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

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July 7, 2024

**Abstract**

The pre-modern construction sector constituted a significant portion of economic output and was a fertile ground for disruptive innovations. Surprisingly, technological change in this pivotal sector of early industrial development has been largely overlooked in economic history. This paper examines a construction technology shock with profound implications for medieval urban development: The introduction of brick technology to the regions north of the Alps. This high economies of scale technology provided cities endowed with the natural resources for brick production with entirely new construction possibilities. Drawing on a novel dataset on brick adoption in medieval German cities and leveraging exogenous variation in city-level brick suitability, I find that cities adopting brick technology experienced a substantial surge in construction activity, resulting in more robust and resilient urban infrastructure.

*I am grateful to Mathias Bühler, Davide Cantoni, Neil Cummins, Jeremiah Dittmar, Lena Greska, Ingrid Hägele, Sebastian Hager, Wolfgang Kemp, and especially Fabian Waldinger. I gratefully acknowledge financial support from the Egon-Sohmen-Foundation.

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# 1 Introduction

Throughout history, great civilizations have allocated enormous resources to the construction of monumental architecture. From the pyramids of Giza and the temples of ancient Greece, to the amphitheatres of imperial Rome, these construction projects engaged a wide array of architectural, craft, and manufacturing activities. Likewise, the construction of cathedrals, town halls, and castles in medieval European cities represented major public sector investments. The construction sites of these grand structures served as "the centre of the earliest, and almost the only, medieval industry" (Le Goff 1988, p. 56). With a significant proportion of economic output dedicated to large-scale construction projects, these endeavors have been a magnet for upper-tail human capital. Hence, the construction sector historically served as a breeding ground for disruptive innovations. Remarkably, economic historians have paid little attention to technological change within the construction sector.

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 lacking natural stone resources had to rely on wood and fieldstones as building materials, which were inferior in many respects. From the mid-12th century onwards, regions lacking natural stone but endowed with the resources necessary for brick production – such as clay and sand – could embark on large-scale construction projects by harnessing these resources to create bricks. By 1550, the tallest building in the world was a brick structure. With a total height of 151 meters, the Marienkirche in Stralsund, one of the most monumental brick-built structures, held this record for several centuries. Using newly collected data on brick adoption in medieval German cities, I demonstrate that cities embracing the novel technology experienced a construction boom following adoption, initiating a significant transition towards more robust and resilient urban infrastructure.

Brick technology's origins are not rooted in medieval Europe; rather, they trace back to ancient Mesopotamia. During the Roman imperial era, brick technology experienced a first significant peak. Although Roman construction crews initially spread this knowledge to the provinces north of the Alps, it faded into obscurity in that region following the collapse of the Roman Empire. However, brick technology survived in Italy. In a sudden turn of events during the second half of the 12th century, knowledge on brick production and use resurfaced in regions north of the Alps. This resurgence coincided with Emperor Frederick Barbarossa's Italian campaigns, during which his German troops encountered the advanced brick technology in Lombardy.

Soon after, the first brick clusters north of the Alps emerged, and brick became the dominant construction material in certain areas.
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 virtues are particularly evident in the context of large-scale construction projects.
This paper seeks to quantify how the technology-induced expansion of the construction possibility frontier affected urban development in medieval Germany. To examine the empirical relationship between the introduction of brick technology and ensuing patterns of urban development, I assemble a novel city-level dataset documenting brick adoption during the medieval period. The dataset includes information on whether and when a city adopted brick technology during the Middle Ages. Data on medieval brick adoption is primarily sourced from the "Dehio Handbuch der deutschen Kunstdenkmäler", which remains the most comprehensive architectural directory encompassing the German territories. Should the Dehio lack precise dates of brick adoption, I consulted additional reference works.
In order to assess the effect of brick adoption on urban development trends over the course of the Middle Ages, I utilize data compiled by Buringh et al. (2020) on church construction activity in medieval cities as main outcome. This dataset includes information on the area of newly constructed churches at the city level, the evolution of church heights over time, and estimates of the changes in church volumes. Church construction activity serves as a focal point for several reasons. Firstly, the construction histories of churches are extensively documented, making church construction activity particularly quantifiable. Moreover, churches constituted the largest architectural structures in pre-modern Europe and served as testing grounds for new construction technologies and architectural styles (Prak, 2011). Lastly, church construction activity offers a plausible proxy for overall construction possibilities at the city level.
To ensure these effects are not limited to churches, I also use data on significant secular construction events in German cities, as recorded in the Deutsches Städtebuch (Keyser et al., eds, 1939-2003, digitized by Cantoni and Weigand 2020). While these data are much coarser than the church construction data and only capture the extensive margin of construction activity, they offer a glimpse into how overall construction activity evolved.

