

From Sticks to Bricks: Construction Technology and Medieval Urban Development*

Robert J. Johannes[†]

February 12, 2026

Abstract

The pre-modern construction sector was a cornerstone of economic activity and a source of disruptive innovation, with far-reaching implications for welfare and regional development. Yet, the link between construction sector productivity and regional development remains understudied. This paper investigates a transformative construction technology shock – the introduction of brick technology to regions north of the Alps – and its effects on medieval urban development. Brick technology, characterized by high economies of scale, enabled cities with suitable natural resources to expand their construction possibilities. Using a novel dataset on brick adoption in medieval German cities and leveraging exogenous variation in city-level brick suitability, I show that cities adopting brick technology underwent a significant transformation. They developed more robust and resilient urban infrastructure that ultimately supported larger urban populations. I also find that brick adoption enhanced cities' resilience to plague-induced demographic shocks. These findings highlight the economic importance of innovation in construction for long-run development.

*I am grateful to Mathias Bühler, Davide Cantoni, Neil Cummins, Jonathan Dingel, Jeremiah Dittmar, Lena Greska, Ingrid Hägele, Sebastian Hager, Stephan Heblich, Taylor Jaworski, Wolfgang Kemp, Yanos Zylberberg, and especially Fabian Waldinger for their valuable feedback. This paper also greatly benefited from discussions with conference audiences at NBER Summer Institute 2024 (DAE) and the CESifo/ifo Workshop on Big Data in Regional and Urban Economics. I gratefully acknowledge financial support from the Egon-Sohmen-Foundation and the Joachim-Herz-Foundation.

[†]Ludwig-Maximilians-Universität München, robert.johannes@econ.lmu.de.

1 Introduction

Throughout history, great civilizations have allocated enormous resources to architecture. From the pyramids of Giza and the amphitheaters of Imperial Rome to the early skyscrapers of Manhattan, these projects have driven advancements in engineering, urban planning, and the organization of labor. Even today, with the construction sector contributing approximately 4.5% of economic output in the United States and 7% in China, its role in modern economies remains substantial.

The economic importance of the construction sector was particularly evident in the cities of medieval Europe, which experienced an unprecedented boom in building activity. The building of cathedrals, town halls, and fortifications served as “the centre of the earliest, and almost the only, medieval industry” (Le Goff, 1988, p. 56), fostering an environment for disruptive innovation. Cities leveraged new construction technologies to strengthen their defenses, expand public goods provision, and accommodate rapidly growing populations. In doing so, these technologies fueled a “golden age of urban growth”, with far-reaching consequences for Europe’s economic and institutional development. Remarkably, economic historians have paid little attention to technological change within the construction sector. As a result, the field has underappreciated the sector’s role in laying the structural foundations for modern economic development.

In this paper, I explore a technology shock that significantly expanded the construction possibility frontier of certain European regions: The re-introduction of brick technology to the regions north of the Alps around 1150. Prior to this technology shock, natural stone was the sole option for constructing large, solid, weather-resistant structures in this area. Regions without access to natural stone typically relied on wood and fieldstone – materials widely regarded as inferior for durable and complex construction.¹ From the mid-12th century onwards, regions lacking natural stone but endowed with the resources necessary for brick production – namely soils containing both clay and sand – could embark on large-scale construction projects by harnessing these resources to create bricks. By 1550, the cityscape of many Northern European cities had become almost entirely red due to the distinctive color of bricks. Notably, the tallest building in the world at the time was also a brick structure: the Marienkirche in Stralsund, which, at 151 meters, held this record for several centuries.²

Bricks surpassed not only wood and fieldstone but also natural stone. They offered advantages such as increased durability, modularization of the construction process through standardized formats, and the ability to be produced by unskilled laborers. Once the necessary infrastructure for brick production was established, construction material could be produced on site at low cost, even for enormous construction volumes. Consequently, brick technology represents a construction method with high economies of scale, whose

¹Wooden structures in the humid climate of Northern Europe are notably short-lived, requiring replacement every few decades. In contrast, fieldstones are weather-resistant but cannot be shaped or carved, limiting their use in the construction of more sophisticated structures.

²This height record was not surpassed until 1880, with the completion of Cologne Cathedral (Zaske, 1964).

virtues are particularly evident in the context of large-scale construction projects. Today, the rising demand for sustainable housing in developing countries has brought renewed focus to bricks, valued for their environmental benefits, affordability, and suitability for fast-growing urban areas, as well as their role as a savings vehicle in regions with underdeveloped financial markets (Banerjee and Duflo, 2011).

Leveraging these advantages, many medieval German cities that adopted brick technology experienced a marked transformation in their built environment. Using newly collected data on brick adoption in medieval German cities, I demonstrate that cities embracing this novel technology experienced a construction boom following adoption, in terms of both extensive and intensive margins. Brick adoption led to a sharp increase in levels of religious and secular construction, initiating a significant transition towards more robust and resilient urban infrastructure. By enhancing medieval cities' capacity to provide essential urban functions, the adoption of brick technology ultimately enabled cities to sustain higher populations.

Brick construction had not been continuously present in northern Europe. The technology dates back to ancient Mesopotamia and reached a first major peak during the Roman imperial era. Although Roman builders brought it to the provinces north of the Alps, the knowledge gradually faded after the Empire's collapse. In Italy, however, the tradition survived. It was only in the second half of the 12th century that brick-building techniques resurfaced north of the Alps. This revival followed Emperor Frederick Barbarossa's Italian campaigns, during which German forces encountered brick construction in northern Italy, prompting their transmission to the German lands (Kluckhohn and Paatz, 1955).

To examine how brick technology affected both religious and secular construction activity, I rely on two complementary data sources. The first is a dataset compiled by Buringh et al. (2020), which provides detailed information on church construction across medieval cities. It captures, for each city and century, the surface area, height, and volume of newly built churches, as well as additional construction resulting from the expansion or reconstruction of existing churches. Church construction offers a particularly rich and quantifiable window into medieval building activity: construction histories are unusually well documented; churches often served as experimental sites for technological and stylistic innovation (Prak, 2011); and many assumed important civic and political functions.³ To capture construction beyond the religious sphere, I complement this with a novel dataset of approximately 4,000 major building events in 168 medieval German cities, including detailed information on the date and material used. This allows me to examine how brick adoption affected the development of essential urban infrastructure – such as town halls, hospitals, market halls, bridges, and mills – structures that were integral to the economic and administrative life of medieval cities.

Using a difference-in-differences (DiD) framework I find strong evidence that cities adopting the novel and superior brick technology in the Middle Ages experienced a significantly

³Examples include Frankfurt's St. Bartholomew, which hosted imperial coronations; Lübeck's Marienkirche, where the city treasury was kept; and Stralsund's Nikolaikirche, which served as the venue for the Treaty of Stralsund (1370) between the Hanseatic League and Denmark.

higher level of construction activity following the adoption. However, there are concerns that these baseline estimates of the effect of city-level brick adoption on construction activity may be biased. For instance, if cities already on a favorable growth trajectory were more likely to adopt the new high-economies-of-scale construction technology, selective adoption could bias the results. To address these concerns, I leverage geographical variation in natural endowments. Certain cities had inherent advantages in stone construction, owing to their proximity to natural stone deposits, while others had access to clay and sand in their local soil, crucial for brick production. Utilizing geological maps, I create city-level indicators of natural stone availability and brick suitability. These indicators provide a basis for leveraging plausibly exogenous variation in city-level brick suitability to instrument brick adoption. In addition, they serve to illustrate how the introduction of brick technology reshaped the geographic center of city development, shifting focus from regions rich in natural stone to those conducive to brick production.

First-stage results indicate that brick suitability strongly predicts actual adoption. Reduced-form estimates show that brick suitability became a statistically significant driver of religious and secular construction, as well as urban population growth, only after the reintroduction of brick technology in the 12th century. Event study evidence supports this pattern: prior to the 12th century, brick-suitable soils had no measurable effect on construction activity, but became a key determinant in the centuries that followed. Second-stage estimates corroborate the earlier OLS findings: cities that adopted brick technology witnessed a 2,000 sqm increase in church construction compared to non-adopting cities. Considering that nearly all cities in the sample had fewer than 10,000 inhabitants by 1500, the observed effect is substantial. The increase in church construction is evident both in aggregate and per-capita terms, highlighting the high economies of scale inherent in brick technology.

Additionally, brick adoption significantly boosted the number of major non-ecclesiastical construction projects within a city. The findings point to a notable increase in the construction of community-oriented structures (e.g., hospitals, almshouses, schools), administrative buildings (e.g., town halls, courts), economic facilities (e.g., market halls, mills), and critical infrastructure (e.g., bridges). Finally, cities adopting brick technology experienced a significant rise in population levels following adoption, indicating that increased productivity in the construction sector fostered growth at the city level. These results are robust toward including a rich set of geographical and institutional controls, addressing spatial autocorrelation through various methods, and focusing solely on within-region variation.

To explore potential mechanisms behind the observed effects, I examine city-level plague outbreaks as a source of exogenous variation in the construction workforce. The plague epidemics of the 14th and 15th centuries led to significant labor shortages. This demographic shock had a differential impact on cities that adopted brick technology: While cities reliant on natural stone, the processing of which required skilled stonemasons, faced a persistent shock to the construction workforce, brick production – requiring no

specialized skills – facilitated a quicker replacement of workers by integrating unskilled rural migrants into the urban construction labor force. The results suggest that cities that adopted brick technology were able to maintain high levels of construction and experience population growth, even when hit by plague-induced demographic shocks.

The paper contributes to three strands of literature. While innovation in the pre-modern construction sector has largely been overlooked in economics, this study engages with a growing body of economic history research that aims to quantify the impact of pre-industrial technologies on economic development. Although these innovations did not result in sustained aggregate economic growth or allow medieval Europe to escape the Malthusian trap (Mokyr, 2005), they nonetheless played a pivotal role in the regional transformation of Europe. For instance, Dittmar (2011) examines how the introduction of the printing press in the mid-1400s accelerated city growth in German cities that adopted the technology. Nunn and Qian (2011) analyze the relationship between the introduction of the potato to Europe and the subsequent rise in urbanization rates and urban population levels. Andersen et al. (2016) argue that the introduction of the heavy plow around 1000 AD explains subsequent urbanization patterns in medieval Denmark. Cantoni and Yuchtman (2014) investigate the role of medieval universities in transmitting knowledge of rediscovered Roman law, fostering economic activity, and facilitating a “commercial revolution” in the late Middle Ages.

Second, the paper complements early (qualitative) studies in the history of the construction sector. It is estimated that around the year 1800, approximately 10% of the manufacturing workforce was employed in construction (Henning, 1985, p. 265). This share was likely significantly higher during the Middle Ages, especially in urban centers, underscoring the importance of the construction sector for the pre-industrial economy. In response to Werner Sombart’s call⁴ to study the economic history of the building sector, several studies have emerged focusing on the construction of Gothic cathedrals, primarily in France and England (Johnson, 1967; Kraus, 1979; Jones, 1987; Lee, 1989). More recently, Stephenson (2019, 2020) and Paker et al. (2023) have examined the labor market in the context of major pre-industrial construction projects through case studies, offering insights into the organization of labor during that period. Several other studies have used data on construction activity to explore shifts in the social and political landscape of medieval and early modern Europe (Belloc et al., 2016; Cantoni et al., 2018; Dittmar and Meisenzahl, 2020; Buringh et al., 2020; Bosshart and Dittmar, 2021; Rusonik, 2025). However, while these contributions provide valuable insights into the role of the construction sector in economic history, they largely overlook technological advancements within the industry itself.

Finally, the paper builds on a growing body of research examining the time-varying influence of geographic fundamentals on historical urban development. Bosker et al. (2013) examine a wide range of geographic factors and their influence on city growth over the course of a millennium, while others focus on specific geographic features that

⁴See, for example, Sombart (1921), II, p. 772-773.

became relevant during particular time periods ([Acemoglu et al., 2005](#); [Nunn and Qian, 2011](#); [Fernihough and O'Rourke, 2021](#)).

The paper is structured as follows: [Section 2](#) discusses the advantages of brick technology, traces its historical diffusion, and presents anecdotal evidence of its transformative impact in selected German regions. [Section 3](#) outlines data and identification strategy. [Section 4](#) presents the main empirical findings alongside several robustness checks. [Section 5](#) explores how brick technology provided advantages in the context of skilled labor shortages. Finally, [Section 6](#) concludes with a discussion of the results and their broader implications.

2 Characteristics and Evolution of Brick Technology

2.1 Advantages of Brick Construction

In multiple respects, brick technology can be considered a revolutionary advancement in the construction sector. Roman architect Vitruvius, in his seminal treatise *De architectura*, noted that bricks offered distinct advantages as a building material, including greater durability and resistance to weathering, as carefully fired bricks are less porous than most natural stones.⁵ Second, brick technology enabled the production of standardized formats. Clay-sand mixtures were pressed into wooden molds, dried, and then fired at high temperatures to ensure consistent quality. This process produced uniform brick units and allowed for specialized decorative elements (so-called molded bricks). Standardization made construction more predictable and efficient by introducing a pre-fabrication element to building work ([Schumann, 2003](#), p. 11). As illustrated in [Figure 1](#), by the mid-15th century brick production was already being carried out in a quasi-industrial manner, with clearly delineated production steps. Third, bricks are incombustible, offering far greater fire resistance than timber or thatch. In pre-modern cities, where devastating fires were common, many councils banned flammable materials like straw thatch and mandated the use of bricks and roof tiles in new buildings as a protective measure ([Binding, 1993](#), p. 96). Lastly, brick technology can be described as a pre-industrial high-economies-of-scale technology. Establishing the required infrastructure, especially firing kilns, was capital-intensive, leading to high fixed costs. However, variable costs were low: brick production relied on unskilled labor, bypassing craft guild regulations, and raw materials were inexpensive. These cost advantages became particularly evident in projects involving large construction volumes.

While many modern construction materials, such as cast stone, reinforced concrete, and glass-steel structures, offer alternatives to bricks, the advantages of bricks are increasingly emphasized – particularly in terms of environmental considerations. Extracting clay and sand for brick production imposes minimal environmental strain. Additionally, bricks provide superior thermal insulation compared to natural stone, enhancing energy efficiency in buildings, and their production generates substantially lower CO₂ emissions

⁵See, for example: [Vitruvius Pollio](#): *De architectura*, Book II, Chapter 3.

Figure 1: Production of bricks (Dutch Bible, ca. 1450, London, British Museum)



This figure illustrates the production of bricks as depicted in a mid-15th-century Dutch Bible. The sequence of activities – from shaping and drying the clay to firing – highlights the standardized and quasi-industrial character of medieval brickmaking.

than concrete (Windsperger and Windsperger, 2015). These features make bricks particularly relevant for rapidly urbanizing developing countries, where the demand for rapid, affordable, and sustainable housing solutions is pressing.

2.2 The Origins

Brick technology is believed to have originated in ancient Mesopotamia, with some of the earliest known examples of fired bricks dating back to around 3500 BC in the region (Hnaihien, 2020, p. 90). The use of bricks as a building material became increasingly widespread throughout the Middle East in the following centuries, facilitated by the development of kiln technology that enabled the mass production of bricks for construction. In Mesopotamia, the word for 'brick,' 'sig,' was synonymous with terms for 'building,' 'city,' and even the god of construction. This association highlights the symbolic and practical significance of bricks in the region's architectural and urban development (Campbell and Pryce, 2016). Over time, the use of bricks spread to other regions of the world, including Europe and Asia.

In Europe, brick technology reached its first major peak during the Roman imperial era, exemplified by structures like the Pantheon, the Colosseum, and the Baths of Caracalla. Through Roman legionnaires, this technology also spread to the Roman provinces north of the Alps. However, since the knowledge of brick production and processing was not passed on to local construction crews, brick technology quickly died out in these regions after the collapse of the Roman Empire (Schumann, 2003, p. 10-11). Nonetheless, brick technology survived in Italy and underwent a period of revitalization in the 11th century, with Lombardy emerging as its prime epicenter. Brickyards provided the rapidly growing cities like Milan, Pavia, and Bergamo with vast quantities of the affordable and durable construction material. By 1100, brick structures formed a significant portion of the urban infrastructure in most North Italian cities (Kluckhohn and Paatz, 1955).

Figure 2: Brick Technology and its Impact on German Cityscape



(a) Near Salzwedel, St. Lorenz (1140s)



(b) Salzwedel, St. Marien (1210s)



(c) Berlin, Palisade Wall (reconstr.)



(d) Lübeck, Holstentor (1460s)



(e) Würzburg, Cathedral (1040s)



(f) Würzburg, St. Marien (1370s)



(g) Köln, Hahnentor (1100s)



(h) Köln, Bayenturm (1220s)

This figure provides suggestive evidence of how the introduction of brick technology transformed the cityscapes of certain German regions (panels a-d), while others remained entirely unaffected (panels e-h).

