in concrete (wells)
OS21.3	Deep foundations, pile walls, micro-piles

OS23	Demolition Works
OS23.1	Demolition of existing structures
OS28	Heating and Air Conditioning Systems
OS28.1	Air conditioning system
OS28.2	Electrical systems
OS30	Electrical Systems
OS30.1	Electrical installations
OS35	Low Environmental Impact Interventions
OS35.1	Microtunnelling and pipe jacking

The selection of these categories incorporates insights from various authoritative sources such as Italian legislation, regional public works price indexes, and analysis of underground works in Italy.

The MST was calculated to establish a network connecting all the nodes (i.e., work categories) while minimizing the total distance, thus identifying the critical links or connections within the price increases network. The resulting MST is visually represented in Fig. 2.

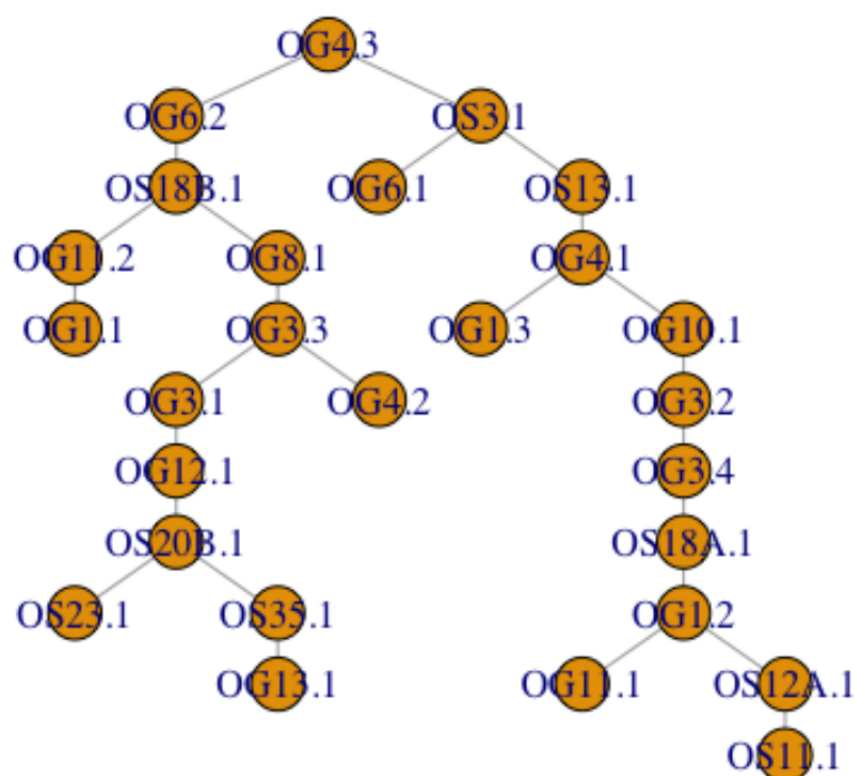


Fig. 2. Minimum Spanning Tree. Displaying the Minimum Spanning Tree the work categories linked according to their minimum Euclidean distance.

The next step involves determining the suboptimal distance between two groups. The suboptimal ultrametric distance matrix $D_{<}$ is derived from the MST. Once the ultrametric distance matrix $D_{<}$ is established, a dendrogram was created to represent the hierarchical structure of the categories based on the price variations at a national level. The dendrogram, shown in Fig. 3, clusters the categories into two groups based on their corresponding suboptimal distances along the y-axis.