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 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 certain cities selectively adopted the new high economies of scale construction technology because they were on a different growth trajectory compared to those not adopting, the results could be spurious. 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 variations 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. Thus, they help demonstrate how technology interacts with natural resources to influence developmental patterns over time.

First stage results indicate that brick suitability strongly predicts actual adoption. Reduced-form estimates demonstrate that brick suitability becomes a statistically significant driver of construction activity subsequent to the re-introduction of brick technology in the 12th century, while it held no relevance before the advent of brick technology. Second-stage estimates corroborate the earlier OLS findings: cities that adopted brick technology witnessed a 2,500 sqm increase in church construction compared to non-adopting cities. This is almost equivalent to the surface area of Westminster Abbey. Considering that almost all cities in the sample had fewer than 10,000 inhabitants by the year 1500, the magnitude of this effect is all the more remarkable. Additionally, brick adoption significantly increased the likelihood of a major secular construction event being recorded in a city. These results are robust toward including a rich set of control variables, addressing spatial autocorrelation through various methods, and focusing solely on within-region variation.

Brick technology is characterized by high economies of scale. Consequently, I expect the adoption of brick technology not only to boost aggregate construction activity but also per capita construction. Indeed, my findings indicate that cities experienced higher per capita construction activity following brick adoption. Furthermore, brick technology made cities more resilient to demographic shocks. The plague epidemics of the 14th and 15th centuries made labor a scarce factor. Since brick production did not require specific skills, workers could be quickly replaced. Thus, brick cities were able to maintain high construction levels even during centuries with local plague outbreaks.

The paper contributes to an expanding body of literature in economic history that seeks to quantify the impact of pre-industrial technologies on economic development. While these innovations did not usher in sustained economic growth or enable the medieval European economy to escape the Malthusian trap (Mokyr 2005, p. 1117), they nonetheless played a crucial role in the regional transformation of Europe. For example, Dittmar (2011) examines how the introduction of the printing press in the mid-1400s, a groundbreaking event in the history of pre-industrial information technology, accelerated city growth in German cities adopting the new technology. Nunn and Qian (2011) examine the relationship between the introduction of the potato to Europe and the subsequent increase 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 medieval universities played in transmitting knowledge of newly rediscovered Roman law and thereby fostering economic activity, ultimately allowing for a "commercial revolution" in the late Middle Ages.

The paper not only contributes to existing research on the consequences of medieval technological advancements, but also complements early studies in the economic history of the construction sector. It is estimated that around the year 1800 circa 10% of the manufacturing workforce was employed in the construction sector (Henning 1985, p. 265). This share must have been significantly higher during the pre-industrial era, highlighting the importance of the construction sector for the pre-industrial economy. In response to Werner Sombart's call[1] to study the economic history of the building sector, several studies emerged focusing on the construction of Gothic cathedrals, primarily in France and England (Johnson 1967, Jones 1987, Lee Owen 1989). More recently, Buringh et al. (2020) have used church construction activity as a means of gauging regional economic development in medieval Europe, thereby addressing the issue of limited data on the medieval economy. Several other research contributions rely on data on construction activity to document changes in the social and political landscape of medieval and early modern Europe. For instance, Cantoni et al. (2018) illustrate a transformation in construction activity from religious to secular purposes in Protestant regions following the Protestant Reformation. This shift highlights the extensive reallocation of resources that accompanied the process of secularization. Dittmar and Meisenzahl (2020) find that during the 16th century, German cities that embraced Protestant church ordinances experienced a significant rise in construction activity related to buildings for education, administration, and

[1] See, for example, Sombart (1921), II, p. 772-773.

social welfare. Such a trend suggests a new culture of public goods provision in response to institutional change.

The paper is organized as follows: Section 2 provides a brief overview of the history of brick technology. Section 3 introduces the data utilized in the empirical analysis, and describes the spatial distribution of German cities adopting brick technology. Section 4 presents descriptive evidence of the impact of brick technology on city-level construction activity. Section 5 presents the primary empirical findings on the relationship between brick adoption and subsequent construction activity. Finally, Section 6 provides concluding remarks.

# 2 Historical Background

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 (Hnaihen 2020, p. 90). The use of bricks as a building material became increasingly widespread throughout the Middle East in the following centuries, with the development of kiln technology enabling the mass production of bricks for construction purposes. The use of bricks in construction subsequently 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. Roman architect Vitruvius, in his seminal treatise "De architectura", observed that bricks offered distinct advantages as building material, including the ability to be produced according to standardized formats, increased durability and resistance to weathering, as well as cost-effectiveness in regions lacking abundant natural stone resources.[2] 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 emerged and 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.