2.3 Diffusion to Northern Europe

Around the year 1150, knowledge of brick production and use diffused to the regions north of the Alps. The historical literature⁶ has emphasized that the rediscovery of brick technology in Germany can be traced back to Emperor Frederick Barbarossa's Italian campaigns (1154-1183). Aimed at consolidating power, these campaigns established a strong military presence in northern Italy. As a result, thousands of German noblemen were temporarily stationed in cities such as Milan, Bergamo, Pavia, and Crema. During their stay, Frederick's entourage encountered the extensive use and full potential of brick construction in these areas (Stiehl, 1898). This exposure led to the emergence of foundational brick architecture in Germany, exemplified by structures such as the Jerichow Collegiate Church, the Ratzeburg Cathedral Chapter, the predecessor of the Mariendom in Lübeck, and the Verden Cathedral.

The technological shock, however, was only manifested in certain regions of Germany. While northern Germany and the Bavarian Alpine foothills, scarce in natural stone but rich in clay and sand, became brick clusters within just a few decades, central Germany, with its natural stone deposits but lacking clay and sand, remained completely unaffected. Panels a) to h) of Figure 2 provide suggestive evidence on how the introduction of brick technology in the mid-12th century transformed the cityscapes of certain regions of Germany, while having no impact on others. In regions without natural stone but with sufficient clay and sand, simple fieldstone churches (Figure 2a) could now be replaced by monumental brick cathedrals (Figure 2b), and palisade walls, vulnerable to weather and fire (Figure 2c), could be replaced with advanced, more durable fortification systems (Figure 2d). In regions with abundant natural stone deposits, however, there was remarkable persistence in construction techniques and materials. When sandstone was readily available, it remained the dominant material for prestigious building projects (Figure 2e and Figure 2f). Similarly, in cities located near tuff and basalt deposits, these materials had already been used for construction before the 12th century and continued to be used thereafter (Figure 2g and Figure 2h).

3 Data and Identification

3.1 Data on Brick Adoption

To determine which German cities adopted brick technology in the Middle Ages and the timing of its adoption, I compile a novel data set of approximately 4,000 major religious and secular construction events and their respective construction materials across 168 cities in present-day Germany, spanning from 700 to 1500. This dataset is based on the digitization of the 21 volumes of the "Dehio Handbuch der deutschen Kunstdenkmäler" (1990-2012), a key reference work in architectural history. The "Dehio" offers detailed

⁶For a detailed qualitative analysis, see: Kluckhohn and Paatz (1955).

Figure 3: Example of an Entry in the *Dehio Handbuch (Sachsen-Anhalt I)*

Marien-K. Pfarrkirche der Altstadt. 5schiffige Backsteinbasilika am sw Rande der Altstadt, im wesentlichen 2. und 3. Drittel 14. Jh. Der langgestreckte Chor mit 5/8Schluß und 2geschossigem Sakristeianbau im S, das Schiff in Querhausbreite, durch seine Verlängerung der WTurm umgangartig umbaut; im NW Vorhalle und ö daneben Bibliotheksanbau. Außerdem Kapellenanbauten des 15. bis 17. Jh. — Urspr. Feldsteinbau 2.H.12. Jh., seit etwa 1210 Backsteinbasilika. Der zugehörige Amtssitz des Propstes von Salzwedel urk. 1223 zum 1. Mal genannt. Um 1300 erweiternder Umbau begonnen, zunächst als 5schiffige Halle, dann als Basilika in der heutigen Form E.14. Jh. vollendet. Zuerst die beiden s, dann nach Erhöhung der Arkaden die beiden n Seitenschiffe errichtet, zwischen 1340 und 1350 der neue Chor, an den um 1500 die Sakristei angefügt wurde. In der 2.H.14. Jh.

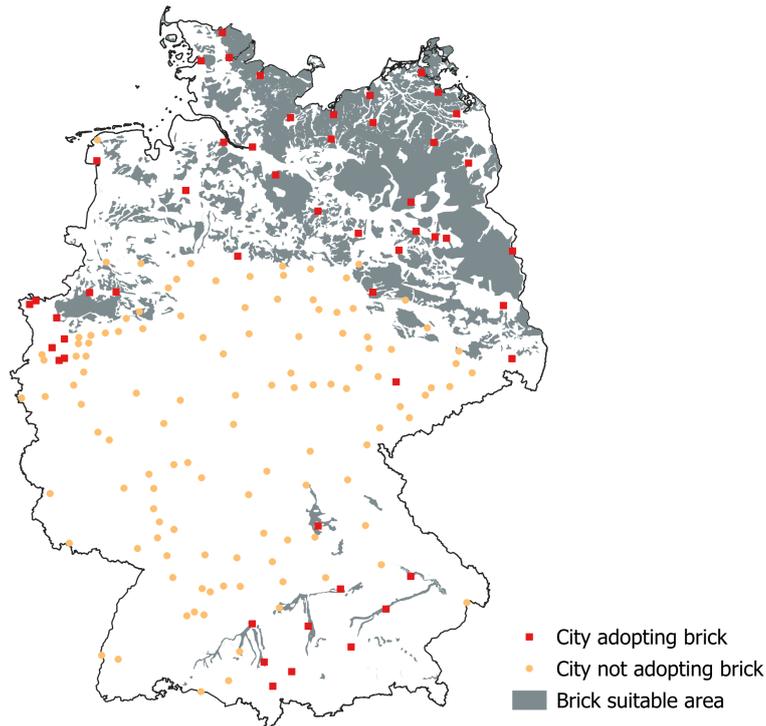
documentation of architectural monuments in Germany, providing information on architectural styles, building techniques, and regional variations, and serves as an essential tool for scholars in the field.

Figure 3 depicts a segment of the entry for the Marienkirche in Salzwedel. The entry indicates that the church was originally constructed as a fieldstone structure in the second half of the 12th century, later undergoing transformation into a brick basilica in 1210. The “Dehio” also lists 11 other significant medieval buildings in the town of Salzwedel, which can be identified as brick structures. However, all of these were constructed after the transformation of the Marienkirche into a brick basilica. Therefore, I infer that Salzwedel was a medieval brick city that adopted brick technology in 1210.

Although the “Dehio” was first published in 1900 and includes buildings that were later destroyed during World War II and the post-war period, it does not account for medieval structures lost in earlier centuries. Given that urban fires were frequent throughout the Middle Ages and the early modern period, and that wars such as the Thirty Years’ War and the War of the Palatinate Succession devastated entire regions, the “Dehio” fails to comprehensively capture all significant medieval urban structures. However, construction projects were well-documented in charters and municipal records. To address this limitation, I supplement the “Dehio” data with information from historical sources on lost buildings. Specifically, I review the medieval history sections of Wikipedia entries for each city and incorporate construction projects that did not survive until 1900 and are thus absent from the “Dehio”. Additionally, I systematically incorporate data from city-specific Wikipedia lists of lost buildings and official registers of architectural monuments to ensure a comprehensive and structured documentation of medieval construction activity.

Figure 4 illustrates the spatial distribution of German cities that adopted brick technology during the Middle Ages. Red squares represent cities that adopted brick technology during the Middle Ages, whereas circles indicate cities that did not adopt brick technology during this period. As illustrated by the map, the focal points of brick architecture are in the North German Plain, east of the River Elbe, along the Lower Rhine, and in the Bavarian Alpine Foreland. Only a few cities are located outside these brick clusters.

Figure 4: Distribution of Cities Adopting Brick Technology in the Middle Ages



This map illustrates the spatial distribution of German cities in my sample. Red squares indicate cities that adopted brick technology during the Middle Ages. The gray shading highlights regions inherently suitable for brick production.

3.2 Instrumenting for Brick Adoption

As brick technology was a pre-industrial innovation characterized by high economies of scale, its adoption is likely endogenous. If cities with more favorable characteristics selectively adopted brick technology, the resulting estimates of its impact would be biased. To address these concerns, I utilize geographic variation in cities' natural endowments. Cities in central and southwestern Germany, characterized by a scarcity of clay and sand deposits but an abundance of natural stone resources, were not well-suited for brick production. In contrast, in the North, Northeast, and Southeast – where natural stone was scarce but clay and sand were plentiful – brick technology provided a viable alternative to inferior materials like wood and fieldstone. This innovation enabled large-scale construction in these regions, substantially lowering costs compared to stone construction (Binding, 1993, p. 272-275).

Utilizing the soil maps "Gruppen der Bodenausgangsgesteine in Deutschland" (Bundesanstalt für Geowissenschaften und Rohstoffe, 2016) as well as "Karte der Bodenarten in Oberböden" (Bundesanstalt für Geowissenschaften und Rohstoffe, 2007), provided by the Federal Institute for Geosciences and Natural Resources, I construct indicators to gauge city-level brick suitability and stone availability. As medieval bricks were produced using clay and sand in an approximate ratio of 3:1 (Wolf, 2003, p. 241), I define brick suitability as the share of land within a 20 km radius of each city where the soil contains

Table 1: Variable Definitions and Summary Statistics

Variable	Description	\bar{x}	s	min	max
Panel A:					
Church construction	Newly built church surface area (in sqm) at the city-century-level. Data source: Buringh et al. (2021)	602.8	1060	0	11531
Secular construction	Number of major non-ecclesiastical construction events at the city-century-level	1.257	2.108	0	19
City population (ihs)	Inverse hyperbolic sine transformation of the estimated city population (in thousands). Data source: Buringh (2021), derived from Bairoch (1988)	1.262	0.941	0	4.499
Panel B:					
Brick Suitability	Share of soil suitable for brick production within a 20 km radius of a given city	0.127	0.216	0	0.841
Stone Availability	Presence of natural stone resources within a 20 km radius of a given city (Federal Institute for Geosciences and Natural Resources 2016)	0.297	0.324	0	0.982
Panel C:					
Ruggedness	Terrain Ruggedness Index (TRI), calculated as the standard deviation of elevation within a 20 km radius of each city	3.668	2.142	0.402	11.67
Log rye yields	Natural logarithm of potential rye yields under rain-fed conditions within a 20 km radius of each city, derived from the FAO's Global Agro-Ecological Zones database	7.422	0.080	7.221	7.549
Elevation	Elevation above sea level (in meters)	170.2	150.5	1	678
Navigable river	Binary variable indicating whether the city is located adjacent to a navigable river	0.387	0.488	0	1
Seaside	Binary variable indicating seaside cities	0.048	0.214	0	1
Roman road	Binary variable indicating whether the city was situated along the network of ancient Roman roads	0.256	0.438	0	1
Free imperial city	Binary variable indicating whether the city held the status of a <i>Reichsstadt</i> (free imperial city) in the Holy Roman Empire	0.208	0.407	0	1
Hanse league	Binary variable indicating whether the city was a member of the Hanseatic League	0.149	0.357	0	1

Notes: This table presents definitions of key variables along with their summary statistics, including mean (\bar{x}), standard deviation (s), and the minimum (min) and maximum (max) values. The table is divided into three panels based on the type of variable. Panel A lists key outcome variables, which vary at the city-century level. The summary statistics provided for these variables are also based on the city-century level. Panel B contains time-invariant city-level natural endowments related to construction potential, including my index for brick suitability, which is used to instrument brick adoption. Panel C presents additional time-invariant geographical and institutional characteristics of cities.

these materials.⁷ Summary statistics for the brick suitability measure, along with variable definitions and descriptive statistics for all key variables, are provided in Table 1. While the choice of a 20 km cutoff radius may appear arbitrary, it is motivated by two main considerations: First, 20 km serves as a reasonable proxy for the rural hinterland of a medieval city. Second, it represents approximately the distance that could be traversed within a day.⁸

The gray-shaded areas in Figure 4 represent regions that are fundamentally suitable for brick production, i.e., areas containing the relevant raw materials. Indeed, most brick

⁷To accurately measure local brick production potential, I require both the upper and lower soil layers to contain clay and sand.

⁸Later, I will show that my results do not rely on this definition and also hold for alternative cutoff radii.

cities are located in or near these brick-suitable areas. The map thereby offers visual support for the first-stage relationship.

To validate that the brick suitability index reflects the potential for brick construction, I analyze (1) how the share of cities adopting brick technology evolved across different suitability groups over the Middle Ages and (2) how the share of buildings constructed with brick developed within these groups over time. Figures 5 and 6 present the respective results. Cities in groups with higher brick suitability not only adopted brick technology earlier and with greater likelihood but also exhibited a higher share of buildings constructed using brick.

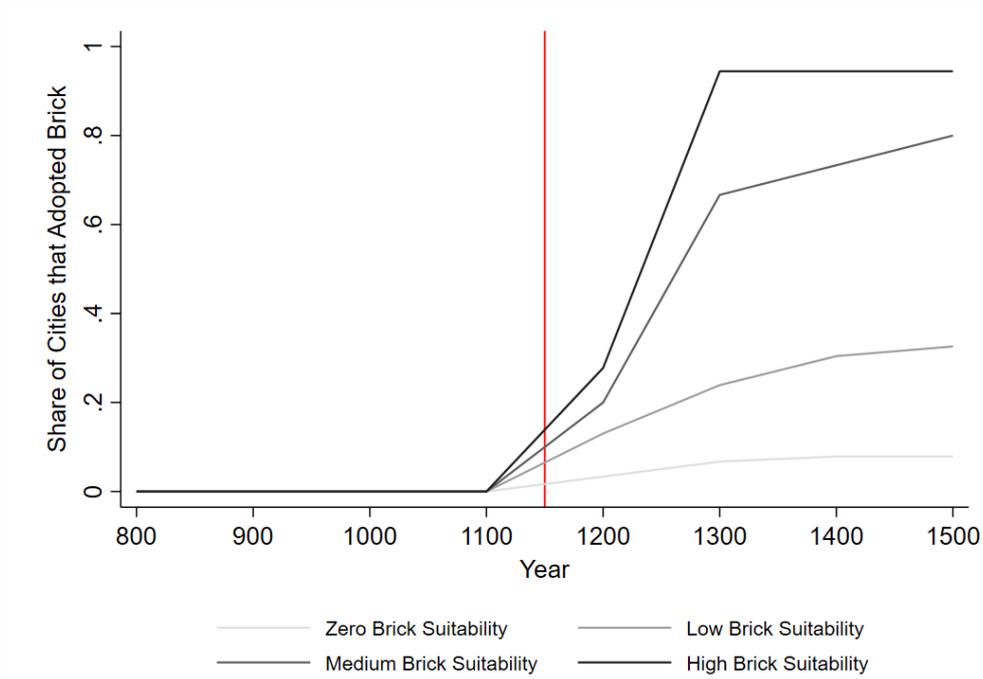
3.3 Additional Relevant City Characteristics

A key concern is that regions suitable for brick production may differ from unsuitable ones in geographic or institutional characteristics. While two-way fixed effects (TWFE) account for time-invariant differences, they do not address potential time-varying effects of these differences on medieval urban development. For instance, areas suitable for brick production might have differentially benefited from medieval agricultural innovations. To address this, I include the (time-interacted) log of potential rye yields under rain-fed conditions within a 20 km radius of each city, sourced from the FAO's Global Agro-Ecological Zones database. Rye cultivation replaced wheat across much of Europe between the 4th and 8th centuries, making it a key indicator of agricultural production potential (Squatriti, 2019). Furthermore, brick-suitable regions may have enjoyed better access to transportation networks, potentially benefiting more from the expansion of long-distance trade in the late Middle Ages. To address this, I incorporate (time-interacted) controls for geographic factors such as coastal proximity, location along navigable rivers, position west of the Elbe River, elevation, terrain ruggedness, and proximity to the Roman road network. Political and institutional characteristics, including free imperial city status and Hanseatic League membership, are also considered. To examine how cities with brick technology coped with labor shortages caused by plague outbreaks – particularly in the construction sector – I use data on city-level plague incidences. The outbreak indicator is based on Büntgen et al. (2012), who digitized and revised the original list compiled by Biraben (1975). Lastly, I measure city-level stone availability as the share of deposits of key building materials – sandstone, tuff, magmatite, and limestone – within a 20 km radius of each city.