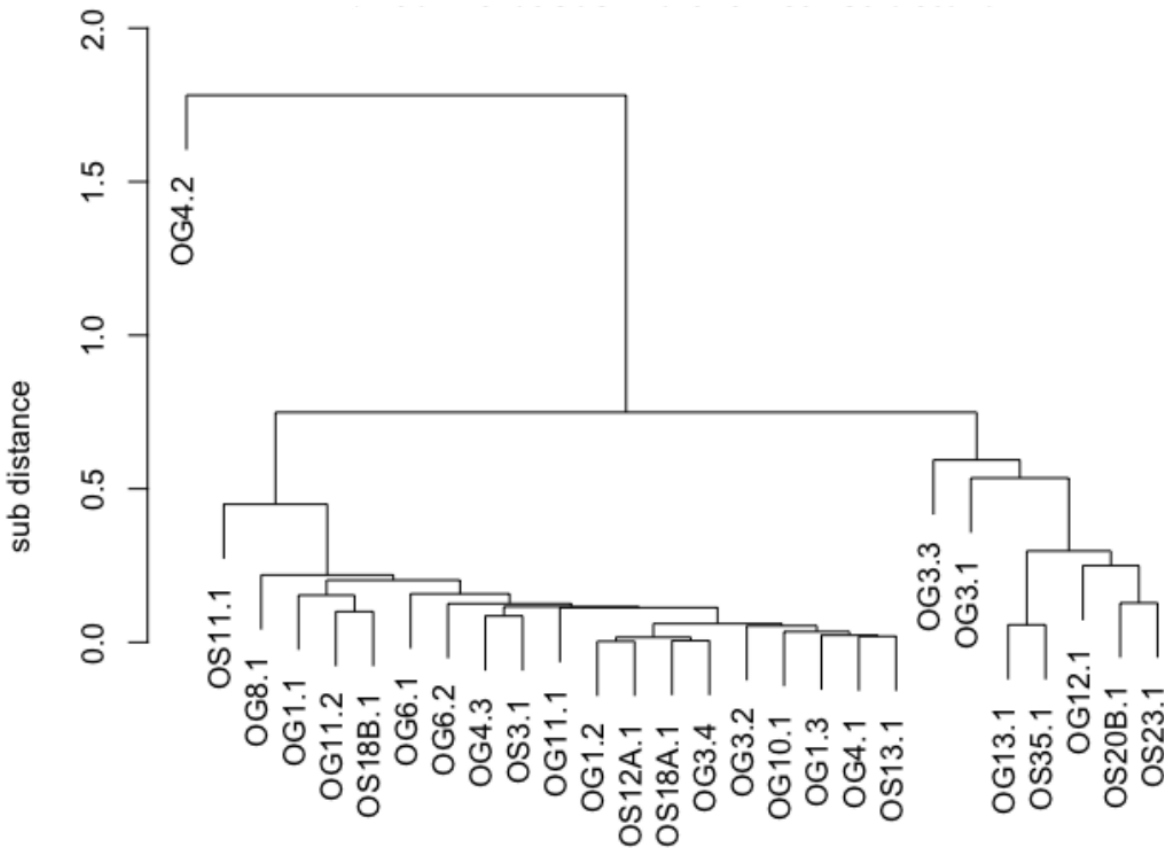


Fig. 3. Price Increases Hierarchical Structure. Displaying the Dendrogram linking the work categories according to their hierarchical structure.

To gain a more detailed understanding at a project level, a Planar Maximally Filtered Graph (PMFG) was created to represent the interconnections between the categories for the projects analyzed. The PMFG offers a comprehensive network of relationships that provides additional information to distinguish and differentiate the characteristics of the five projects. Fig.

4 illustrates the resulting PMFG for the categories, capturing the intricate connection between the categories and enabling a deeper exploration of their interdependencies.