Around the year 1150, knowledge of brick production and use diffused to the regions north of the Alps. The historical literature[3] has emphasized that the rediscovery of

[2]See, for example: Pollio, Marcus Vitruvius: "De architectura", Book II, Chapter 3.

[3]For a detailed qualitative analysis, see: Kluckhohn and Paatz (1955).

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 ecountered 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 scale of these founding structures, some towering over 100 meters high and with nave lengths reaching up to 130 meters, surpassed anything previously seen in the region.

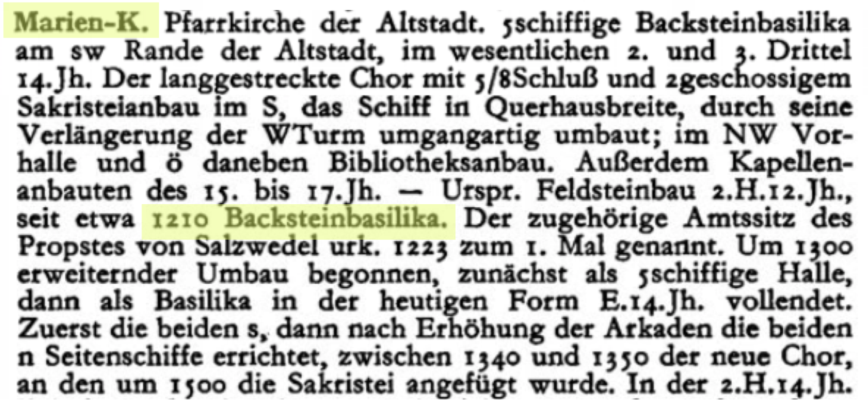
In its early stages, the novel technology was primarily used for the construction of clerical buildings. Indeed, nearly all of the foundational structures of brick architecture were either churches or monasteries. However, from the 13th century onwards, secular brick buildings such as city fortifications and town halls were also constructed on a large scale (Schumann 2003, p. 14-15). The resilience of brick made it especially favored in the construction of defensive structures, as evidenced by the imposing Teutonic castles in the Baltic region, such as Malbork Castle, which remains the largest castle in the world measured by land area. With the urban elite increasingly embracing this technology during the late Gothic period, brick also became the predominant material for the construction of private homes and commercial establishments in brick-suitable regions (Naumann 1993, p. 23). By the end of the Middle Ages, several distinct brick regions had emerged in Germany: one in the North German Plain, another east of the Elbe River, one along the Lower Rhine, and one in the Bavarian Alpine Foreland. Therefore, the introduction of brick technology is often regarded as the transformative force that reshaped the architectural landscape of these regions unlike any other pre-modern innovation (Warnke 1984, p. 28).

# 3 Data

## 3.1 Data on Brick Adoption

At the core of this analysis lies a newly assembled dataset on brick adoption in medieval German cities. The dataset includes records for each city indicating whether it adopted brick technology during the Middle Ages (i.e., until the year 1500). Additionally, it provides the year of brick adoption, rounded to 10-year intervals. The

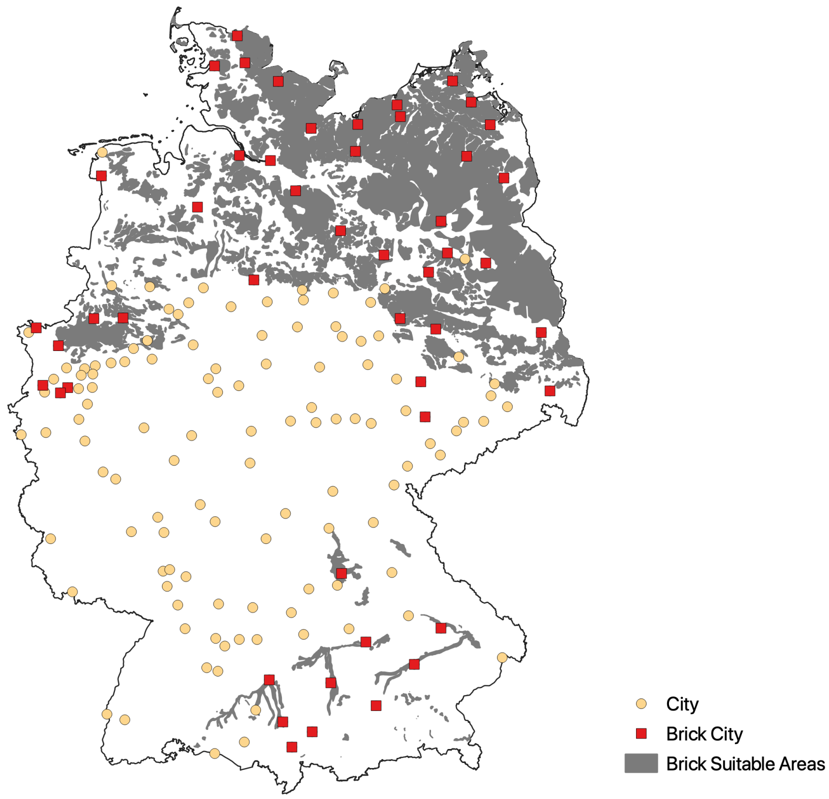
Figure 1: Example of an Entry in the *Dehio Handbuch (Sachsen-Anhalt I)*



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.