3.4 Measuring Urban Development

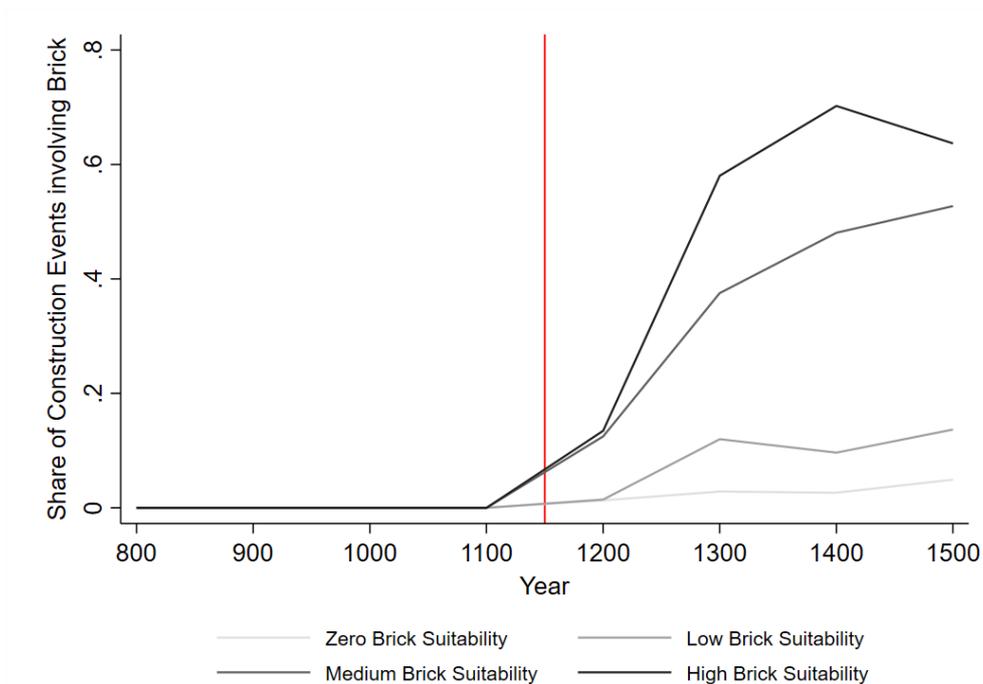
To evaluate the impact of brick technology on urban development, I use three datasets, two of which document construction activity in medieval cities. The primary dataset, compiled by Buringh et al. (2020), serves as the starting point for this analysis, as it provides a uniquely detailed and quantifiable record of medieval construction activity. It systematically traces the construction histories of approximately 1,700 major churches

Figure 5: Share of Cites with Brick Technology by Brick Suitability, 700-1500



This figure shows the evolution of the share of cities with brick technology across four groups categorized by brick suitability: cities with zero suitability, low suitability ($0 < \text{brick suitability} \leq 0.25$), medium suitability ($0.25 < \text{brick suitability} \leq 0.5$), and high suitability ($\text{brick suitability} > 0.5$).

Figure 6: Share of Structures Built Using Brick by Brick Suitability, 700-1500



This figure shows the evolution of the share of significant structures built using brick across four groups categorized by brick suitability: cities with zero suitability, low suitability ($0 < \text{brick suitability} \leq 0.25$), medium suitability ($0.25 < \text{brick suitability} \leq 0.5$), and high suitability ($\text{brick suitability} > 0.5$).

across Western Europe between 700 and 1500 CE, including major churches in 173 German cities.⁹ Crucially, it captures not only the extensive margin of construction – such as the founding of new churches – but also the intensive margin, documenting expansions, reconstructions, and modifications in surface area, height, and volume. An illustration of how construction activity can be quantified using the construction histories of medieval churches is provided in [Figure A.1](#) in the Appendix, using the Marienkirche in Salzwedel as an illustrative example. The aggregate evolution of newly built church surface areas and volumes between 700 and 1500 is presented in [Figure A.2](#) in the appendix.

While church construction does not capture the entirety of urban construction activity, it serves as a reliable proxy for overall construction possibilities at the city level. Given that churches were typically not only the largest in terms of area but also the tallest, most ambitious, and most cost-intensive structures in medieval cities, the effects of a technology-induced expansion of construction possibilities should be most pronounced here. Churches consistently served as testing grounds for new building technologies and architectural trends ([Prak, 2011](#)). Consequently, they were the first structures in which the novel brick technology was utilized north of the Alps, as mentioned above. Additionally, the construction histories of churches are exceptionally well-documented, providing insights into intensive-margin construction possibilities rather than just extensive-margin. Therefore, church construction activity is particularly suitable for a quantitative analysis of the effects of a new construction technology.

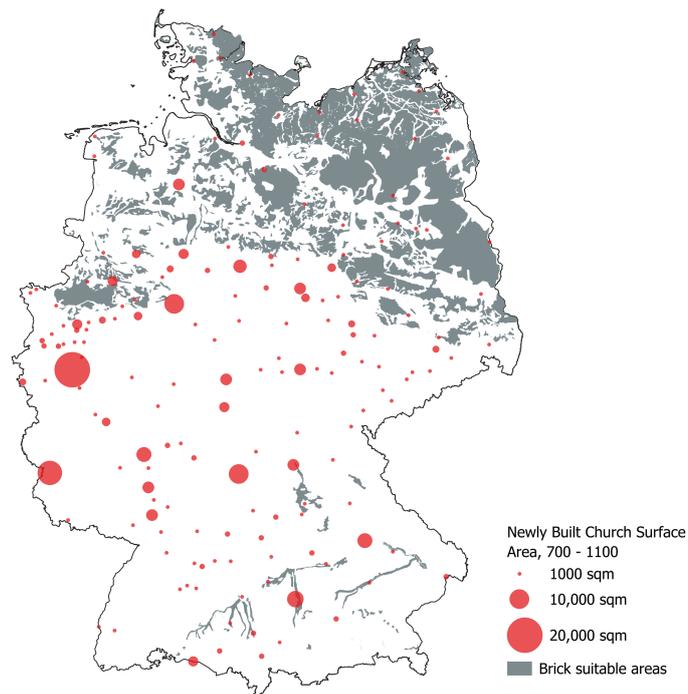
These data provide evidence that the introduction of brick technology reshaped the geographic focus of church construction activity in medieval Germany. Between the 8th and 11th centuries, construction was largely concentrated in regions abundant in natural stone resources. In contrast, areas such as Northern and Northeastern Germany, the Lower Rhine, and the Alpine foothills, which lacked natural stone, saw limited large-scale construction due to the absence of suitable building materials. This pattern changed dramatically in the 12th century, as brick technology enabled these regions to exploit local clay and sand for construction.

[Figure 7a](#) illustrates the geographic concentration of church construction in Germany prior to the adoption of brick technology (8th to 11th century). Cities like Cologne saw substantial construction activity, with the total surface area of newly built and expanded churches reaching nearly 20,000 square meters. This pattern aligns with the availability of natural stone resources, as shown in [Figure A.4](#) in the Appendix, where construction activity was concentrated in regions with easy access to stone. In contrast, areas theoretically suitable for brick production – such as the north and northeast – exhibited far less large-scale construction, reflecting the constraints imposed by the absence of suitable building materials before the introduction of brick technology.

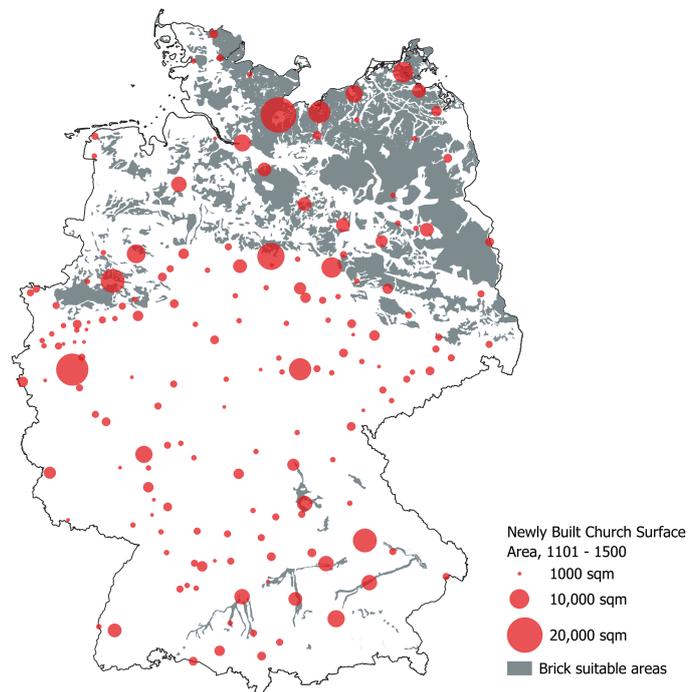
[Figure 7b](#) highlights the transformative impact of brick technology on construction patterns. While cities like Cologne and Erfurt, rich in natural stone resources, maintained

⁹To be included in the sample, cities needed at least one urban church exceeding 1,000 sqm in floor area and a population of at least 5,000 at any point between 800 and 1800 or more than 100,000 in the year 2000.

Figure 7: The Locus of Church Construction Activity in Medieval Germany



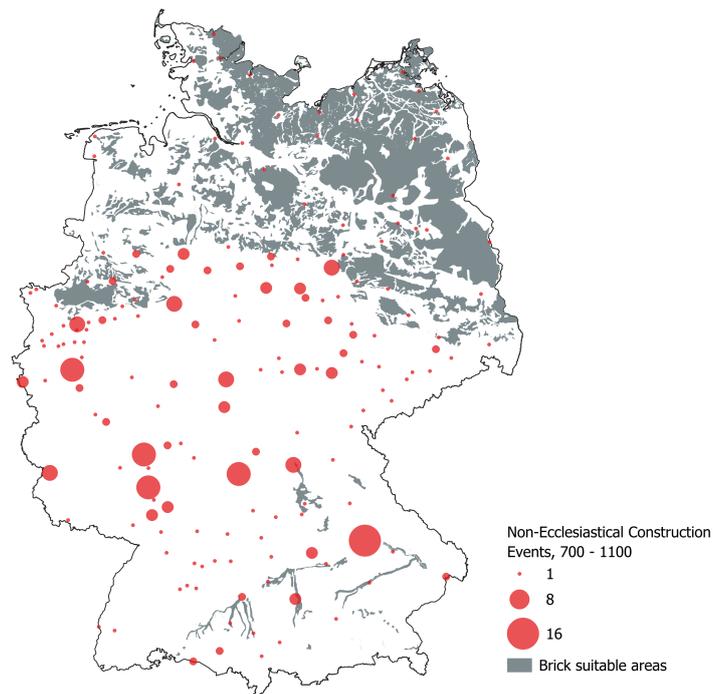
(a) 8th to 11th Century



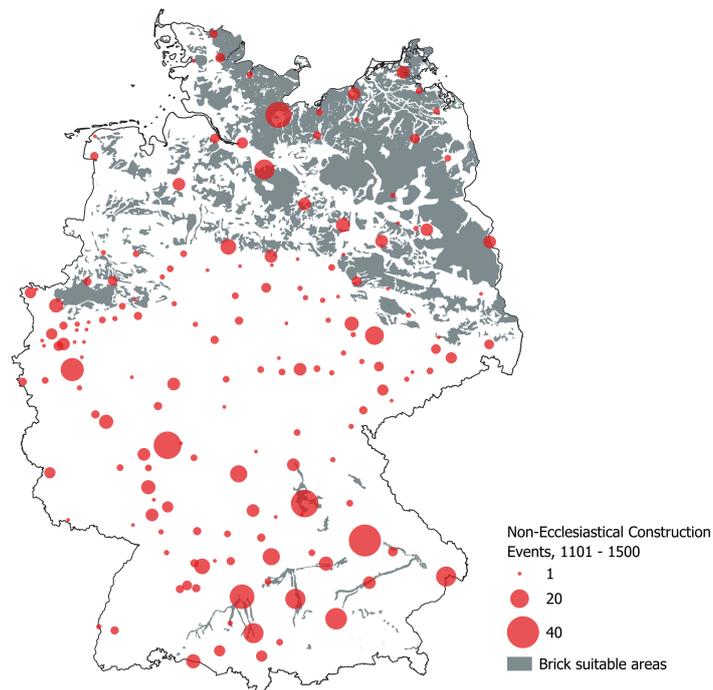
(b) 12th to 15th Century

The two maps illustrate the geographical center of church construction activity in medieval Germany. Panel (a) represents the period before the advent of brick technology (8th to 11th century), while panel (b) represents the period after the advent of brick technology (12th to 15th century). Red circles denote German cities, with the size of the circle representing the level of church construction activity. Gray shaded areas indicate regions suitable for brick production.

Figure 8: The Locus of Non-Ecclesiastical Construction Activity in Medieval Germany



(a) 8th to 11th Century



(b) 12th to 15th Century

The two maps illustrate the geographical center of non-ecclesiastical construction activity in medieval Germany. Panel (a) represents the period before the advent of brick technology (8th to 11th century), while panel (b) represents the period after the advent of brick technology (12th to 15th century). Red circles denote German cities, with the size of the circle representing the non-ecclesiastical construction events. Gray shaded areas indicate regions suitable for brick production.

high construction levels, new clusters of activity emerged in brick-suitable areas, particularly in Northern Germany and the Bavarian Alpine foreland. Lübeck, for example, became the leading city in terms of church construction, with its cityscape still dominated by medieval brick structures. These observations offer preliminary evidence that the advent of brick technology shifted the geographical focus of urban development in Germany, enabling construction in regions that were previously constrained by the lack of suitable building materials.

To provide a broader perspective on city-level construction activity, I compiled a novel dataset encompassing not only major ecclesiastical but also non-ecclesiastical construction events from 700 to 1500. This dataset includes detailed information on the construction materials used, enabling a distinction between brick and non-brick buildings. It covers entirely new structures as well as the rebuilding and extension of existing ones. As outlined in [Section 3.1](#), the data was primarily sourced from [Dehio \(1944\)](#) and further supplemented by a comprehensive review of additional sources documenting preserved and lost medieval structures, aiming for a comprehensive account of medieval construction activity. The dataset encompasses a wide range of construction events, including non-ecclesiastical religious buildings (e.g., monasteries, synagogues, episcopal residences), administrative structures (e.g., town halls, courts), social and welfare institutions (e.g., hospitals, almshouses, schools), as well as economic facilities and critical infrastructure (e.g., market halls, mills, bridges). While it does not capture data on building volumes, focusing instead on the number of major construction events, it provides valuable insights into overall construction activity at the city level. The aggregate trend in the number of major non-ecclesiastical construction events from 700 to 1500 is shown in [Figure A.3](#) in the appendix.

[Figure 8](#) illustrates the focal points of non-ecclesiastical construction activity before ([Figure 8a](#)) and after ([Figure 8b](#)) the introduction of brick technology to the regions north of the Alps, following the same approach as in [Figure 7](#) for church construction activity. A similar pattern emerges: Prior to the construction technology shock, non-ecclesiastical construction activity was concentrated in central and southwestern Germany, with minimal activity observed in brick-suitable areas. However, the advent of brick technology in the 12th century marked a dramatic shift. Brick-suitable regions in northern Germany and the Bavarian Alpine foothills began to experience significant non-ecclesiastical construction activity.

The previous data sets focus on construction activity, capturing the immediate impact of brick technology on urban building dynamics. However, increased construction possibilities likely had broader implications. By enabling more resilient infrastructure, public goods provision, and stronger urban defenses, brick technology may have influenced city growth. To investigate this, I incorporate city population data to assess the broader urban impact of this technological shift. To assess the broader impact of brick technology on urban dynamics, I draw on [Buringh \(2021\)](#) updated dataset of historical urban populations in Europe, which builds on and refines [Bairoch et al. \(1988\)](#) seminal work by integrating

new historical data and revisions.

4 Empirical Results

4.1 The Empirical Relationship of Interest

This paper examines the impact of city-level brick adoption on immediate outcomes, such as construction activity, as well as broader urban outcomes, like city population growth. I estimate the following regression:

$$construction_{it} = \alpha_i + \delta_t + \beta adopted_{it} + \sum_{j=800}^{1500} X_i' I_t^j \theta_j + \varepsilon_{it} \quad (1)$$

In this framework, I analyze how medieval urban development responds to the adoption of brick technology using a panel dataset of cities, where outcomes are observed at 100-year intervals. I regress $outcome_{it}$ – which represents church construction activity, non-ecclesiastical construction activity, or city population – on $adopted_{it}$, a binary indicator that equals 1 in the century when city i adopted brick technology and remains 1 in all subsequent centuries. For example, if Salzwedel adopted brick technology around the year 1210, $adopted_{it}$ equals 0 from the 8th to the 12th century and 1 from the 13th century onward. The regression equation also includes a comprehensive set of time-interacted controls (as described in [Section 3.3](#)), along with time and city fixed effects.