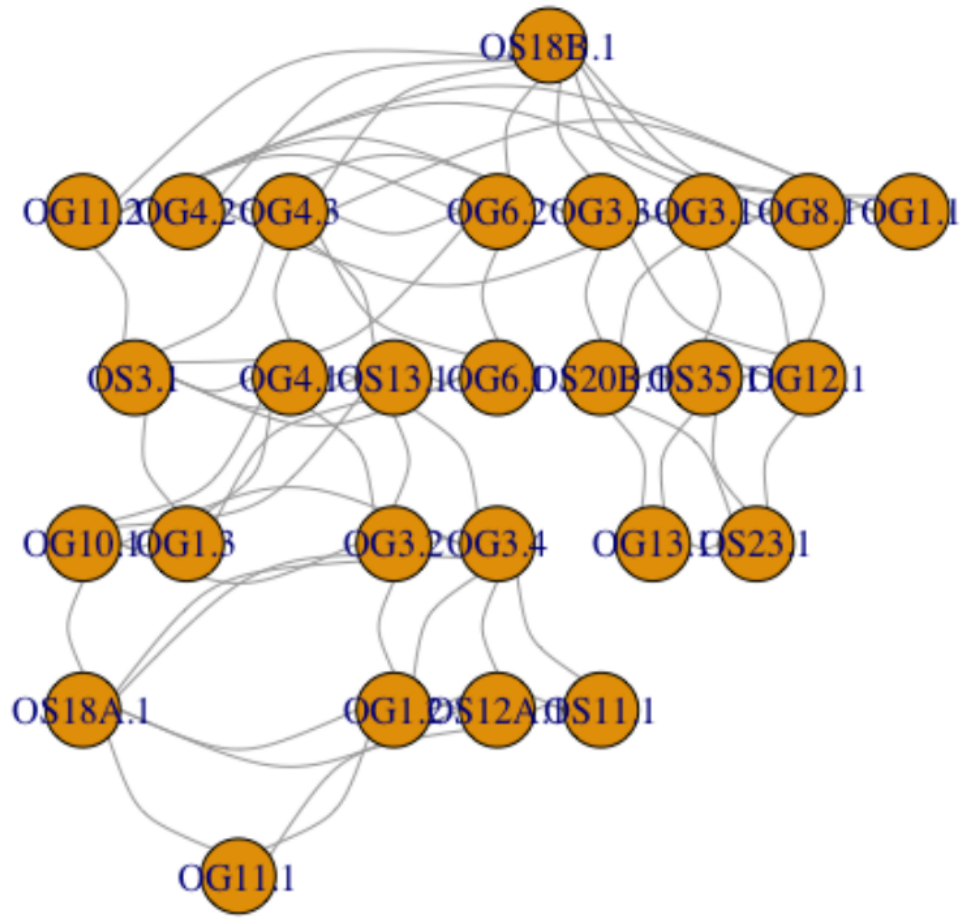


Fig. 4. Planar Maximally Filtered Graph. Displaying the interconnections between the categories according to their interdependencies.

The PMFG was calculated the five projects to identify the 24 4-cliques, though it is important to note that the number of potential cliques in a network of 27 nodes could be determined as $\binom{27}{4} = 17550$. Fig. 5 depicts the average distance within each of the 24 PMFG's 4-cliques in ascending order (shown in blue), while the 3-cliques are illustrated in black.

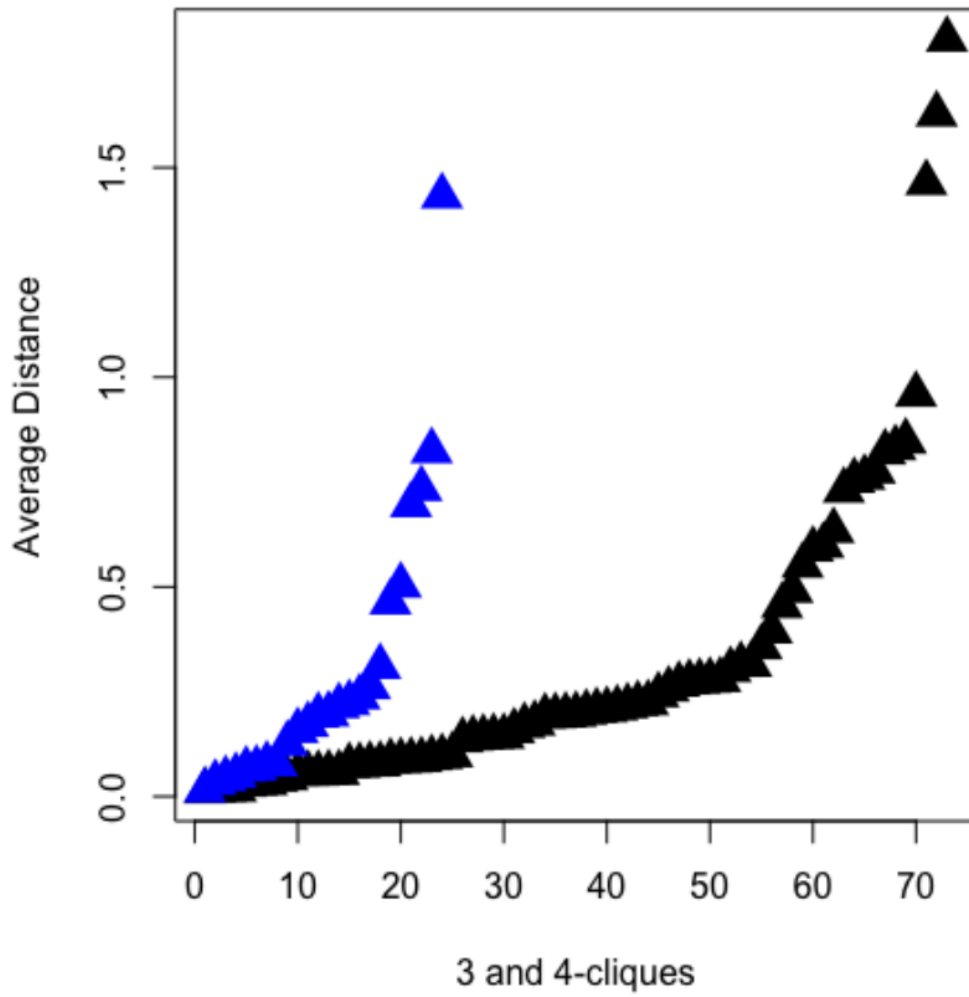


Fig. 5. Average Distance within each of the 24 PMFG's 4-cliques. Displaying the average distance within each of the 4-cliques in ascending order (shown in blue), while the 3-cliques are illustrated in black.