21 volumes of the “Dehio Handbuch der deutschen Kunstdenkmäler” (1990-2012) served as the basis for data collection. The “Dehio” has remained a staple reference in the field of architectural history due to its comprehensive coverage of German art monuments, spanning from the Middle Ages to the 20th century. Documenting approximately 100,000 architectural monuments, it meticulously captures architectural styles, techniques, and regional variations, providing researchers with invaluable insights into the evolution of German architecture and rendering it an indispensable tool for scholars in the discipline. Figure 1 depicts a segment of the entry for the Marienkirche in Salzwedel. The entry clearly 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 brick buildings in the town of Salzwedel. 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. However, the construction period of a building is not always precisely indicated in the “Dehio” entry. In such cases, additional reference works were consulted, including Stiehl (1898), Untermann (1984), Böker (1988) and Schumann (2003). If the year of adoption of brick technology could still not be determined accurately, the latest possible point in time based on the reported period in the literature was assigned. Figure 2 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. Notably, among the adopting cities, the “first movers” include Lübeck, Schwerin, Schleswig, Verden, and Brandenburg (Havel), which adopted brick technology shortly after its inception. In contrast, other cities adopted brick technology only in the late Middle Ages, such as

Figure 2: 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.

Kempten (Allgäu), Dorfen, and Zinna. 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. Table 1 provides summary statistics on key variables for the empirical analysis, revealing that around 30% of the German cities in the sample embraced the novel brick technology during the Middle Ages.

## 3.2 Data on Construction Activity

To evaluate the impact of the introduction of brick technology on urban development, I utilize two datasets documenting construction activity in medieval cities. The primary dataset, compiled by Buringh et al. (2020), documents the construction

Table 1: Summary Statistics

| Variable | Mean | Std. Dev. | Min | Max |
|---|---|---|---|---|
| Construction | 4854.54 | 4972.53 | 506 | 38,229 |
| Brick | 0.301 | 0.459 | 0 | 1 |
| Adoption year (if Brick=1) | 1259 | 68.94 | 1165 | 1434 |
| Brick suitability | 0.127 | 0.229 | 0 | 0.840 |
| Stone availability | 0.332 | 0.322 | 0 | 0.983 |
| Share loess soils | 0.225 | 0.244 | 0 | 0.946 |
| Log potential rye yields | 7.419 | 0.080 | 7.221 | 7.549 |
| Free imperial city | 0.202 | 0.403 | 0 | 1 |
| Navigable river | 0.374 | 0.485 | 0 | 1 |
| Hansa league | 0.147 | 0.355 | 0 | 1 |
| Roman road access | 0.257 | 0.438 | 0 | 1 |

history of approximately 1,700 churches in Western Europe from 700 to 1500 CE, including major churches in 163 German cities. The dataset offers insights into the extent of church construction or expansion in each city for every century between 700 and 1500. Additionally, it tracks the evolution of church heights and volumes in each city over the course of the Middle Ages.

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. 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.

To capture a broader picture of city-level construction activity, I also use data on significant secular construction events recorded in the Deutsches Städtebuch (Keyser et al., eds, 1939-2003, digitized by Cantoni and Weigand 2020). These events include the construction of administrative buildings (e.g., town halls), military structures (e.g., city fortifications), and social buildings (e.g., hospitals), among others. Although this dataset does not capture construction potential at the intensive margin, it provides a general impression of construction activity at the city level.

## 3.3 Data on Brick Suitability

To address concerns regarding the endogeneity of brick adoption, I utilize geographic disparities in cities' natural endowments. As detailed earlier, the spread of medieval brick architecture was regionally confined, with a weak presence in central and southwestern Germany. This is unsurprising given the region's scarcity of clay and sand deposits but abundance of natural stone resources. In the North, Northeast, and Southeast, regions devoid of natural stone resources but abundant in clay and sand, brick technology offered an alternative to inferior construction materials like wood and fieldstone. This innovation rendered large-scale construction feasible in these areas, significantly reducing costs compared to stone construction (Binding 1993, p. 272-5).