4.2 First-Stage Relationship

Since brick adoption is likely influenced by other factors driving city development, a naive Difference-in-Differences approach comparing outcomes between adopting and non-adopting cities would be biased. For identification, I exploit geographical variation in cities' natural endowments (i.e., the presence of clay and sand resources) and the sudden diffusion of brick technology to regions north of the Alps in the mid-12th century. Brick adoption is instrumented using the interaction of a city-level brick suitability index – capturing the availability of raw materials for brick production in nearby soils – and an indicator for the period following the technology shock. Intuitively, this instrument captures latent brick production potential that is activated in the 12th century. The first-stage regression is specified as follows:

$$adopted_{it} = \alpha_i + \delta_t + \beta (brick\ suitability_i \times Post\ 1150_t) + \sum_{j=800}^{1500} X_i' I_t^j \theta_j + \varepsilon_{it} \quad (2)$$

Here, $adopted_{it}$ is regressed on the interaction of the city-level brick suitability index with a binary indicator for the centuries following the advent of brick technology north of the Alps in the 12th century. As before, the regression includes time-interacted controls, along

Table 2: First Stage and Reduced Form

Dependent Variable:	First Stage			Reduced Form		
	Brick adoption (<i>adopted</i>)			Church construction activity in sqm		
	(1)	(2)	(3)	(4)	(5)	(6)
<i>Brick Suitability</i> × <i>Post 1150</i>	1.1322*** (0.0879) [0.1540]	0.9530*** (0.2011) [0.1108]	1.0301*** (0.2117) [0.1246]	1699.99*** (364.87) [298.41]	1744.23*** (513.12) [371.83]	2056.18*** (556.63) [389.72]
Time-interacted controls		Yes	Yes		Yes	Yes
City FE	Yes	Yes	Yes	Yes	Yes	Yes
Century FE	Yes	Yes		Yes	Yes	
Century × Region FE			Yes			Yes
R^2	0.449	0.580	0.650	0.105	0.236	0.324
F-Statistic	165.7	22.44	23.66			
Number of Cities	168	168	168	168	168	168
Number of Observations	1,344	1,344	1,344	1,344	1,344	1,344

Notes: In first-stage regressions (columns 1-3), the dependent variable is *adopted*. *adopted* equals 1 for cities following brick adoption. *Brick suitability* denotes the share of soil suitable for brick production within a 20 km radius of a given city. The independent variable is interacted with an indicator for the period post-1150. In reduced-form regressions (columns 4-6) the dependent variable measures church construction (in sqm) at the city-century-level. Standard errors in parentheses are clustered at the territory-level. Standard errors in brackets are estimated allowing for arbitrary spatial correlation within 200 kilometers, following the methodology of Colella et al. (2019). Statistical significance at the 90%, 95%, and 99% confidence level denoted “*”, “**”, and “***”.

with time and city fixed effects. To address potential concerns of spatial autocorrelation in the error terms, I compute standard errors clustered at the territory level, based on territorial boundaries around the year 1400.¹⁰ In robustness checks, I implement standard errors that account for arbitrary spatial autocorrelation within a 200-kilometer radius, following the methodology proposed by Colella et al. (2019).

Columns 1-3 of Table 2 present first-stage results. As shown by the coefficient estimate in column 1 (controlling only for time and city fixed effects), brick suitability following the technology shock in the mid-1100s strongly influenced cities to adopt brick technology. The effect is positive, large in magnitude, and statistically significant at the 1% level. Column 2 demonstrates that adding the full set of time-interacted geographical and institutional controls reduces the coefficient to 0.95, yet the effect remains substantial, positive, and highly significant. Column 3 presents first-stage results from my preferred specification, which relies solely on within-region-century variation, confirming a similarly strong and statistically significant effect. The city with the highest brick suitability in my data is Neubrandenburg with a value of 0.84. The coefficient presented in column 3, using my preferred specification that relies solely on within-century-region variation, suggests that Neubrandenburg had a 0.87 percentage point higher probability of adopting brick technology compared to a city with a brick suitability index of 0, such as Heidelberg. The first-stage F-statistics presented in columns 1-3 of Table 1 indicate that my city-level brick suitability index is a strong predictor of actual brick adoption.

¹⁰As territorial boundaries shifted throughout the Middle Ages, I select a specific reference year to ensure consistent clustering of standard errors over time. Since territories consolidated into more stable political units in the late Middle Ages, I use territorial boundaries as of the year 1400.

4.3 Reduced-Form: Raw Data

The reduced-form relationship links cities' natural endowments to construction activity. Before the emergence of brick technology, cities far from natural stone deposits but rich in raw materials for brick production faced constraints in large-scale construction. However, from the 12th century onward, these cities gained access to an alternative building material, dramatically expanding their construction potential. To examine this shift, I categorize the sample of 168 German cities with church construction data into three groups: (1) cities with natural stone resources but lacking raw materials for brick production, (2) cities without natural stone resources but endowed with raw materials for brick production, and (3) cities endowed with both.¹¹

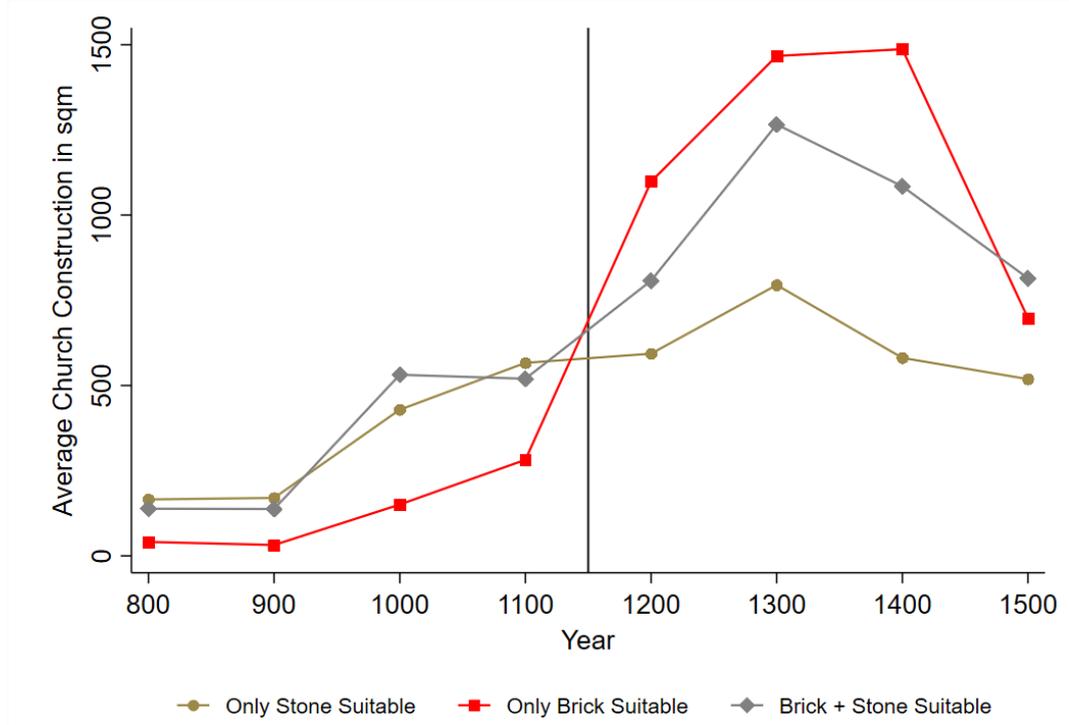
Figure 9 depicts the average newly built church surface area (in square meters), capturing both the construction of entirely new churches and the expansion of existing ones, across the three groups of cities from the 8th to the 15th century. It is important to note that the variable of interest represents a flow rather than a stock, reflecting church construction activity within each century. Between the 8th and 11th centuries, construction activity was substantial in cities with access to natural stone resources (group 1, beige; and group 3, grey), while cities lacking natural stone but situated in areas with brick-suitable soils – though unable to exploit them before the advent of brick technology (group 2, red) – experienced significantly lower levels of construction. The parallel trends in construction activity between cities with natural stone but no brick-suitable soils (group 1) and those with both stone and brick raw materials (group 3) suggest that, in the absence of brick technology, brick-suitable and non-brick-suitable regions with natural stone followed similar development trajectories. However, the introduction of brick technology in the mid-12th century marks a decisive shift. Cities with access only to natural stone resources (group 1, beige) continue to see stable and substantial construction activity but no longer maintain their relative advantage. By contrast, cities with either only raw materials for brick production (group 2, red) or both stone and brick materials (group 3, grey) exhibit a sharp and sustained increase in church construction activity from the 12th century onward. A similar pattern is observed when examining the evolution of major non-ecclesiastical construction events. However, the trends are noisier due to the coarser underlying data (see Figure A.5 in the Appendix).

4.4 Reduced Form: Results

To formally test whether brick suitability unlocked construction potential following the advent of brick technology in the 1150s, I account for potential confounders – such as institutional or geographical factors – that may have independently influenced the development of brick suitable cities. To address these concerns, I estimate the following

¹¹To accurately capture stone and brick construction potential, I classify a city as only stone suitable if it has a stone availability index of at least 0.05. Similarly, a city is classified as only brick suitable if it has a brick suitability index of at least 0.05. For cities classified as brick and stone suitable, both indices must exceed 0.05.

Figure 9: Reduced Form in Raw Data



This graph illustrates the evolution of church construction activity, measured in surface area (in square meters), throughout the Middle Ages. The sample is divided into three groups of cities based on their natural endowments: cities endowed with natural stone resources but lacking the necessary raw materials for brick production (brown), cities without natural stone resources but with the necessary raw materials for brick production (red), and cities with both natural stone resources and the necessary raw materials for brick production (gray).

reduced-form relationship:

$$construction_{it} = \alpha_i + \delta_t + \beta(brick\ suitability_i \times Post\ 1150_t) + \sum_{j=800}^{1500} X_i' I_t^j \theta_j + \varepsilon_{it} \quad (3)$$

The outcome variable $construction_{it}$ represents the surface area of newly built and expanded churches at the city-century level. The independent variables are the same as those with Equation (2). Brick suitability becomes a significant driver of church construction activity following the advent of brick technology in the 12th century. The coefficient presented in column 4 of Table 1, based on a specification that includes only city and century fixed effects, is positive and highly significant. This indicates that cities with natural conditions favorable for brick production experienced a notable increase in church construction activity after the introduction of brick technology in Germany, relative to earlier centuries. The coefficient of 1,700 implies that a city with a brick suitability index of 0.84 (e.g., Neubrandenburg) saw approximately 1,400 additional square meters of church construction compared to a city with a brick suitability index of 0. Adding a comprehensive set of time-interacted geographical and institutional controls in column 5 – accounting for other factors correlated with brick suitability that may have influenced

city development after the 12th century – slightly increases the coefficient, which remains significant at the 1% level. The coefficient on *brick suitability* \times *Post* in column 6, which is based on a specification that relies exclusively on within-region-century variation to control for unobserved regional trends, is slightly above 2,000. This suggests that cities with a brick suitability index of 0.84 saw approximately 1,700 additional square meters of church construction after the advent of brick technology compared to cities with a brick suitability index of 0. This is equivalent to the floor space of a large supermarket.

To ensure that these results are not limited to church construction alone, I run similar reduced-form regressions for additional outcomes related to urban development: non-ecclesiastical construction activity and city population. I use the inverse hyperbolic sine transformation (*asinh*) for both outcome variables to address the presence of extreme outliers and the skewness in the data, while retaining observations with zero non-ecclesiastical construction events or city populations, which is particularly common in the earlier centuries.¹² Table B.1 in the Appendix presents the corresponding results. Indeed, following the 12th century, brick suitability not only positively impacted church construction activity but also significantly increased the (*asinh*-transformed) number of major non-ecclesiastical construction events and (*asinh*-transformed) city populations. Thus, with the advent of brick technology, new potential for urban development was unlocked in locations with brick production potential.

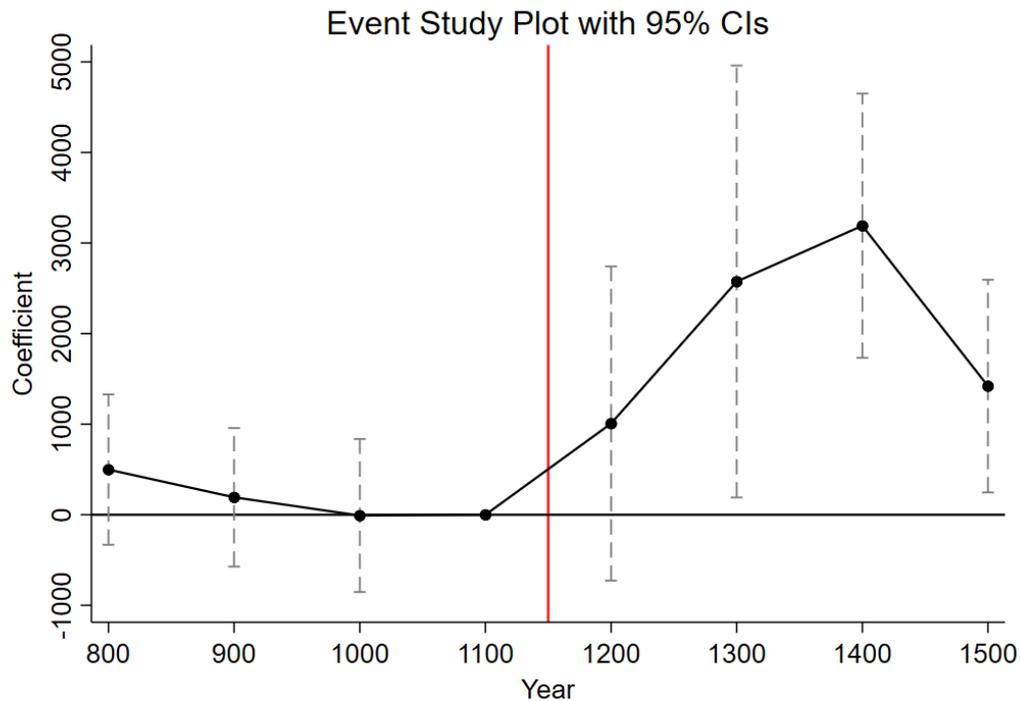
4.5 Reduced Form: Event Study

To further verify that the positive impact of brick suitability in the late Middle Ages is linked to the sudden diffusion of brick technology to regions north of the Alps in the 12th century, I estimate a reduced-form event study following the approach of Acemoglu et al. (2005) and Nunn and Qian (2011). In this specification, the indicator for city-level brick suitability is interacted with century fixed effects, spanning from the 8th to the 15th century. This allows me to examine the period when the impact of natural endowments conducive to brick production on church construction activity first became statistically significant. The specification controls for city and region \times century fixed effects but does not include additional controls. Since the brick suitability index is constant over time and the model accounts for both city and region \times century fixed effects, the β_j coefficients are measured relative to the 11th century as the baseline time period.

The coefficients, including 95% confidence intervals (using standard errors clustered at the territory level), are plotted in Figure 10. The figure compellingly demonstrates a clear discontinuity in the 12th century. In the preceding centuries, there was no relationship between brick suitability and church construction activity. This changed dramatically in the 12th century, with the coefficient on the interaction term turning positive, and in the 13th and 14th centuries, it became statistically significant at the 95% level. Notably,

¹²Dropping observations with a reported city population of less than 1,000 (coded as zero in Buringh (2021)) would result in the loss of 290 observations, or 22% of the sample. Similarly, excluding observations without a major non-ecclesiastical construction event would lead to the loss of 717 observations, or 53% of the sample.

Figure 10: Reduced Form Event Study – Plot of Coefficient Estimates



This graph presents coefficient estimates of a reduced-form specification that interacts the instrumental variable (city-level brick suitability) with an indicator for each century, using the 11th century as the baseline period. The black dots represent point estimates, while the grey dashed lines denote 95% confidence intervals. The vertical red line indicates the advent of brick technology north of the Alps in the mid-12th century.

the coefficient of interest declines after a peak in the 13th century, which may reflect a consolidation of church construction activity in brick regions following a remarkable catch-up process. This consolidation is consistent with the historical literature emphasizing that from the 15th century onward, the development of brick construction increasingly shifted to non-ecclesiastical domains (Schumann, 2003, p. 19). Indeed, examining the reduced-form event study presented in Figure A.6 in the appendix – this time using the (asinh of) number of major non-ecclesiastical construction events as the outcome – reveals that the coefficient on brick suitability steadily increases from the 12th century onward, with a small exception during the 14th century, likely reflecting the disruptions caused by the Black Death.

4.6 Main Results

Since my data allow me to precisely track the century each city adopted brick technology – if ever – I can advance beyond a purely reduced-form analysis to directly estimate the effect of brick adoption on subsequent urban development. To this end, I consider both OLS DiD estimates, leveraging the staggered adoption of brick technology, and a DiD IV approach, using brick suitability after the technology shock as an instrument for adoption.

OLS and IV estimates, with church construction activity in square meters as the outcome, are presented in Panel A of [Table 3](#). The previously hypothesized pattern is confirmed: In both OLS and IV specifications, brick adoption had a positive and statistically significant impact on subsequent city-level church construction activity. It is important to note that brick adoption was staggered, with some cities adopting as early as the 12th century, and others adopting later. Therefore, caution is warranted when interpreting the Two-Way-Fixed Effects (TWFE) OLS results. However, [Table B.2](#) in the Appendix demonstrates that the coefficient estimates remain robust toward employing alternative DiD estimators proposed by [Borusyak et al. \(2024\)](#), [Callaway and Sant'Anna \(2021\)](#), [De Chaisemartin and d'Haultfoeuille \(2020\)](#), and [Sun and Abraham \(2021\)](#). Given the non-staggered nature of the reduced form, these adjustments are irrelevant for the IV specifications.