Similar to the MST, the PMFG consists of a group of strongly correlated cliques with very small distances between them, along with some less correlated cliques. However, unlike the MST, the PMFG allows for sorting these cliques, revealing the most significant interactions between the nodes. This measure is related to the concept of betweenness but uses the concept of cliques, which serves as building blocks of the PMFG. The participation index, considering both the 3- and 4-cliques, is presented in Table 3. This index provides valuable insights into the importance of node interactions within the network.

Table 3. Participation Index for 3- and 4-cliques for the categories of the PMFG

ID	PI3	pi4
OG4.3	0.826923	0.833333
OS13.1	0.826923	0.833333
OS18B.1	0.826923	0.833333
OG11.2	0.79545	0.8
OG3.1	0.795455	0.8
OG3.3	0.795455	0.8
OS3.1	0.795455	0.8
OG3.4	0.795455	0.8
OG1.2	0.75	0.75
OG4.1	0.75	0.75
OS20B.1	0.75	0.75
OG8.1	0.75	0.75
OG12.1	0.75	0.75
OS18A.1	0.75	0.75
OG3.2	0.75	0.75
OG10.1	0.75	0.75
OG6.2	0.678571	0.666667
OS35.1	0.678571	0.666667
OS12A.1	0.678571	0.666667
OG6.1	0.55	0.5
OS23.1	0.55	0.5
OG1.3	0.55	0.5
OG1.1	0.55	0.5
OG11.1	0.25	0
OG13.1	0.25	0
OG4.2	0.25	0
OS11.1	0.25	0

In a project, the level of exposure to price fluctuation during a crisis is directly related to the number of categories that belong to the most correlated 4-cliques. Figure 6 illustrates the categories utilized by each of the 5 projects to analyze the project's vulnerability to price changes.