Utilizing the soil maps "Gruppen der Bodenausgangsgesteine in Deutschland" as well as "Karte der Bodenarten in Oberböden", 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 a ratio of approximately 3:1 (Wolf 1999), I define brick suitability as the share of soils within a 20 km radius of each city that contain these materials. While this cutoff radius may seem arbitrary, it is chosen for two principal reasons: 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's work. Later, I will show that my results do not rely on this definition and also hold for alternative cutoff radii. Similarly, the stone availability measure is established by analyzing the share of sandstone, tuff, magmatite, and limestone deposits within a 20 km radius of each city. This arguably exogenous variation in natural endowments is then utilized to predict brick adoption in medieval German cities.

## 3.4 Additional Relevant City Characteristics

A major concern is that regions suitable for brick production may differ from those unsuitable in terms of other geographical or institutional factors. For example, brick suitable areas may inherently exhibit higher levels of agricultural productivity. To address this issue, I incorporate two indicators of agricultural productivity: the proportion of highly fertile Loess soils within a 20 km radius of each city, and potential rye yields under rain-fed agriculture within the same distance, based on data from the FAO's Global Agro-Ecological Zones database. Additionally, brick suitable areas may have been particularly advantaged in terms of access to transportation networks, thereby potentially having benefited to a greater extent from the expansion of long-distance trade in the late Middle Ages. Hence, additional controls include geographic indicators such as those for coastal towns, settlements along navigable rivers, towns west of the River Elbe, elevation above sea level, terrain ruggedness, and access to the Roman road network. Additionally, political-institutional characteristics including free imperial city status and membership in the Hanseatic League are also taken into account.

# 4 Descriptive Evidence

## 4.1 Brick Technology and the Locus of Construction Activity

This section aims to demonstrate how the introduction of brick technology altered the geographical distribution of construction activity in Germany during the Middle Ages. This becomes particularly evident when comparing maps depicting the focal points of church construction in Germany before and after the advent of brick technology. I hypothesize that construction activity was regionally concentrated from the 8th to the 11th century, primarily in areas with abundant natural stone resources. However, regions lacking in natural stone, such as Northern Germany, Northeastern Germany, the Lower Rhine region, and the Alpine foothills, had limited capacity for large-scale construction projects due to their scarcity of suitable building materials. This situation changed in the 12th century when these regions suddenly had the means to utilize resources from their local soils for brick production.

Figure 3 illustrates the geographical concentration of church construction activity in German cities before the advent of brick technology. The red circles represent cities, with the size of the circle indicating the aggregated surface area of newly built or extended churches between the 8th and 11th centuries. The light gray regions denote areas that are inherently suitable for brick production, although cities in these regions were unable to generate building materials from the resources in their soils during this time period. It is evident that church construction activity prior to the advent of brick technology was concentrated in the western and central regions of Germany. Cities like Cologne experienced a boom in construction activity with an aggregate surface area of newly built and extended churches reaching nearly 20,000 square meters. In contrast, despite being theoretically suitable for brick production, regions in the north, northeast, and Alpine foothills, which lacked natural stone resources, experienced significantly lower levels of construction activity due to the absence of knowledge about brick technology during that period.

This changes dramatically in the period after the advent of brick technology, as illus-