A comparison of OLS and IV estimates indicates that OLS estimates in this scenario tend to be downward biased. This discrepancy likely arises because IV estimates capture the local average treatment effect (LATE), identifying the impact of brick adoption specifically for cities that adopted the technology due to abundant local raw materials suitable for brick production. These cities were particularly well-positioned to fully exploit the advantages of brick technology, leading to a stronger estimated effect compared to the average treatment effect estimated by OLS. The coefficient estimate for the second-stage specification, encompassing all time-interacted controls as reported in column 5, suggests that brick adoption resulted in a notable increase in church construction activity by approximately 1,800 square meters. To provide context, this is equivalent to the surface area of seven tennis courts. These findings remain robust even when focusing solely on within-region and century variation, addressing concerns about specific regions driving the results. In fact, the parameter estimates reported in column 6 are even slightly higher.

How exactly did the advent of brick technology impact the construction sector? Was its effect purely developmental, enabling cities without natural stone resources to engage in significant construction? Or did brick architecture offer distinct advantages over traditional natural stone-based construction? To investigate this further, I re-estimate the regressions using a subsample of German cities with access to nearby natural stone resources.¹³ Regression results, presented in [Table B.3](#) in the appendix, suggest that brick adoption provided additional advantages even to cities that had previously been capable of large-scale construction using natural stone.

City-level brick adoption not only led to a significant increase in church construction activity but also expanded the potential for non-ecclesiastical construction. Panel B of [Table 2](#) presents regression results using the inverse hyperbolic sine transformation of the number of major non-ecclesiastical construction events as the outcome variable, based on my novel dataset compiled from [Dehio \(1944\)](#) and various additional sources. Even though the inverse hyperbolic sine (IHS) transformation has the advantage of addressing the right skewness of the outcome data without dropping observations with zero values, the

¹³Brick cities with access to natural stone resources are: Bautzen, Coesfeld, Düsseldorf, Emmerich, Hannover, Ingolstadt, Kaufbeuren, Kempten (Allgäu), Landshut, Memmingen, München, Münster, Neuss, Nürnberg, Straubing, Ulm, Viersen, and Wesel.

Table 3: Main OLS and IV Results

	OLS			IV		
	(1)	(2)	(3)	(4)	(5)	(6)
Panel A						
Dependent variable: Church construction activity (in sqm)						
<i>Adopted</i>	763.95*** (172.61) [174.94]	604.37*** (190.77) [199.67]	581.51*** (198.02) [191.16]	1501.48*** (332.93) [335.10]	1830.21*** (558.34) [443.28]	1996.12*** (572.95) [394.85]
Panel B						
Dependent variable: Non-ecclesiastical construction events (asinh)						
<i>Adopted</i>	0.9390*** (0.0911) [0.0869]	1.0428*** (0.0992) [0.1073]	1.0341*** (0.1252) [0.1069]	0.8742*** (0.1407) [0.1372]	1.4932*** (0.2642) [0.2721]	1.5938*** (0.3380) [0.2405]
Panel C						
Dependent variable: City Populations in 1000s (asinh)						
<i>Adopted</i>	0.3636*** (0.1082) [0.0789]	0.2600** (0.1010) [0.0782]	0.2667** (0.1024) [0.1079]	0.7372*** (0.2072) [0.1446]	0.4553 (0.3358) [0.2093]	0.7761*** (0.2996) [0.2082]
Time-interacted controls		Yes	Yes		Yes	Yes
City FE	Yes	Yes	Yes	Yes	Yes	Yes
Century FE	Yes	Yes		Yes	Yes	
Century × Region FE			Yes			Yes
Number of Cities	168	168	168	168	168	168
Number of Observations	1,344	1,344	1,344	1,344	1,344	1,344

Notes: This table presents the main OLS (columns 1-3) and IV (columns 4-6) results for the key outcomes. Panel A reports regression results with church construction (in sqm) at the city-century level as outcome variable. Panel B uses the asinh-transformed number of major non-ecclesiastical construction events as the outcome. Panel C examines the asinh-transformed city population (in 1000s) as the outcome. The independent variable, *adopted*, equals 1 for cities following brick adoption. Standard errors (in parentheses) are clustered at the territory level. Additional standard errors (in brackets) account for arbitrary spatial correlation within 200 kilometers and serial correlation over a 500-year temporal window, following Colella et al. (2019). Statistical significance at the 90%, 95%, and 99% confidence level denoted “*”, “***”, and “****”.

interpretation of the estimated coefficients is not straightforward. I calculate the marginal effects based on Norton (2022), who applies the nonparametric smearing estimate proposed by Duan (1983). The coefficient estimate for my preferred specification, using only within-region and century variation as presented in column 6, is approximately 1.6 and statistically significant at the 1% level. This corresponds to a marginal effect of nearly 3.4, indicating that cities adopting brick technology experienced the asinh of 3.4 additional major non-ecclesiastical construction events. This effect is remarkable in magnitude, as the average city experienced the asinh of only 5.6 major non-ecclesiastical construction events cumulatively between 700 and 1500.

The data also provides an opportunity to examine whether the impact of brick adoption on construction activity varied across different types of buildings. Did brick technology have a particularly strong effect on specific categories of construction, or did it contribute to a more general expansion of urban infrastructure? To investigate this, I divide non-ecclesiastical construction into five distinct categories: social and welfare institu-

Table 4: Non-Ecclesiastical Construction Activity by Building Category

Dependent Variable (asinh)	Social	Administrative	IV Economic	Castle	Other Religious
	(1)	(2)	(3)	(4)	(5)
<i>Adopted</i>	0.5442*** (0.1677) [0.1461]	0.4421*** (0.1539) [0.1963]	0.5207*** (0.1999) [0.2143]	0.1108 (0.1856) [0.1610]	0.7622*** (0.2688) [0.2608]
Time-interacted controls	Yes	Yes	Yes	Yes	Yes
City FE	Yes	Yes	Yes	Yes	Yes
Century FE					
Century × Region FE	Yes	Yes	Yes	Yes	Yes
Number of Cities	168	168	168	168	168
Number of Observations	1,344	1,344	1,344	1,344	1,344

Notes: This table presents Instrumental Variable estimates for non-ecclesiastical construction activity, disaggregated into the following building categories: social buildings (column 1), administrative buildings (column 2), economic and infrastructure buildings (column 3), castles (column 4), and religious, non-ecclesiastical buildings (column 5). The independent variable, *adopted*, equals 1 for cities that adopted brick technology. Standard errors (in parentheses) are clustered at the territory level. Additional standard errors (in brackets) account for arbitrary spatial correlation within a 200-kilometer radius and serial correlation over a 500-year temporal window, following Colella et al. (2019). Statistical significance at the 90%, 95%, and 99% confidence levels is denoted by “*”, “**”, and “***”.

tions (e.g., hospitals, almshouses, schools), administrative structures (e.g., town halls, courts), economic facilities and essential infrastructure (e.g., market halls, mills, bridges), castles, as well as non-ecclesiastical religious buildings (e.g., monasteries, synagogues, episcopal residences). For the number of major non-ecclesiastical construction events by building category, I once again use the inverse hyperbolic sine transformation. Table 4 presents the instrumental variable regression results based on my preferred specification, which includes time-interacted controls, city fixed effects, and region × century fixed effects. The findings suggest that brick adoption led to a comprehensive increase in non-ecclesiastical construction activity, with significant positive effects on the construction of social buildings, administrative structures, economic and infrastructure facilities, and other non-ecclesiastical religious buildings. The construction of castles, however, appears to have been unaffected by brick adoption.

As described above, the expanded construction opportunities enabled by brick adoption facilitated the development of critical urban infrastructure, driving increased construction of both ecclesiastical and non-ecclesiastical structures. This enhanced infrastructure likely contributed to improved urban living standards. Did this transformative development also translate into city growth? Regression results presented in Panel C of Table 2 provide evidence that brick adoption significantly contributed to higher city populations. Using the inverse hyperbolic sine transformation of city populations (in thousands), based on estimates from Buringh (2021), the coefficient in my preferred specification (relying solely on within-region and century variation) is statistically significant at the 1% level and nearly 0.8. This implies that brick adoption was associated with an increase in the asinh-transformed population by 1.6. This effect is remarkable, given that in 1100, the average city in my sample had an estimated population of 2,000, which corresponds to an (asinh) value of approximately 1.2. The results underscore the transformative role of brick

technology, unlocking potential for urban development across vast German regions.

4.7 Robustness

Several factors related to the characteristics of adopting cities or regions suited for brick production could potentially distort the effects observed in [Table 2](#). To rule out the possibility that specific types of cities are driving the findings, this section explores various sample restrictions to test the robustness of the results. One concern is that regions naturally conducive to brick production might also exhibit higher agricultural productivity, which could confound the results. To address this, in addition to controlling for agricultural productivity, I exclude all cities in the sample that fall within the upper quartile of agricultural productivity, as measured by log rye yields under rain-fed agriculture. This ensures that my results are not driven by exceptionally fertile regions where urban expansion might have followed a different trajectory. As rye was the most important cereal crop in medieval Germany, this measure provides a particularly relevant proxy for agricultural productivity in the context of my analysis. As shown in column 1 of [Table B.4](#), the estimates for the two construction-related outcomes remain positive and highly significant. The effect on city population, however, loses significance, likely due to the reduced number of observations in this restricted sample. However, it remains positive. Another potential concern is that the results may be driven by large cities such as Bremen, Lübeck, and Hamburg. To address this, the next step involves excluding all cities that reached a population of 10,000 by the 15th century.¹⁴ The results, shown in column 2 of [Table B.4](#), demonstrate that all three coefficients remain remarkably stable despite this sample restriction.

Empirical results might also be influenced by the German territorial expansion east of the Elbe River. This region, predominantly pagan around the year 1000, underwent a process of Christianization, which led to increased church construction activity. Additionally, these areas lacked natural stone resources but were highly suited for brick technology. To account for this potential confounding factor, the regressions were re-estimated by excluding cities from previously Slavic regions that were colonized by Germanic peoples after the 8th century, as described by [Kuhn \(1973\)](#). The results, shown in column 3 of [Table B.4](#), demonstrate robustness to this exclusion.

Another potential concern is that regions close to the North and Baltic Seas, characterized by high brick suitability indices, may have benefited from an expansion in maritime long-distance trade during the 12th century. This trade could have led to increased construction budgets and growth potential. To address this, the IV models are re-estimated, excluding all cities located on the North and Baltic coasts. The findings, presented in column 4 of [Table B.5](#), show that the coefficient estimates remain practically unchanged and are still highly significant. Notably, all of these cities were major centers of medieval brick

¹⁴The cities excluded are: Stralsund, Lübeck, Hamburg, Frankfurt (Oder), Erfurt, Magdeburg, Braunschweig, Bremen, Goslar, Lüneburg, Aachen, Köln, Frankfurt, Ulm, Speyer, Nürnberg, Augsburg, München, and Regensburg.

architecture, underscoring the robustness of the results.

A final sample restriction involves dropping cities with foundation dates after the 1150s to address concerns that the results are driven by newly urbanized regions. Again, this restriction does not compromise the magnitude and significance of the estimates presented in column 5 of [Table B.4](#).

As a next step, I examine whether the results remain robust to alternative definitions of the brick suitability index, varying the cutoff radii used to measure brick-suitable soils. [Table B.4](#) in the Appendix replicates the estimates presented in column 6 of Panel A in [Table 2](#), instrumenting brick adoption using the share of brick-suitable soils within cutoff radii of 10 km and 40 km. The coefficient estimates remain consistently positive, substantial in magnitude, and highly significant. Notably, as the radius extends to 20 km, the estimated effect increases before stabilizing at larger radii, while standard errors grow. This pattern suggests that different cutoff radii capture different margins of treatment intensity. The smaller radius (10 km) identifies cities that relied on highly localized raw material extraction, while the larger radii (20 km and beyond) include cities that may have sourced clay and sand from more dispersed areas. The fact that the strongest effects appear at the 20 km radius suggests that this distance represents the relevant sourcing range for brick production in the medieval period. Beyond this point, additional brick-suitable areas may be less relevant due to transportation costs or diminishing influence on adoption decisions, which in turn affects the estimated LATEs.

To assess whether the results for non-ecclesiastical construction events are influenced by the data sources used, I perform an additional robustness check. A key concern arises from the reliance on the Dehio Handbook and the supplementary sources I utilize to complement it. As an architectural directory, the Dehio may involve subjective selection criteria for the buildings it includes. This could lead to an overrepresentation of specific architectural styles or building types in certain regions, while others may be systematically underrepresented. For instance, it would be problematic if the Dehio placed disproportionate emphasis on structures from the Brick Gothic period, a highly significant architectural epoch. Such overreporting could bias the estimated effects of brick adoption on subsequent non-ecclesiastical construction activity.

To address this concern, I incorporate data on non-ecclesiastical construction activity from German cities, as recorded in the Deutsches Städtebuch ([Keyser and Stoob, 1974](#), digitized by [Cantoni and Weigand, 2020](#)). These data have been extensively used as a proxy for economic activity in the economic history literature (e.g., [Cantoni et al., 2018](#); [Dittmar and Meisenzahl, 2020](#); [Bosshart and Dittmar, 2021](#); [Cantoni et al., 2024](#)). However, they present certain limitations for my analysis. The Deutsches Städtebuch predominantly relies on documentary sources, frequently treating the first recorded mention of a building as equivalent to its actual construction date. This methodology introduces potential inaccuracies, as it may not reliably capture the precise timing of construction. Column 4 of [Table B.7](#) in the Appendix presents instrumental variable regression results, using the inverse hyperbolic sine-transformed number of construction events from the

Deutsches Städtebuch as the outcome variable. As in previous regressions, the model includes a comprehensive set of geographic and institutional controls, along with city and region-century fixed effects. The results show a positive and statistically significant effect of brick adoption, confirming that the relationship between brick adoption and non-ecclesiastical construction activity is not solely dependent on the Dehio handbook as a data source.

5 Brick Technology and the Labor Market

The plague epidemics of the 14th and 15th centuries, commonly known as the Black Death, were among the most significant and transformative events in medieval Europe. They led to the deaths of approximately one-third of the population and fundamentally reshaped the social, economic, and cultural landscapes. Several recent studies in economic history have explored plague-induced institutional transformations (Wahl, 2019; Dittmar and Meisenzahl, 2020; Bosshart and Dittmar, 2021). With unprecedented mortality rates, particularly in cities, labor became a scarce production factor following the plague, significantly increasing the bargaining power of workers. This shift marked a “golden age of labor” (Postan, 1972; Voigtländer and Voth, 2013). As rural populations flowed into cities, craft guilds controlled access to trades and training, exacerbating the scarcity of skilled workers (Bergoldt, 2000, p. 206-207).

The scarcity of skilled craftsmen dramatically affected the skill- and labor-intensive medieval construction sector. Plague outbreaks at the city level frequently led to the postponement or abandonment of numerous large-scale construction projects and significantly reduced church construction activity (Campbell, 2016, p. 310-313). Ljungqvist et al. (2018) find that plague outbreaks significantly correlated with declines in construction activity across Europe, as evidenced by tree-felling dates. In some regions, particularly England, shortages of skilled craftsmen directly influenced architectural styles. The emergence of the Perpendicular Gothic Style exemplifies this adaptation. This style, characterized by its simplicity and reduced ornamentation, contrasts sharply with its highly ornate predecessors. The shift was practical, driven by the reduced availability of skilled stonemasons due to plague-induced labor shortages (Stewart, 2023).

During the plague centuries, the epicenter of church construction activity shifted to Northern Europe, particularly to regions where brick was the dominant building material. Buringh et al. (2020) attribute the resilience of these areas to institutional factors. However, I argue that this resilience was closely linked to the distinctive labor market characteristics associated with brick technology, which may have offered advantages in adapting to the labor shortages caused by the plague.

Unlike the processing of natural stone, brick production required no skilled stonemasons. Tasks such as clay extraction, brick molding, and firing did not demand specialized expertise and were often carried out by day laborers (Holst, 2014). Moreover, brick production operated outside the confines of guild regulations, fostering an environment of free enter-

prise. Consequently, cities that relied on brick technology were less susceptible to local labor shortages caused by plague outbreaks. The loss of workers could be mitigated by employing unskilled rural migrants, as seasonal workers often dominated brick production (Kessler and Lucassen, 2013). This adaptability provided a significant advantage in maintaining construction activity during periods of demographic upheaval. Panel A of Table 5 provides evidence that cities adopting brick technology were able to sustain high levels of construction activity, even during periods of severe population decline caused by plague outbreaks. Estimates are based on the following regression model:

$$\begin{aligned} construction_{it} = & \alpha_i + \delta_t + \beta_1 adopted_{it} + \beta_2 plague_{it} + \beta_3 (adopted \times plague)_{it} \\ & + \sum_{j=800}^{1500} X_i^j I_t^j \phi_j + \varepsilon_{it} \end{aligned} \quad (4)$$

The church construction data from Buringh et al. (2020) is particularly valuable because it provides detailed insights into the intensive margin of construction activity. Accordingly, the dependent variable I focus on first is the city-century-level newly built church surface area (in square meters). In addition to the explanatory variable *adopted*, the variables *plague* and *adopted × plague* are included. *plague* is a dummy variable indicating whether city *i* experienced a plague outbreak in century *t*. *adopted × plague* is an interaction term between the two aforementioned variables, indicating city-century-level plague outbreaks in cities that had adopted brick technology.