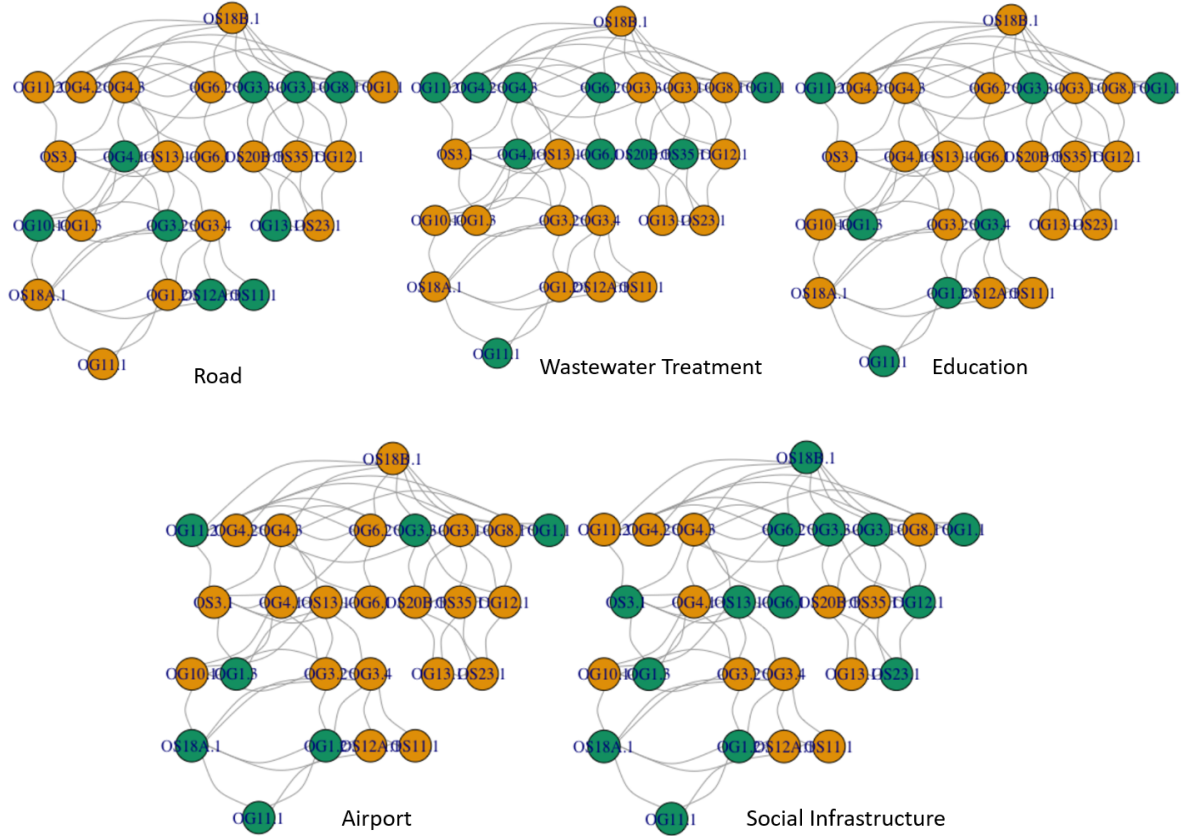


Fig. 6. Categories used by each project (green nodes). Displaying the categories utilized by each of the 5 projects to analyze the project’s vulnerability to price changes.

The rationale behind this measure is that project risk exposure increases as the number of categories used within the same clique grows. This relationship can be quantified using the 3-cliques correlation (C3i) for each of the analyzed projects. By combining the C3 metric with the participation index, it is possible to gain a more comprehensive understanding of the risk associated with price fluctuations in each project. Fig. 7 illustrates this combination, where the x-axis represents the value of C3 of the categories used by a specific project, and the y-axis shows the average Participation Index of those categories.

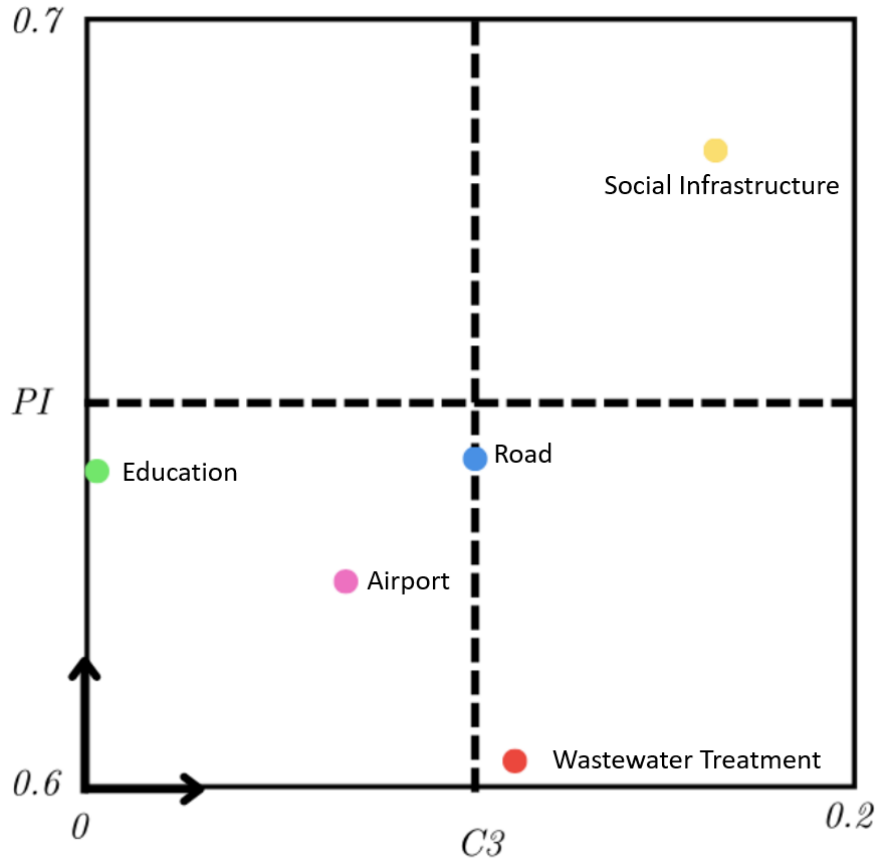


Fig. 7. Participation Index and C3 per Infrastructure Sectors Analyzed. Displaying the value of C3 of the categories used by a specific project in the x-axis and the average Participation Index of those categories in the y-axis.