Figure 3: The Locus of Construction Activity, 8th to 11th Century

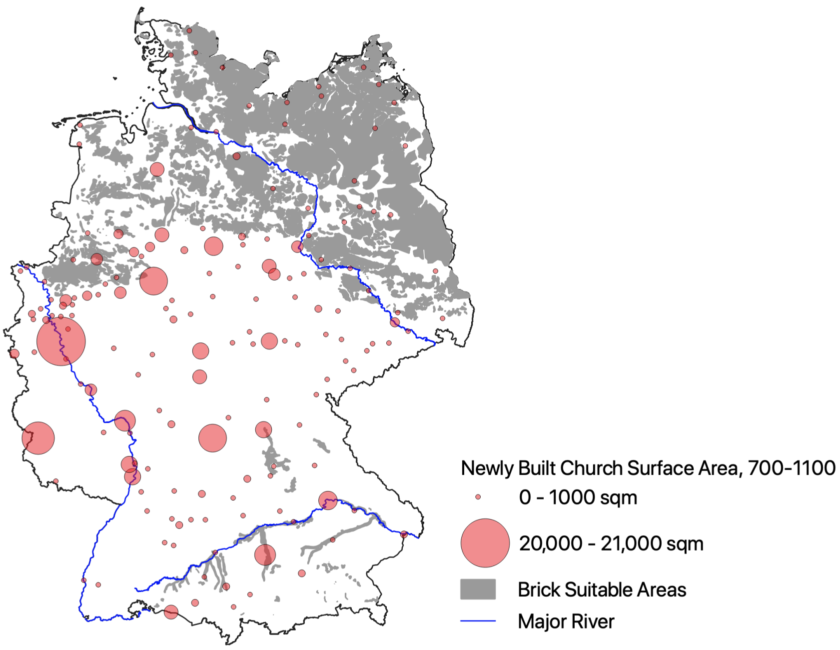
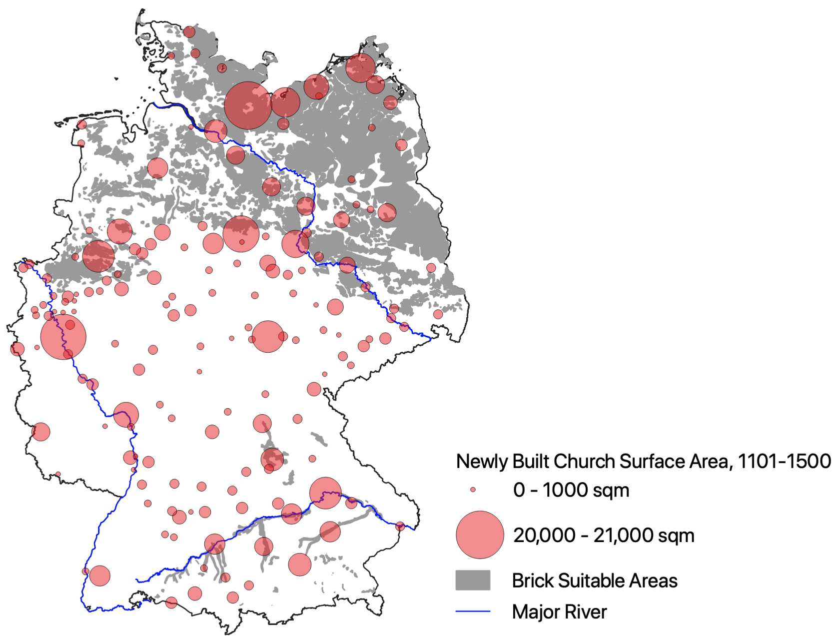



Figure 4: The Locus of Construction Activity, 12th to 15th Century




The two maps illustrate the geographical center of church construction activity in Germany. The map above represents the period before the advent of brick technology (8th to 11th century), while the one below 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.

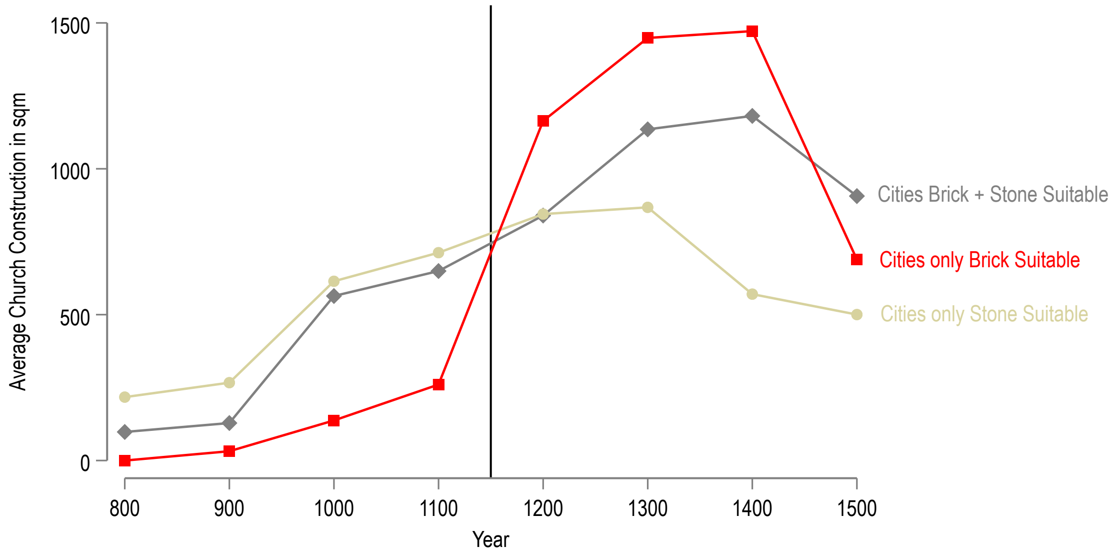
trated by Figure 4. While cities like Cologne and Erfurt, with access to natural stone resources, continue to experience intense construction activity, church construction is no longer concentrated solely in the western and central German regions. Suddenly, construction clusters emerge in the brick suitable areas of northern Germany as well. The city with the highest construction output is now Lübeck, whose cityscape is still characterized by the magnificent brick structures of the medieval period to this day. And intensive construction is also observed in the Bavarian Alpine Foreland, similarly brick suitable. This can be interpreted as initial evidence of how the novel brick technology fundamentally shifted the geographical focus of city development in Germany.