The intensity of plague outbreaks and mortality likely differed across regions, potentially resulting in less severe shocks in areas with cities adopting brick technology. While Izdebski et al. (2022) suggest that northeastern Germany – a region where brick became the dominant building material during the late Middle Ages – experienced lower Black Death mortality, Bosshart and Dittmar (2021) and related studies find no significant differences in mortality or household desertion rates between eastern and western regions of German-speaking Europe. This aligns with broader evidence indicating that the overall magnitude of plague shocks was broadly similar across regions, despite local variations (e.g., Gingerich and Vogler, 2021). To ensure robustness against the possibility of regional variation in plague mortality, all specifications rely solely on within-region-century variation.

Surprisingly, when examining the effect of plague outbreaks independently of brick adoption, the results suggest that plague outbreaks had no significant impact on church construction activity in either the OLS or IV specifications (see Panel A, columns 2 and 5). However, when the interaction term between brick adoption and plague outbreaks is included (Panel A, columns 3 and 6), a different picture emerges: The effect of plague outbreaks becomes negative and statistically significant. Notably, this negative effect is absent in cities that had adopted brick technology prior to a plague outbreak. These cities managed to sustain high levels of construction activity even during plague centuries. Remarkably, the coefficient on the interaction term *adopted × plague* is so substantial that it more than offsets the negative impact of plague outbreaks.

Table 5: Labor Market Implications: Brick Technology and Plague Outbreaks

	OLS		IV	
	(1)	(2)	(3)	(4)
Panel A				
Dependent variable: Church Construction Activity (in sqm)				
<i>Adopted</i>	576.12*** (194.83) [193.38]	418.41** (197.79) [173.30]	2021.69*** (600.94) [409.09]	1569.27** (654.00) [480.31]
<i>Plague</i>	106.30 (186.48) [198.18]	-422.81** (209.79) [135.64]	26.44 (186.74) [205.49]	-593.37** (281.90) [255.09]
<i>Adopted</i> × <i>Plague</i>		1386.28*** (402.48) [354.62]		1662.01** (693.31) [802.63]
Panel B				
Dependent variable: Non-ecclesiastical construction events (asinh)				
<i>Adopted</i>	1.0190*** (0.1207) [0.1057]	0.9821*** (0.1185) [0.1049]	1.5804*** (0.3519) [0.2422]	1.5077*** (0.3724) [0.2439]
<i>Plague</i>	0.2349** (0.1060) [0.1054]	0.1111 (0.1391) [0.1671]	0.2038* (0.1048) [0.1018]	0.1042 (0.1577) [0.1615]
<i>Adopted</i> × <i>Plague</i>		0.3241 (0.2033) [0.1847]		0.2672 (0.3119) [0.1854]
Panel C				
Dependent variable: City Populations in 1000s (asinh)				
<i>Adopted</i>	0.2453** (0.0968) [0.0800]	0.1844** (0.0897) [0.0803]	0.8162*** (0.3180) [0.2046]	0.6848** (0.3093) [0.2195]
<i>Plague</i>	0.1479 (0.1151) [0.1233]	-0.0567 (0.1308) [0.0826]	0.1163 (0.1200) [0.1218]	-0.0637 (0.1461) [0.1008]
<i>Adopted</i> × <i>Plague</i>		0.5360** (0.2066) [0.1775]		0.4827** (0.2412) [0.1991]
Time-interacted controls	Yes	Yes	Yes	Yes
City FE	Yes	Yes	Yes	Yes
Century FE				
Century × Region FE	Yes	Yes	Yes	Yes
Number of Cities	168	168	168	168
Number of Observations	1,344	1,344	1,344	1,344

Notes: This table presents OLS (columns 1-2) and IV (columns 3-4) regression results. In Panel A, the dependent variable is church construction activity in square meters at the city-century level. Panel B uses the inverse hyperbolic sine-transformed number of major non-ecclesiastical construction events at the city-century level as the dependent variable. In Panel C, the outcome variable is the inverse hyperbolic sine-transformed city population, measured in thousands. The explanatory variables include *adopted*, a dummy variable equal to 1 for cities following the adoption of brick technology, and *plague*, a dummy variable indicating the occurrence of city-century-level plague outbreaks. Additionally, the interaction term *adopted* × *plague* identifies city-century-level plague outbreaks in cities that had already adopted brick technology. Standard errors (in parentheses) are clustered at the territory level. Standard errors (in brackets) account for arbitrary spatial correlation within a 200-kilometer radius and serial correlation over a temporal window of 500 years, as proposed by Colella et al. (2019). Statistical significance at the 90%, 95%, and 99% confidence levels is denoted by "*", "**", and "***".

Panel B of [Table 4](#) presents estimates based on equivalent regression models, this time using the inverse hyperbolic sine of the number of major non-ecclesiastical construction events as the dependent variable. While the coefficient on the interaction term *adopted* \times *plague* is positive, it is not statistically significant. Similar effects as those observed for church construction activity are not evident here. This is likely due to the much coarser nature of the underlying data. Unlike the data from [Buringh et al. \(2020\)](#), these records do not capture the intensive margin of non-ecclesiastical construction (e.g., the scale or size of the projects) but merely the number of construction events. Consider the following scenario: Suppose city *i* was struck by a plague outbreak in 1348, just after initiating a major construction project. Due to the outbreak, construction had to be halted and could only resume and be completed in the 15th century. In this case, the construction project would be recorded within the plague century, even though significant progress was not made until the 15th century. The plague-induced construction halt would not be reflected in the data.

Finally, I analyze the differential impacts of plague outbreaks on the population dynamics of brick and non-brick cities. Panel C of [Table 4](#) presents regression results using inverse hyperbolic sine-transformed city populations (in thousands) as the outcome variable. Both OLS and Instrumental Variable estimates, reported in columns 2 and 4, respectively, suggest that cities adopting brick technology not only experienced population growth following its adoption, but also continued to grow during centuries marked by plague outbreaks. This contrasts with non-adopting cities, where population growth stagnated. The performance of brick cities during plague outbreaks can likely be attributed to the resilience of their construction sectors, shaped by the unique labor market characteristics of brick production. In brick cities, unskilled rural migrants could quickly integrate into the brick production process, which facilitated their inclusion in the economic life of medieval cities. In contrast, cities that relied on natural stone faced stricter control by craft guilds, which tightly regulated access to training and trades. This exclusionary system systematically marginalized rural migrants, preventing their participation in key economic activities within the construction sector ([Bergoldt, 2000](#), p. 206).

6 Conclusion

This paper examines a technology shock to the medieval construction sector that reshaped the trajectory of urban development across Europe: the diffusion of brick technology to regions north of the Alps in the 12th century. This innovation substantially enhanced the ability of certain regions to undertake large-scale construction projects. For cities lacking local natural stone resources, brick technology provided an economically viable alternative to the exorbitant costs of importing stone. Moreover, bricks offered distinct advantages over natural stone, such as inexpensive raw materials, the capacity for standardized production that facilitated modular construction, and reduced reliance on a highly specialized labor force, thereby making the construction process more flexible and

accessible. This implied economies of scale in construction for cities that adopted the new technology. To test whether these cities actually realized such benefits, I assemble a novel dataset on city-level ecclesiastical and non-ecclesiastical construction, including detailed information on the construction materials used. The dataset is based on the most comprehensive architectural directory covering the German-speaking region, enabling me to trace when, if ever, a city adopted brick technology during the Middle Ages.

To analyze the impact of brick technology on subsequent urban development, I complement my novel dataset with detailed city-level church construction data from [Buringh et al. \(2020\)](#) and population estimates from [Buringh \(2021\)](#). By examining variations in the availability of construction materials, I provide descriptive evidence that cities lacking access to natural stone resources lagged behind in construction activity prior to the introduction of brick technology in the 12th century. The adoption of brick technology enabled such cities, particularly those with deposits of clay and sand, to harness these materials for construction. From the 12th century onward, these cities experienced a construction boom, reflecting the transformative impact of brick technology.

Since the adoption of brick technology was likely not exogenous, I construct an index of city-level brick suitability. This index reflects the share of soils within a 20-kilometer radius around each city that contain the optimal mix of clay and sand necessary for brick production. Since this index is time-invariant, I interact it with an indicator marking the period following the introduction of brick technology in Germany in the 12th century. The interaction of these two variables is then used to instrument brick adoption.

As indicated by the first-stage regression results, my brick suitability index is a strong predictor of brick adoption in medieval German cities. Second-stage results show that cities adopting brick technology experienced a significant boost to urban development following adoption. Estimates based on my preferred specification, which includes a comprehensive set of geographical and institutional controls and relies exclusively on within-region-century variation, suggest that the adoption of brick technology resulted in an increase in church construction activity by 2,000 square meters. This is equivalent to the surface area of seven tennis courts. Furthermore, as a pre-industrial technology with high economies of scale, brick adoption also significantly boosted per-capita church construction activity.

These effects were not confined to church construction alone. Cities that adopted brick technology also experienced a significant rise in non-ecclesiastical construction. This included a wide range of buildings, such as community-oriented institutions (e.g., hospitals, almshouses, schools), administrative structures (e.g., town halls, courts), economic facilities (e.g., market halls, mills, grain storage), critical infrastructure (e.g., bridges), and religious, non-ecclesiastical buildings (e.g., monasteries, synagogues, episcopal residences). The improved provision of essential urban infrastructure contributed to a broader urban development process, ultimately leading to population growth in cities that adopted brick technology. As indicated by several sample restrictions, the observed results are not driven by regions with particularly high agricultural productivity, large

cities, cities influenced by the German territorial expansion east of the Elbe River, coastal cities, or newly urbanized areas.

Exploring potential mechanisms, I show that cities adopting brick technology exhibited greater resilience to demographic shocks caused by plague outbreaks. Cities that adopted brick technology not only maintained remarkably high levels of church construction activity during plague centuries, but also saw population growth, while other cities stagnated. This resilience stemmed from the adaptability of their construction sectors, driven by the distinct labor market characteristics of brick production. Unlike natural stone processing, which required skilled craftsmen, brick production allowed unskilled rural migrants to integrate quickly into the urban brick-making process. This enabled brick cities to sustain high levels of construction activity while fostering the economic integration of rural migrants into medieval urban life.

The paper advances our understanding of technological change in the construction sector, arguably the only pre-modern economic sector exhibiting industrial characteristics. The findings suggest that the introduction of new construction technologies reduced constraints on construction activity in regions suited for their adoption, facilitating the development of more robust and resilient urban infrastructure and supporting city growth. Specifically, the study demonstrates how the adoption of brick technology enabled cities to avoid the high costs of natural stone imports and benefit from economies of scale through standardized, modular construction processes. By highlighting these mechanisms, the paper offers valuable insights into the broader drivers of economic and social change. These insights remain highly relevant for developing countries today, particularly in addressing the urgent need for rapid housing solutions while promoting sustainable urban development.

References

- Acemoglu, D., S. Johnson, and J. A. Robinson (2005). The rise of europe: Atlantic trade, institutional change, and economic growth. *American Economic Review* 95(3), 546–579.
- Andersen, T. B., P. S. Jensen, and C. V. Skovsgaard (2016). The heavy plow and the agricultural revolution in medieval europe. *Journal of Development Economics* 118(1), 133–149.
- Bairoch, P., J. Batou, and P. Chèvre (1988). *La population des villes européennes, 800–1850: Banque de données et analyse sommaire des résultats*. Librairie Droz.
- Banerjee, A. V. and E. Duflo (2011). *Poor Economics: A Radical Rethinking of the Way to Fight Global Poverty*. New York: PublicAffairs.
- Belloc, M., F. Drago, and R. Galbiati (2016). Earthquakes, religion, and transition to self-government in italian cities. *The Quarterly Journal of Economics* 131(4), 1875–1926.
- Bergoldt, K. (2000). *Der Schwarze Tod in Europa: Die Grosse Pest und das Ende des Mittelalters*. München: C. H. Beck.
- Binding, G. (1993). *Baubetrieb im Mittelalter*. Darmstadt: Wissenschaftliche Buchgesellschaft.
- Biraben, J.-N. (1975). *Les hommes et la peste en France et dans les pays européens et méditerranéens: La peste dans l'histoire*. Paris: Mouton.
- Borusyak, K., X. Jaravel, and J. Spiess (2024). Revisiting event study designs: Robust and efficient estimation. *Review of Economic Studies* 91, 3253–3285.
- Bosker, M., E. Buringh, and J. L. van Zanden (2013). From baghdad to london: Unraveling urban development in europe and the arab world, 800-1800. *Review of Economics and Statistics* 95(4), 1418–1437.
- Bosshart, L. and J. E. Dittmar (2021). Political competition and economic divergence: European development before and after the black death. Discussion Paper 16447, CEPR.
- Bundesanstalt für Geowissenschaften und Rohstoffe (2007). Karte der bodenarten in oberböden 1:1,000,000 (boart1000ob). Polygon Shapefile.
- Bundesanstalt für Geowissenschaften und Rohstoffe (2016). Gruppen der bodenausgangsgesteine in deutschland 1:5,000,000 (bag5000). Polygon Shapefile.
- Büntgen, U., C. Ginzler, J. Esper, W. Tegel, and A. J. McMichael (2012). Digitizing historical plague. *Clinical Infectious Diseases* 55, 1586–1588.
- Buringh, E. (2021). The population of european cities from 700 to 2000. *Research Data Journal for the Humanities and Social Sciences* 6(1), 1–18.

- Buringh, E., B. M. Campbell, A. Rijpma, and J. L. van Zanden (2020). Church building and the economy during europe's 'age of the cathedrals', 700-1500 ce. *Explorations in Economic History* 76, 101316.
- Callaway, B. and P. H. C. Sant'Anna (2021). Difference-in-differences with multiple time periods. *Journal of Econometrics* 225(2), 200–230.
- Campbell, B. M. S. (2016). *The Great Transition: Climate, Disease and Society in the Late-Medieval World*. Cambridge: Cambridge University Press.
- Campbell, J. W. P. and W. Pryce (2016). *Brick: A World History*. London/New York: Thames & Hudson.
- Cantoni, D., J. E. Dittmar, and N. Yuchtman (2018). Religious competition and reallocation: The political economy of secularization in the protestant reformation. *Quarterly Journal of Economics* 133(4), 2037–2096.
- Cantoni, D., C. Mohr, and M. Weigand (2024). The rise of fiscal capacity: Administration and state consolidation in the holy roman empire. *Econometrica* 92(5), 1439–1472.
- Cantoni, D. and M. Weigand (2020). Princes and townspeople: A collection of historical statistics on german territories and cities. 5: Construction activity. Harvard Dataverse, Version 2.
- Cantoni, D. and N. Yuchtman (2014). Medieval universities, legal institutions, and the commercial revolution. *Quarterly Journal of Economics* 129(2), 823–887.
- Colella, F., R. Lalive, S. O. Sakalli, and M. Thoenig (2019). Inference with arbitrary clustering. IZA Discussion Paper No. 12584.
- De Chaisemartin, C. and X. d'Haultfoeuille (2020). Two-way fixed effects estimators with heterogeneous treatment effects. *American Economic Review* 110(9), 2964–96.
- Dehio, G. (1940-1944). *Handbuch der deutschen Kunstdenkmäler*, Volume 5. Berlin: Deutscher Kunstverlag.
- Dittmar, J. E. (2011). Information technology and economic change: The impact of the printing press. *The Quarterly Journal of Economics* 125(3), 1133–1172.
- Dittmar, J. E. and R. R. Meisenzahl (2020). Public goods institutions, human capital, and growth: Evidence from german history. *Review of Economic Studies* 87(2), 959–996.
- Duan, N. (1983). Smearing estimate: A nonparametric retransformation method. *Journal of the American Statistical Association* 78(383), 605–610.
- Fernihough, A. and K. H. O'Rourke (2021). Coal and the european industrial revolution. *The Economic Journal* 131(635), 1135–1149.