Discussion of Results

The identification of a hierarchical structure in the price categories (as shown in Fig. 2) supports the idea that their time series are differently affected by economic factors. The analysis reveals that the number and the relative influence of these factors significantly vary across the categories. Overall, price categories that appear early in the tree (at high values of the distance $d(i, j)$) are primarily influenced by unique factors that are specific to their respective groups. Consequently, these categories are less susceptible to broader macroeconomic changes, such as fluctuations in inflation rates, disruptions in global supply chains, or increases in commodities prices because of other causes. Interestingly, Fig.2 demonstrates that these less susceptible categories are associated with critical activities within transportation and underground infrastructure works, such as *Road Superstructure* (OG3.3), *Earthworks* (OG3.1), and *TBM*

tunneling (OG4.2). It is noteworthy that *TBM tunneling* forms a separate branch in the tree, distinct from the remaining two categories, indicating different influencing factors for each branch.

Conversely, when the departure occurs for lower values of d , it indicates that the categories are influenced by either macroeconomic factors or specific factors unique to particular groups. The extent to which these factors play a role is quantified by the length of the segment (or segments) observed for each group from one branch to the next. Notably, in the dendrogram (Fig. 2), the categories with the longest segments are *Elevator and Hoist Installations* (OG1.2), *Road Safety Barriers* (OS12A.1), *Structural Steel Components* (OS18A.1), and *Metal Structures for Transportation Projects* (OG3.4). These categories are grouped in the same branch of the tree, indicating their common reliance on steel as a critical material. Steel is a globally traded commodity, and its prices are extremely volatile, particularly during macroeconomic crises that may impact on supply chain disruptions, tariffs, and production slowdowns in key steel-producing countries led to significant price increases and delays.

Furthermore, by combining the analysis of the Participation Index and 3-cliques (Fig. 5), a more nuanced understanding of the implications for each infrastructure sector can be achieved, as follows.

Two projects situated in the lower-left quadrant in Fig. 6, namely, *Education* and *Airport*, demonstrated low correlation values (C3) and low Participation Index. This positioning indicates that the fluctuations of the main categories composing the cost breakdown structure of these projects are not strongly correlated with each other and also participate in only a few cliques within the network. The participation in a few cliques of the cost breakdown structure of the education and airport projects analyzed, resulted in less diversification, which increase the reliance of cost performance on specific materials. Low diversification in the cost breakdown structure means a high concentration of risk in a few materials, which can either mitigate or exacerbate cost increases depending on how these specific materials are affected by a macroeconomic crisis. This is evidenced in the heterogeneous cost performance of the projects with less diversification. In the *Airport* project, the high-cost escalation corresponds to the low

diversification coupled with the heavy reliance on steel and aluminum whose prices are determined by global market conditions in terms of supply and demand dynamics. Conversely, the *Education* project, although also performing a low diversification, relied more significantly on concrete, wall bricking, and finishes whose prices are increasingly determined by local factors such as regional manufacturing capabilities, transportation, and local demand; less sensible to the macroeconomic issues experienced during the pandemic. The gap between both projects also is derived from the projects' differences in terms of construction methods and delivery systems (Table 1). In the *Airport* project, the combination of Construction Management delivery system (as opposed to the Build-Lease-Transfer PPP in the *Education* project) and off-site construction steel method (as opposed to on-site operations for concrete pouring, wall bricking, and finishes in the *Education* project) entailed an incentive misalignment derived from the contractor's fee established as a percentage of the total project cost in conjunction with lack of fixed pricing structures and transportation disruption at different levels affecting off-site steel subcontractors.

Two infrastructure types, *Road* and *Wastewater Treatment*, share in common experienced the lowest cost escalations due to price escalation and their position in the lower-right quadrant in Fig. 5, which is characterized by high correlation values (C3) and low Participation Index values. For these infrastructure types, the categories show a high level of clustering and interconnection within more extensive cost breakdown structures. However, despite the high C3 values and the associated increased risk, the average Participation Index for *Road* and *Wastewater Treatment* projects is low. This indicates that these cost categories participate in only a few cliques within the network. While this limited participation does not eliminate the risk entirely, it does serve as a mitigating factor compared to projects with higher participation in multiple cliques. Particularly, this was reflected in the project with the lowest Participation Index (*Wastewater*) that performed the lowest cost escalation across the five cases analyzed. The best performance of this project respecting the other project in the same quadrant (*Road*) can be understood because of the impact of the construction method and delivery method (Table 1). The combination of an integrated Design-Build delivery system (as opposed to the separate Design-Bid-Build in the *Road* project) and off-site construction concrete method entailed closer collaboration and

streamlined communication among stakeholders since the pre-construction while a higher reliance on locally produced concrete, resulting in mitigated cost escalations.