## 4.2 Reduced Form in Raw Data

This section aims to investigate whether cities located far from natural stone deposits but rich in raw materials for brick production had a disadvantage regarding construction possibilities before the emergence of brick technology, which later transformed into an advantage from the 12th century onwards. To achieve this, I divided the sample of 163 German cities for which I have data on church construction activity into three groups: 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. Therefore, the latter two groups had the opportunity to benefit from the new construction technology from the 12th century onwards. Accordingly, these two groups of cities should have encountered a discontinuity in construction activity in the 12th century.

Figure 5 plots the average area (in square meters) of newly constructed and expanded churches across the three groups of cities from the 8th to the 15th century. Please note that the variable of interest represents a flow rather than a stock variable. From the 8th to the 11th century, the trends for cities endowed with natural stone resources but lacking the necessary raw materials for brick production and cities with both natural stone resources and the necessary raw materials for brick production run in parallel. The construction level in these cities is significantly higher than the level of cities without natural stone resources but with the necessary raw materials for brick production. The low construction activity in the latter cities is not surprising, given that they effectively had no building materials available prior to the advent of brick technology. This seemed to have dramatically changed in the 12th century. The construction activity in the originally disadvantaged cities without natural stone resources skyrocketed, suddenly surpassing that of cities abundant in natural stone.

Figure 5: Church Construction in sqm and Natural Endowments

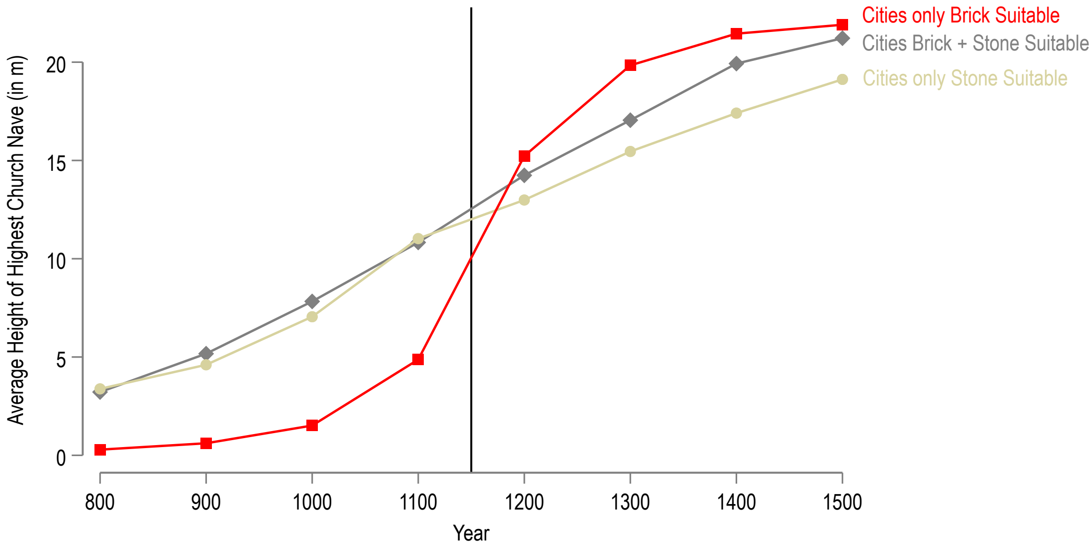



This graph illustrates the evolution of church construction activity, measured in surface area (in square meters), throughout the Middle Ages. The sample is divided into three groups of cities based on their natural endowments: cities endowed with natural stone resources but lacking the necessary raw materials for brick production, 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.

Comparing the trajectory of trends in both groups of cities endowed with natural stone resources from the 12th century onwards reveals a notable distinction. While both groups had access to natural stone, only one could adopt the new construction technology alongside traditional methods. In the 12th century, cities able to adopt brick technology started diverging from the trend of cities relying solely on natural stone. The construction boom evident here offers preliminary evidence that cities endowed with the raw materials for brick production were presented with entirely new construction possibilities following the advent of this new technology.

A similar pattern emerges when examining the evolution of church heights over time. This analysis introduces another dimension beyond the mere quantity of construction activity. While the surface area of pre-industrial buildings is largely determined by the availability of building materials, the height of church naves serves as a clear indicator of the technological sophistication in the construction sector and the quality of the construction material. While natural stone presented the inherent unpredictability of a natural product, bricks introduced a level of precision planning, thereby opening new avenues for construction, especially in terms of vertical expansion. Figure 6 presents the temporal evolution of church nave heights in the three city groups during the Middle Ages. The height of the tallest church nave is coded for each of the

Figure 6: Evolution of Church Heights and Natural Endowments




This graph illustrates the evolution of church heights over the course of 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.