- Gingerich, D. W. and J. P. Vogler (2021). Pandemics and political development: The electoral legacy of the black death in germany. *World Politics* 73(2), 1–48.
- Henning, F. W. (1985). *Das vorindustrielle Deutschland 800 bis 1800*. Paderborn: Schöningh.
- Hnaihien, K. H. (2020). The appearance of bricks in ancient mesopotamia. *Athens Journal of History* 6(1), 73–96.
- Holst, J. C. (2014). Kam der backstein mit den klöstern? In *Backsteinbaukunst. Beiträge zur Tagung vom 1. und 2. September 2011, Backsteinfunde der Archäologie, Beiträge zur Tagung vom 6. und 7. September 2012, Klosterformat und Klöster*, pp. 112–123. Bonn: Monumente Publikationen.
- Izdebski, A., P. Guzowski, R. Poniak, L. Masci, J. Palli, C. Vignola, M. Bauch, C. Coccozza, R. Fernandes, F. C. Ljungqvist, T. Newfield, A. Seim, D. Abel-Schaad, F. Alba-Sánchez, L. Björkman, A. Brauer, A. Brown, S. Czerwiński, A. Ejarque, M. Filoc, A. Florenzano, E. D. Fredh, R. Fyfe, N. Jasiunas, P. Kołaczek, K. Kouli, R. Kozáková, M. Kupryjanowicz, P. Lagerås, M. Lamentowicz, M. Lindbladh, J. A. López-Sáez, R. Luelmo-Lautenschlaeger, K. Marcisz, F. Mazier, S. Mensing, A. M. Mercuri, K. Milecka, Y. Miras, A. M. Noryskiewicz, E. Novenko, M. Obremaska, S. Panajiotidis, M. L. Papadopoulou, A. Pędziszewska, S. Pérez-Díaz, G. Piovesan, A. Pluskowski, P. Pokorny, A. Poska, T. Reitalu, M. Rösch, L. Sadori, C. Sá Ferreira, D. Sebag, M. Słowiński, M. Stančikaitė, N. Stivrins, I. Tunno, S. Veski, A. Wacnik, and A. Masi (2022). Palaeoecological data indicates land-use changes across europe linked to spatial heterogeneity in mortality during the black death pandemic. *Nature Ecology & Evolution* 6, 297–306.
- Johnson, H. T. (1967). Cathedral builders of the middle ages. *Economic History Review* 20(1), 40–56.
- Jones, G. P. (1987). Building in stone in medieval western europe. In E. e. a. Miller (Ed.), *The Cambridge Economic History of Europe from the Decline of the Roman Empire: Trade and Industry in the Middle Ages*, pp. 762–787. Cambridge: Cambridge University Press.
- Kessler, G. and J. Lucassen (2013). Labour relations, efficiency and the great divergence: Comparing pre-industrial brickmaking across eurasia, 1500-2000. In M. Prak and J. L. v. Zanden (Eds.), *Technology, Skills and the Pre-Modern Economy in the East and the West*, pp. 157–191. Leiden: Brill.
- Keyser, E. and H. Stoob (Eds.) (1939–1974). *Deutsches Städtebuch. Handbuch städtischer Geschichte, Vol. 1–11*. Stuttgart: Verlag W. Kohlhammer.
- Kluckhohn, E. and W. Paatz (1955). Die bedeutung italiens für die romanische baukunst und bauornamentik in deutschland. *Marburger Jahrbuch für Kunstwissenschaft* 16, 1–120.
- Kraus, H. (1979). *Gold Was the Mortar: The Economics of Cathedral Building*. London: Routledge.

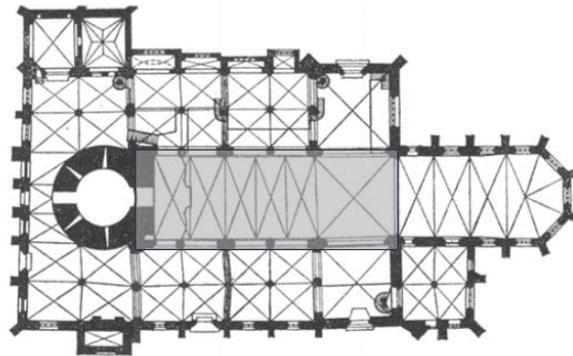
- Kuhn, W. (1973). *Vergleichende Untersuchungen zur Mittelalterlichen Ostsiedlung*. Köln/Wien: Böhlau.
- Le Goff, J. (1988). *Medieval Civilization, 400-1500*. Oxford: Blackwell.
- Lee, Owen, V. (1989). The economic legacy of gothic cathedral building: France and england compared. *Journal of Cultural Economics* 13(1), 89–100.
- Ljungqvist, F. C., W. Tegel, P. J. Krusic, A. Seim, F. M. Gschwind, K. Haneca, F. Herzig, K.-U. Heussner, J. Hofmann, D. Houbrechts, R. Kontic, T. Kyncl, H. H. Leuschner, K. Nicolussi, C. Perrault, K. Pfeifer, M. Schmidhalter, M. Seifert, F. Walder, T. Westphal, and U. Büntgen (2018). Linking european building activity with plague history. *Journal of Archaeological Science* 98, 81–92.
- Mokyr, J. (2005). Long-term economic growth and the history of technology. In P. Aghion et al. (Eds.), *The Handbook of Economic Growth*, Volume 1B. Amsterdam: Elsevier.
- Norton, E. C. (2022). The inverse hyperbolic sine transformation and retransformed marginal effects. *The Stata Journal* 22(3), 702–712.
- Nunn, N. and N. Qian (2011). The potato's contribution to population and urbanization: Evidence from a natural experiment. *The Quarterly Journal of Economics* 126(1), 593–650.
- Paker, M., J. Stephenson, and P. Wallis (2023). Job tenure and unskilled workers before the industrial revolution: St paul's cathedral 1672-1748. *The Journal of Economic History*. forthcoming.
- Postan, M. (1972). *The Medieval Economy and Society: An Economic History of Britain, 1100–1500*. Berkeley/Los Angeles: The University of California Press.
- Prak, M. R. (2011). Mega-structures of the middle ages: the construction of religious buildings in europe and asia, c. 1000-1500. *Journal of Global History* 6(3), 381–406.
- Rusonik, A. (2025). Institutional commitment and economic revival: Evidence from palace-building in renaissance rome. Working Paper, HEC Paris.
- Schumann, D. (2003). Zur technik des backsteinbaus in norddeutschland. eine historische einföhrung. In E. Badstübner and D. Schumann (Eds.), *Backsteintechnologien in Mittelalter und Neuzeit*. Berlin: Lukas Verlag.
- Sombart, W. (1921). *Der moderne Kapitalismus: historisch-systematische Darstellung des gesamteuropäischen Wirtschaftslebens von seinen Anfängen bis zur Gegenwart*, Volume I & II. München/Leipzig: Duncker & Humblot.
- Squatriti, P. (2019). Rye's rise and rome's fall: Agriculture and climate in europe during late antiquity. In A. Izdebski and M. Mulryan (Eds.), *Environment and Society in the Long Late Antiquity*, pp. 342–351. Leiden: Brill.

- Stephenson, J. (2019). 'real' wages? contractors, workers, and pay in london building trades, 1650-1800. *Economic History Review* 71(1), 106–132.
- Stephenson, J. (2020). Working days in a london construction team in the eighteenth century: evidence from st paul's cathedral. *Economic History Review* 73(2), 409–430.
- Stewart, Z. (2023). The plague, the parish, and the perpendicular style: Theories of change in late medieval english architecture from john aubrey to john harvey. In A. I. Sullivan and K. G. Sweeney (Eds.), *Lateness and Modernity in Medieval Architecture*, AVISTA Studies in the History of Medieval Technology, Science, and Art, pp. 131–152. Routledge.
- Stiehl, O. (1898). *Backsteinbauten romanischer Zeit besonders in Oberitalien und Norddeutschland*. Leipzig: Baumgaertner.
- Sun, L. and S. Abraham (2021). Estimating dynamic treatment effects in event studies with heterogeneous treatment effects. *Journal of Econometrics* 225(2), 175–199.
- Vitruvius Pollio, M. (1931). *De architectura*, Volume I. Cambridge, MA: Harvard University Press.
- Voigtländer, N. and H.-J. Voth (2013). The three horsemen of riches: Plague, war, and urbanization in early modern europe. *The Review of Economic Studies* 80(2), 774–811.
- Wahl, F. (2019). Political participation and economic development. evidence from the rise of participative political institutions in the late medieval german lands. *European Review of Economic History* 23(2), 193–213.
- Windsperger, A. and B. Windsperger (2015, Mai). Co2-bilanzierung von bauprodukten: Aktuelle praxis der klimabewertung von holz- und massivbaustoffen – überlegungen zu neuen methodischen ansätzen der bilanzierung. Technical report, Institut für Industrielle Ökologie, St. Pölten. Final Report.
- Wolf, S. (2003). Naturwissenschaftliche untersuchungen zur herstellungstechnik der backsteine von st. urban. In E. Badstübner and D. Schumann (Eds.), *Backsteintechnologien in Mittelalter und Neuzeit*, pp. 239–258. Berlin: Lukas Verlag.
- Zaske, N. (1964). *Die gotischen Kirchen Stralsunds und ihre Kunstwerke: Kirchliche Kunstgeschichte von 1250 bis zur Gegenwart*. Berlin.

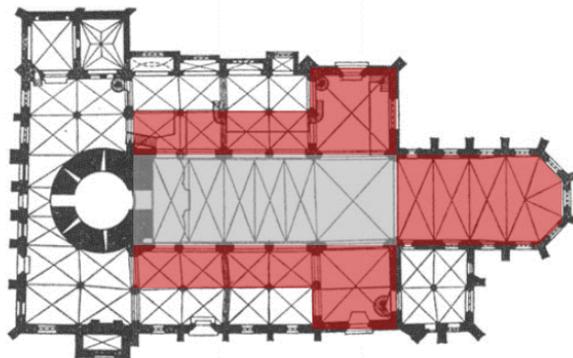
Appendix

A Additional Figures

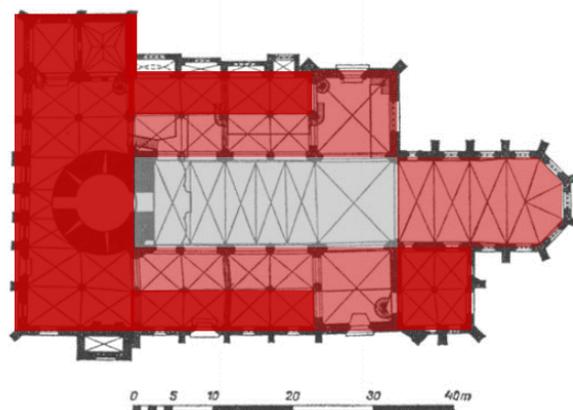
Figure A.1: Quantifying Church Construction Activity



(a) The structural layout around 1150



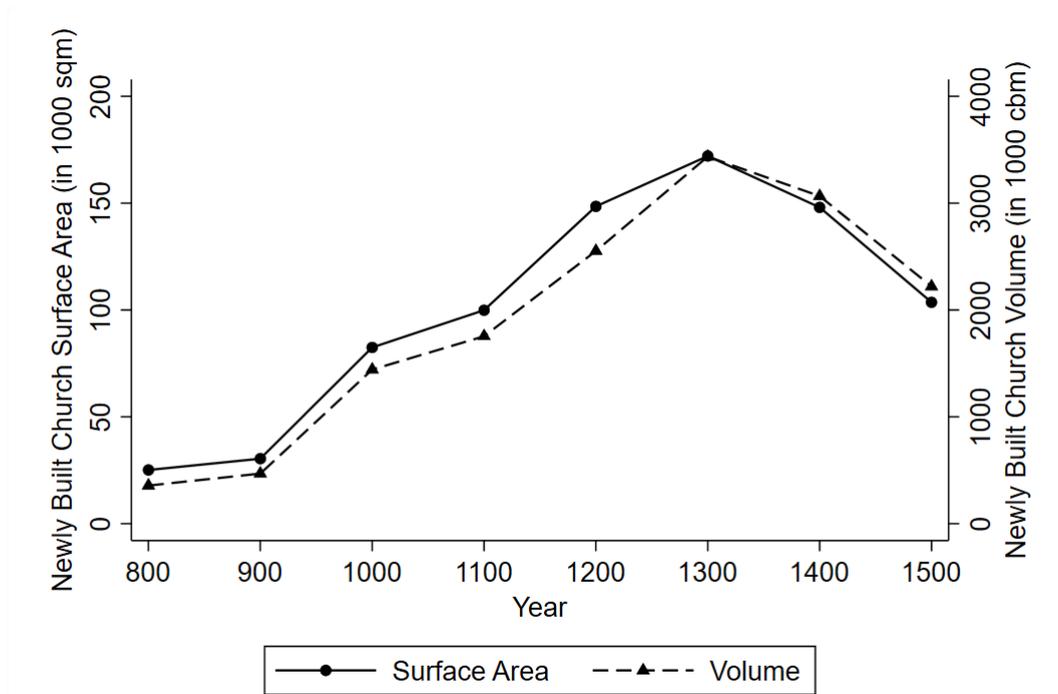
(b) The structural layout after 1210



(c) The structural layout in the 15th century

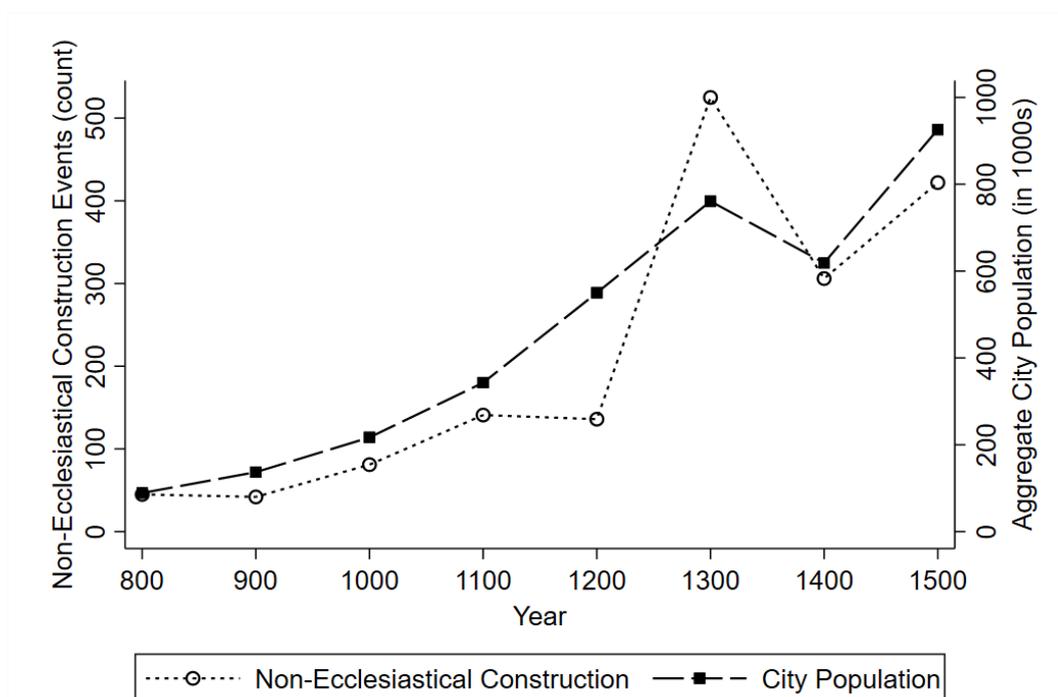
The figure illustrates the approach of [Buringh et al. \(2020\)](#) using the construction history of the Marienkirche in Salzwedel as an example. The gray-shaded area in Panel a) represents the original structure as a fieldstone church from the mid-12th century. Panel b) highlights in light red the expansions made during its transformation into a brick basilica around 1210. The dark red areas in Panel c) depict the further enlarged surface area associated with its conversion into a brick hall church in the 15th century. Floorplans are sourced from [Dehio \(1944\)](#).

Figure A.2: Evolution of Aggregate Church Construction Activity in Medieval Germany



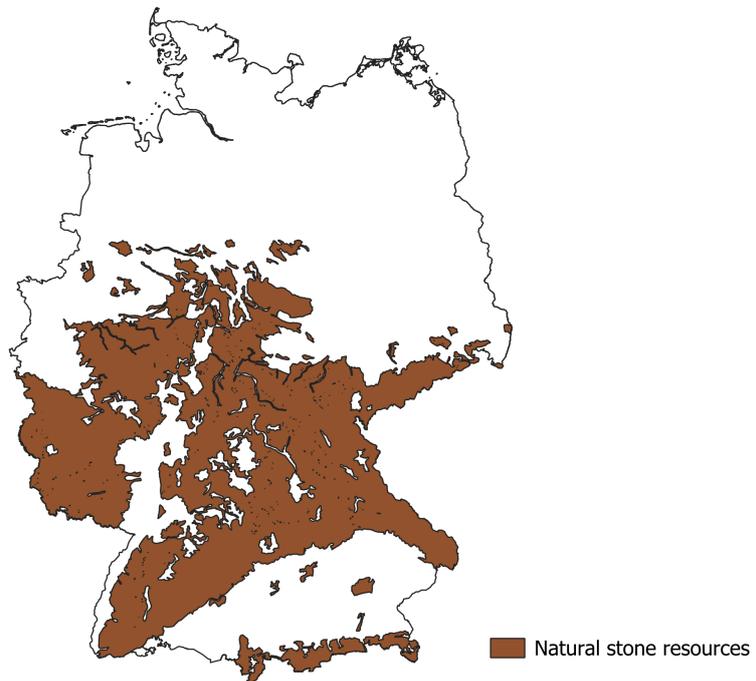
This figure illustrates the temporal evolution of aggregate ecclesiastical construction activity, measured both in surface area (square meters, left axis) and volume (cubic meters, right axis), throughout the Middle Ages (700–1500).