The *Social Infrastructure* project analyzed stands out as the only sector positioned in the upper-right quadrant, characterized by high C3 values and a high Participation Index. This placement indicates that this project heavily relies on cost categories that are both tightly clustered and interconnected, which exposes them to a higher risk of price fluctuations under changing macroeconomic conditions. The strong clustering and interconnection of cost categories within this infrastructure sector imply a high degree of correlation among the various elements that contribute to its overall cost. This interdependence means that changes in one cost category are likely to have a cascading effect on the other closely related categories. As a result, any price fluctuations in specific construction materials, labor costs, or other economic factors that impact these interconnected categories could have a magnified effect on the overall cost of social infrastructure projects. This is reflected in the fact that even though the *Social Infrastructure* project had the more extensive cost breakdown structure, it reached the second highest cost escalation. This underperformance is also understood because of the construction method and delivery system derived from the combination of a separate Design-Bid-Build delivery system (as opposed to lifecycle approaches to mitigate risks such as PPP or integrated Design-Build) and off-site construction method for the sandwich panels (closely related to the detrimental dynamics of steel and aluminum).

Contributions and Implications

This study's findings aim to constitute the starting point of a discussion on how to increase the cost resilience of large infrastructure projects considering multiple characteristics such as price diversification and clustering within the cost breakdown structure, delivery system and contract, and market competition. The results of this study contribute to the existing body of knowledge and offer relevant insights for project managers and the public sector's decision-makers involved in projects. Specifically, the findings enhance the understanding of common

factors that may affect price increases in those projects, particularly in the context of extraordinary macroeconomic shocks like the one triggered by the COVID-19 pandemic. Overall, this study offers elements to inform project managers and public sector decision-makers on potential ways to enhance construction risk management derived from price increases. Public entities may consider this study's findings to explore the suitability of prioritizing integrated delivery systems, such as design-build, that promote enhanced collaboration, proactive risk management, aligned incentives, and adaptability for managing complexities and volatilities. Moreover, public sector stakeholders may also consider giving high priority to projects more reliant on materials whose supply chain and prices are reliant on regional context (e.g., concrete pouring) over those driven by global market conditions (e.g., steel, aluminum) during times of significant macroeconomic volatility and global crises. Complementary, for projects with higher reliance on global market-driven materials, the cases analyzed in this study suggest that owners and contractors should prioritize early procurement and acquisition of highly volatile resources in projects under macroeconomic crises.

The dendrogram based on sub-optimal distances of the pricing calculated at a national level significantly contributes to the existing literature on projects by a clear methodological approach for providing a hierarchical structure that group cost categories together according to their similarity, allowing for identifying those that are more sensitive to macroeconomic shocks. The merging height of clusters in the dendrogram indicates the level of similarity between them and helps identify outliers that are less susceptible to fluctuations caused by macroeconomic factors, such as category number OG4.2 within the Italian market analyzed. This is particularly valuable for effective risk management during potential global crises, like escalated global inflation, the COVID-19 pandemic, or disruptions in the global supply chain. By recognizing these categories' sensitivity, risk contingency plans can be developed to protect them during such crises.

Moreover, the graphic representation of the pairing of 3-cliques and the Participation Index provides insights into the price diversification and risk of price increases under macroeconomic shocks, specifically tailored to different infrastructure types. This finding serves

as a crucial starting point for discussions on how to enhance cost resilience in specific infrastructure types, effectively countering the “iron rule of projects,” which involves cost overruns and delays.

Overall, this study provides valuable insights that public and private entities can take into account for further exploration when planning construction risk management derived from price increases.

The identification of a hierarchical structure among price categories aligns with the notion that their time series are influenced in diverse ways by economic factors. The analysis reveals substantial variation in both the number and relative impact of these factors. In general, price categories that diverge early from the tree are predominantly influenced by unique factors specific to their respective groups and, consequently, they display lower susceptibility to macroeconomic fluctuations. Interestingly, these less susceptible categories are closely associated with critical activities within transportation infrastructure works and breakdown structures more reliant on underground works, such as *Road Superstructure* (OG3.3), *Earthworks* (OG3.1), and *TBM tunneling* (OG4.2). For public entities, this insight can serve to inform potential strategies to allocate resources strategically during periods of macroeconomic volatility and global crises. Given the lower vulnerability of transportation- and underground-related categories to macroeconomic shocks, redirecting resources towards such projects can help mitigate risks and ensure the long-term success of infrastructure development.