Figure A.3: Evolution of Non-Ecclesiastical Construction and City Populations



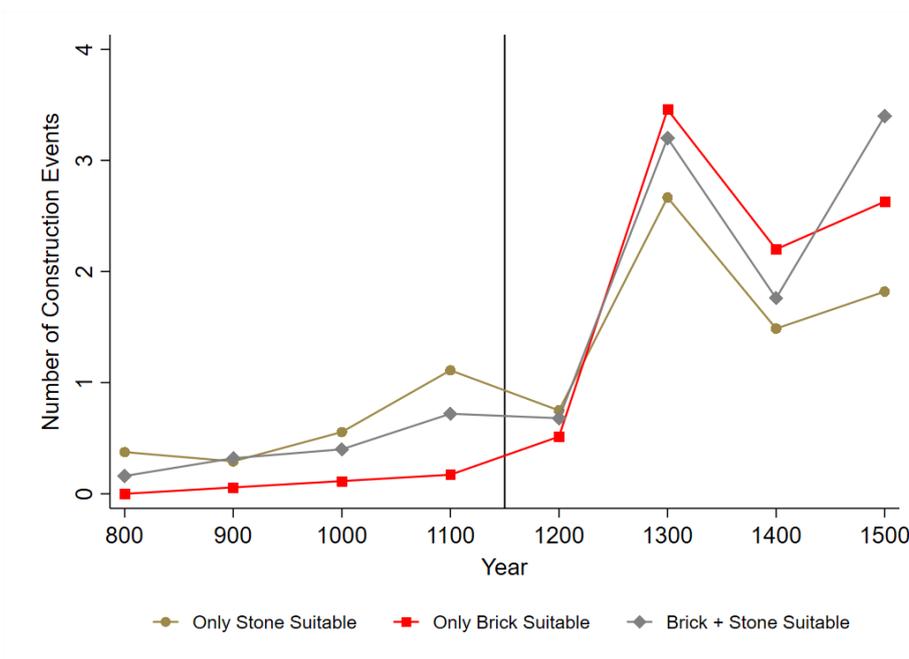
This figure illustrates the temporal evolution of the number of non-ecclesiastical construction events (left axis) and the aggregate city population (right axis) in Germany throughout the Middle Ages (700–1500).

Figure A.4: Distribution of Natural Stone Resources in Germany



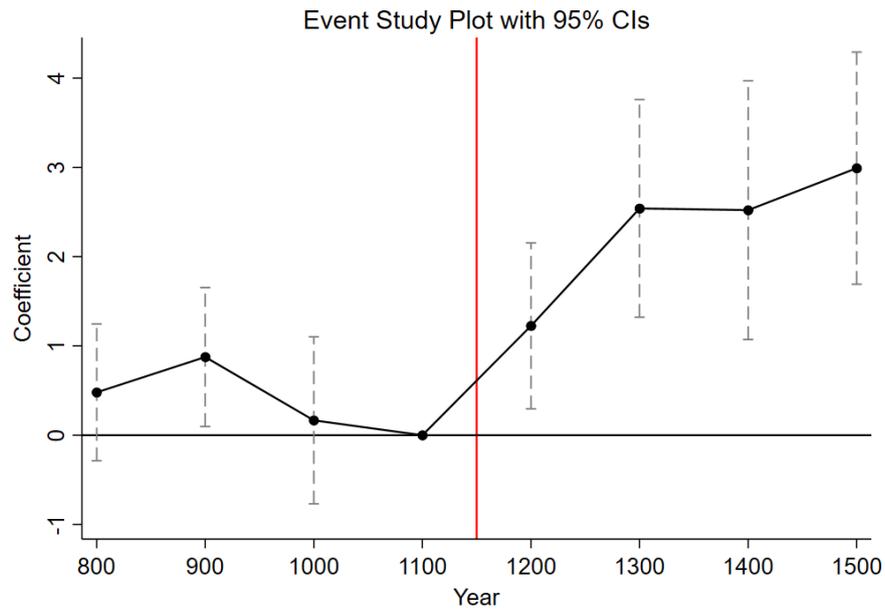
This map illustrates the spatial distribution of natural stone resources in Germany, highlighting deposits of key building materials such as sandstone, limestone, tuff, and magmatite.

Figure A.5: Reduced Form in Raw Data (Non-Ecclesiastical)



This graph illustrates the evolution of the number of significant non-ecclesiastical construction events throughout the Middle Ages. The sample is divided into three groups of cities based on their natural endowments: cities endowed with natural stone resources but lacking the necessary raw materials for brick production, cities without natural stone resources but with the necessary raw materials for brick production, and cities with both natural stone resources and the necessary raw materials for brick production.

Figure A.6: Reduced Form Event Study – Non-Ecclesiastical Construction (asinh)



This graph presents coefficient estimates of a reduced-form specification that interacts the instrumental variable (city-level brick suitability) with an indicator for each century, using the 11th century as the baseline period. The black dots represent point estimates, while the grey dashed lines denote 95% confidence intervals. The vertical red line indicates the advent of brick technology north of the Alps in the mid-12th century.

B Additional Tables

Table B.0: Overview of Brick Cities

Name	Territory (1500)	Brick Suitability	Adoption Year
Zerbst	Anhalt	0.4893	1235
Augsburg	Augsburg	0.1587	1182
Muenchen	Bavaria	0.0046	1190
Straubing	Bavaria	0.0772	1368
Ingolstadt	Bavaria-Ingolstadt	0.0919	1255
Landshut	Bavaria-Landshut	0.1073	1200
Cottbus	Bohemia	0.2178	1201
Bautzen	Bohemia	0.0653	1240
Salzwedel	Brandenburg	0.4719	1196
Nauen	Brandenburg	0.4147	1320
Frankfurt (Oder)	Brandenburg	0.4947	1253
Stendal	Brandenburg	0.3513	1188
Prenzlau	Brandenburg	0.5392	1240
Berlin	Brandenburg	0.8412	1230
Brandenburg	Brandenburg	0.3036	1160
Berlin-Spandau	Brandenburg	0.5309	1210
Bremen	Bremen	0.1835	1185
Neuss	Cologne	0	1200
Hamburg	Hamburg	0.3853	1220
Kiel	Holstein	0.8408	1240
Duesseldorf	Juelich-Berg	0	1288
Kaufbeuren	Kaufbeuren	0	1325
Kempten (Allgaeu)	Kempten	0.0004	1440
Kleve	Kleve	0	1275
Emmerich	Kleve	0	1230
Wesel	Kleve	0.2484	1291
Duisburg	Kleve	0.0444	1200
Neu Ruppin	Lindow	0.6243	1246
Luebeck	Luebeck	0.7623	1173
Lueneburg	Lueneburg	0.5570	1174
Hannover	Lueneburg	0.2167	1256
Neubrandenburg	Mecklenburg	0.8402	1240
Rostock	Mecklenburg	0.6139	1230
Wismar	Mecklenburg	0.7135	1251
Memmingen	Memmingen	0.0930	1340
Krefeld	Moers	0	1170
Muenster	Muenster	0.5297	1300
Coesfeld	Muenster	0.5522	1180
Emden	Muenster	0.0630	1200
Nuernberg	Nuernberg	0.3138	1250
Stralsund	Pommern	0.5486	1250
Greifswald	Pommern	0.5822	1242
Anklam	Pommern	0.4975	1250
Altenburg	Sachsen	0	1165
Husum	Schleswig	0.2950	1494
Flensburg	Schleswig	0.4028	1270
Schleswig	Schleswig	0.5294	1180
Schwerin	Schwerin	0.6490	1171
Stade	Stade	0.2791	1210
Ulm	Ulm	0.1401	1316
Guestrow	Werle	0.7594	1275

Notes: This table gives an overview of all cities in the sample that adopted brick technology between 1150 and 1500. *Brick Suitability* represents the share of soil suitable for brick production within a 20 km radius of a city. *Adoption Year* refers to the earliest known use of brick in urban construction, as recorded in historical sources. *Territory* refers to the city's political affiliation based on the territorial structure of the Holy Roman Empire around 1500.

Table B.1: Reduced Form for Additional Outcome Variables

Dependent Variable:	Non-Ecclesiastical Construction (asinh)			City Population in 1000s (asinh)		
	(1)	(2)	(3)	(4)	(5)	(6)
<i>Brick Suitability</i> × <i>Post 1150</i>	0.9898*** (0.1917) [0.2124]	1.4230*** (0.3140) [0.3455]	1.6418*** (0.3852) [0.3389]	0.8347*** (0.2282) [0.1621]	0.4340 (0.3677) [0.2046]	0.7995** (0.3483) [0.1981]
Time-interacted controls		Yes	Yes		Yes	Yes
City FE	Yes	Yes	Yes	Yes	Yes	Yes
Century FE	Yes	Yes		Yes	Yes	
Century × Region FE			Yes			Yes
Number of Cities	168	168	168	168	168	168
Number of Observations	1,344	1,344	1,344	1,344	1,344	1,344

Notes: This table presents reduced-form estimates for additional city development outcomes. Columns 1-3 use the inverse hyperbolic sine transformation of the number of major non-ecclesiastical construction events in a city-century as the dependent variable. Columns 4-6 analyze city population (in thousands), also transformed using the inverse hyperbolic sine. The independent variable, *Brick suitability*, represents the share of soil suitable for brick production within a 20 km radius of a city and is interacted with an indicator for the post-1150 period. Standard errors (in parentheses) are clustered at the territory level. Additional standard errors (in brackets) account for arbitrary spatial correlation within 200 kilometers and serial correlation over a 500-year temporal window, following Colella et al. (2019). Statistical significance at the 90%, 95%, and 99% confidence level denoted “*”, “**”, and “***”.

Table B.2: Alternative Difference-in-Differences Estimators

	Dependent variable: Church construction activity (in sqm)		
	Point Estimate	Standard Error	95% Confidence Interval
Borusyak-Jaravel-Spiess	748.29***	169.22	[416.63; 1079.95]
Callaway-Sant’Anna	520.44***	199.48	[129.46; 911.41]
DeChaisemartin-D’Haultfeuille	1642.94***	632.84	[402.61; 2883.28]
Sun-Abraham	674.65***	190.09	[302.08; 1047.22]

Notes: This table presents the robustness of my baseline estimate using alternative difference-in-differences estimators proposed by Borusyak et al. (2024), Callaway and Sant’Anna (2021), De Chaisemartin and d’Haultfoeuille (2020), and Sun and Abraham (2021). The outcome variable is city-century-level newly built church surface area (in sqm). The regressions underlying the table do not include controls, but city and century fixed effects. Standard errors are clustered at the territory level. Statistical significance at the 90%, 95%, and 99% confidence level denoted “*”, “**”, and “***”.

Table B.3: Restricting the Sample to Cities with Access to Natural Stone Resources

	Dependent variable: Church construction activity (in sqm)					
	OLS			IV		
	(1)	(2)	(3)	(4)	(5)	(6)
<i>Adopted</i>	634.68** (276.63) [270.42]	539.74* (280.88) [276.80]	636.23** (289.54) [254.03]	1661.54** (710.33) [607.41]	1942.82** (796.28) [706.90]	2049.87*** (794.07) [650.28]
Time-interacted controls		Yes	Yes		Yes	Yes
City fixed effects	Yes	Yes	Yes	Yes	Yes	Yes
Century fixed effects	Yes	Yes		Yes	Yes	
Century × Region FE			Yes			Yes
Number of Cities	120	120	120	120	120	120
Number of Observations	960	960	960	960	960	960

This table presents the main OLS (columns 1-3) and IV (columns 4-6) regression results based on a subsample of cities with access to natural stone resources. The outcome variable is church construction (measured in square meters) at the city-century level. The independent variable, *adopted*, takes the value of 1 for cities following brick adoption. Standard errors (reported in parentheses) are clustered at the territory level. Additional standard errors (in brackets) adjust for arbitrary spatial correlation within a 200-kilometer radius and serial correlation over a 500-year temporal window, as per Colella et al. (2019). Statistical significance at the 90%, 95%, and 99% confidence levels is denoted by *, **, and ***, respectively.

Table B.4: Robustness to Sample Restrictions

Sample Restriction:	w/o High Yields	w/o Large Cities	w/o Late Settled	w/o Coastal	w/o After 1150
	(1)	(2)	(3)	(4)	(5)
Panel A					
Dependent Variable: Church construction activity (in sqm)					
<i>Adopted</i>	1574.36*** (407.60) [367.46]	1704.19*** (486.02) [337.87]	1672.53*** (464.15) [384.52]	2187.54*** (583.95) [381.89]	1625.83*** (436.01) [381.69]
Panel B					
Dependent Variable: Non-ecclesiastical construction events (asinh)					
<i>Adopted</i>	1.4167*** (0.3222) [0.2315]	1.5796*** (0.4424) [0.3231]	1.3025*** (0.3183) [0.1928]	1.6909*** (0.3651) [0.2658]	1.5434*** (0.3084) [0.2272]
Panel C					
Dependent Variable: City populations in 1000s (asinh)					
<i>Adopted</i>	0.4766 (0.3170) [0.2206]	0.6439* (0.3638) [0.2664]	0.6730* (0.3486) [0.2430]	0.8178*** (0.3158) [0.2403]	0.5579** (0.2515) [0.1838]
Time-interacted controls	Yes	Yes	Yes	Yes	Yes
City FE	Yes	Yes	Yes	Yes	Yes
Century FE					
Century × Region FE	Yes	Yes	Yes	Yes	Yes
Number of Cities	126	149	131	160	119
Number of Observations	1,008	1,192	1,048	1,280	952

This table replicates the main IV results for my three primary outcome variables from Table 2, applying several sample restrictions: excluding cities in the top quartile of agricultural productivity (column 1), cities with populations exceeding 10,000 inhabitants in 1500 (column 2), cities affected by the German eastward expansion (column 3), coastal cities (column 4), and cities founded after the introduction of brick technology in Germany (column 5). The independent variable, *adopted*, is set to 1 for cities that adopted brick technology. Standard errors (in parentheses) are clustered at the territory level, while additional standard errors (in brackets) account for arbitrary spatial correlation within a 200-kilometer radius and serial correlation over a 500-year temporal window, following Colella et al. (2019). Statistical significance is indicated by *, **, and *** at the 90%, 95%, and 99% confidence levels, respectively.

Tabe B.5: Instrumental Variable Estimates Using Alternative Cutoff Radii

	Dependent variable: Church construction activity (in sqm)		
	10 kilometers	20 kilometers	40 kilometers
	(1)	(2)	(3)
<i>Adopted</i>	1219.75** (562.71) [393.53]	1996.12*** (572.95) [394.85]	2096.21*** (736.71) [496.08]
Time-interacted controls	Yes	Yes	Yes
City FE	Yes	Yes	Yes
Century FE			
Century \times Region FE	Yes	Yes	Yes
First-Stage F-Statistic	19.69	23.66	13.89
Number of Cities	168	168	168
Number of Observations	1,344	1,344	1,344

Notes: This table presents instrumental variable results based on alternative cutoff radii for the brick suitability index. My main specification uses the share of brick-suitable soils within 20 km of each city as an instrument. Additionally, I present estimates for alternative radii of 10 km and 40 km. The dependent variable is *construction*. *construction* measures church construction (in sqm) at the city-century-level. *adopted* equals 1 for cities following brick adoption. Standard errors in parentheses are clustered at the territory-level. Additional standard errors (in brackets) account for arbitrary spatial correlation within 200 kilometers and serial correlation over a 500-year temporal window, following Colella et al. (2019). Statistical significance at the 90%, 95%, and 99% confidence level denoted **, ***, and ****.

Table B.6: Alternative Outcomes

Dependent Variable:	IV			
	Area (m ²)	Volume (m ³)	Area per capita	Non-ecclesiastical (asinh) Cantoni and Weigand (2020)
	(1)	(2)	(3)	(4)
<i>Adopted</i>	1996.12*** (572.95) [394.85]	38,689.06*** (13,136.43) [8,868.11]	0.5974*** (0.2279) [0.1237]	0.9368** (0.3708) [0.2274]
Time-interacted controls	Yes	Yes	Yes	Yes
City FE	Yes	Yes	Yes	Yes
Century FE				
Century \times Region FE	Yes	Yes	Yes	Yes
Number of Cities	168	168	168	168
Number of Observations	1,344	1,344	1,106	1,344

Notes: This table presents instrumental variable estimates using alternative outcome variables, supplementing the primary analysis of city-century-level newly built church surface area in square meters (column 1). The additional outcomes include city-century-level newly built church volume in cubic meters (column 2), newly built church surface area per capita (column 3), and the inverse hyperbolic sine-transformed number of major non-ecclesiastical construction events recorded in the Deutsches Städtebuch (Keyser and Stooß, 1974, digitized by Cantoni and Weigand, 2020). The variable *adopted* equals 1 for cities following brick adoption. Standard errors in parentheses are clustered at the territory-level. Additional standard errors (in brackets) account for arbitrary spatial correlation within 200 kilometers and serial correlation over a 500-year temporal window, following Colella et al. (2019). Statistical significance at the 90%, 95%, and 99% confidence level denoted **, ***, and ****.