Simultaneously, private entities can leverage this knowledge to consider specific activities in projects that are more reliant on materials whose prices are driven by global markets (e.g., steel, aluminium). Project managers may proactively plan for potential disruptions or cost increases by identifying alternative suppliers and securing critical materials. For instance, a contractor may take the initiative to establish contacts with multiple steel suppliers, ensuring they have contingency options in case the initial contractor suppliers encounter difficulties in delivering material as per the agreed-upon schedule and price. By diversifying their supplier base, projects can enhance their resilience and adaptability under unforeseen events. By focusing on

activities with lower sensitivity to material costs, private entities can enhance cost efficiency and better navigate uncertainties caused by fluctuations in the global market.

This finding carries significant implications for project managers and policymakers involved in these infrastructure types. The diversification of cost categories provides a more stable foundation for budget planning and cost contingency management. It offers greater resilience against unforeseen events, such as global crises or commodity price surges, which creates increasing financial challenges for other infrastructure types with less diversified cost structures. Complementary, if macroeconomic conditions get worse during project execution, project managers of infrastructure types with low price diversification can use these findings to prioritize negotiation of highly risky categories that entail a significant proportion of the construction costs. This requires timely decision-making from project managers to promptly use contingency budgets to reduce the potential impact of these shocks on construction costs. Simultaneously, implementing this measure necessitates contract flexibility and strong collaborative ties between the public and private sectors. The goal is to effectively leverage these measures, which may involve potential contractual modifications to increase the contractor's liquidity. One approach could be transferring some reserve accounts for periods longer than one year, with the understanding that these funds must be repaid along with accrued interest. By adopting this strategy, both parties can work together to ensure the financial stability of the project and provide the contractor with additional support during critical phases of development.

Conclusions

This study gives valuable insights into the hierarchical structure of price categories in projects and their susceptibility to macroeconomic shocks. The identification of distinct clusters and interconnections among cost categories sheds light on their diverse influences and risk profiles. Projects falling within the lower-left quadrant (low C3 and high Participation Index) exhibit higher cost diversification, reducing their vulnerability to price fluctuations. Such infrastructure types, including Education and Airport projects, can be prioritized during periods

of significant macroeconomic volatility and global crises due to their lower risk exposure. In contrast, projects in the lower-right quadrant (high C3 and low Participation Index), such as Road and Wastewater Treatment, face a trade-off between clustering efficiency and cost diversification, necessitating careful risk management strategies.

The findings contribute to the literature by offering a valuable tool for planning construction risk management, derived from price increases. The dendrogram based on suboptimal distances provides a hierarchical structure, facilitating the identification of categories more sensitive to macroeconomic shocks. This insight allows for the development of risk contingency plans during potential global crises, such as inflation escalation, the COVID-19 pandemic, or supply chain disruptions.

Moreover, the graphic representation of the pairing of 3-cliques and the Participation Index enables a nuanced understanding of price diversification and risk across different infrastructure sectors. It serves as a starting point for discussions on enhancing cost resilience in specific infrastructure types and countering the "iron rule of projects," which involves cost overruns and delays.

While the study provides valuable contributions, it also has some limitations. Firstly, this study is focused on analytic generalization (i.e., facilitate the generalization of theories) through an embedded study design rather than statistical generalization (i.e., quantify occurrences) relying on sampling for statistical generalization. While the main unit of analysis is the Italian Construction Market based on the calculation of price increases in those resources' macro-categories was done at a national level, the embedded unit of analysis is the major projects conducted by one of the top 10 largest construction companies in Italy during the pandemic allowing for showcasing cost breakdown structures commonly used in specific infrastructure types in similar contexts. In order to get broader generalization, future research may rely on statistical generalizations built upon large samples of projects.

Secondly, the study focuses on price fluctuations, but other factors, such as regulatory changes or political instability, could also influence cost structures. Future research could incorporate scenario analysis and risk modeling to assess the impact of various unforeseen events

on infrastructure projects. Additionally, examining the influence of non-economic factors on cost categories would provide a more comprehensive understanding of the drivers of price fluctuations. Furthermore, the study assumes a static cost structure, but cost may evolve over the project's lifecycle. Incorporating dynamic cost modeling would allow for better tracking and management of price fluctuations throughout the project's execution. Moreover, a deeper analysis of specific infrastructure types, such as Social Infrastructure, could provide valuable insights into sector-specific risk management strategies.

Disclosure statement

No potential conflict of interest was reported by the authors.

Data availability

Data generated or analyzed during the study are freely available from the corresponding authors by request.

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