163 cities for every century between 700 and 1500. Then, the average height for each group of cities is computed and plotted across the centuries. Please note that church heights represent a stock variable. It's important to avoid confusion about the presence of unusually low church heights between 800 and 1000 AD. This is because many cities did not have a major church during the early Middle Ages, resulting in a coded height of 0, which affects the calculated averages.

As observed previously, there is a discontinuity resulting from the emergence of brick technology in the 12th century. The trajectory of cities exclusively dependent on natural stone resources and those with both natural stone resources and raw materials for brick production closely aligns until the 11th century. However, starting from the 12th century, the latter group of cities could embrace the new construction technology, causing a discernible trend break for them. Even more striking is the scenario observed in cities that remained reliant on wood and fieldstones until the 11th century, yet possessed the raw materials for brick production. Subsequently, from the 12th century onwards, they were able to capitalize on the new construction technology. For these cities, the average height of the tallest church nave increased by over 10 meters within a century. This leap persists even when restricting the analysis to cities that already had at least one church by the 11th century.

# 5 Quantifying the Effect of Brick Adoption

The previous section centered on descriptive evidence regarding the consequences of the advent of brick technology. In doing so, it abstracted from actual brick adoption and instead focused on different natural endowments and their effect on church construction activity. Initial descriptive evidence was provided that cities with the potential for brick production experienced a construction boom after the advent of brick technology in the 12th century. The objective now is to quantify the influence of actual brick adoption on subsequent city development.

## 5.1 First-Stage and Reduced-Form Estimates

As brick adoption could be influenced by different growth trajectories and be endogenous to city development, the empirical analysis focuses on a DiD-IV approach. Brick adoption is instrumented using an index of city-level brick suitability, which captures the availability of raw materials for brick production in nearby soils. This yields the following first-stage regression:

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

In this framework, $adopted_{it}$ is a binary indicator that takes the value 1 in the century when city $i$ adopted brick technology and in the subsequent centuries. For example, if the town of Salzwedel adopted brick technology around the year 1210, $adopted_{it}$ takes the value 0 from the 8th to the 12th century and the value 1 from the 13th century onwards. This variable is then regressed on an interaction between the index of city-level brick suitability and a binary indicator for centuries following the advent of brick technology north of the Alps in the 12th century. Additionally, the regression equation includes a comprehensive set of time-interacted controls (as described in section 3.4), as well as time and city fixed effects.
Columns 1 and 2 of Table 2 present first-stage results. Please note that the coefficient of interest in column 1 is slightly larger than 1, despite the dependent variable being a binary indicator taking only the values 0 or 1. This discrepancy arises because there are no cities with a brick suitability index of 1. The city with the highest brick suitability 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 0.82 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

Table 2: First Stage and Reduced Form

| | First Stage | | | Reduced Form | | |
|---|---|---|---|---|---|---|
| | (1) | (2) | (3) | (4) | (5) | (6) |
| *Brick suitability* × *Post* | 1.035*** | 0.972*** | 0.979*** | 1722.05*** | 2187.85*** | 2366.07*** |
| | (0.056) | (0.134) | (0.173) | (331.17) | (624.12) | (697.03) |
| | [0.142] | [0.122] | [0.127] | [296.40] | [402.93] | [563.55] |
| Time-interacted controls | No | Yes | Yes | No | Yes | Yes |
| City fixed effects | Yes | Yes | Yes | Yes | Yes | Yes |
| Century fixed effects | Yes | Yes | No | Yes | Yes | No |
| Century × Region FE | No | No | Yes | No | No | Yes |
| $R^2$ | 0.480 | 0.569 | 0.642 | 0.144 | 0.275 | 0.379 |
| F-Statistic | 343.19 | 52.61 | 32.57 | | | |
| Number of Cities | 163 | 163 | 163 | 163 | 163 | 163 |
| Number of Observations | 1,304 | 1,304 | 1,304 | 1,304 | 1,304 | 1,304 |

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 "***".

of Table 2 indicate that my city-level brick suitability index is a strong predictor of actual brick adoption.

Reduced-form estimates are reported in columns 4-6 of Table 2. The corresponding regression model is given by:

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

In this specification, the dependent variable is $construction_{it}$, which indicates the surface area of newly built and expanded churches at the city-century level. The independent variables remain unchanged relative to equation 1.

As hinted at in Section 4, brick suitability becomes a significant driver of church construction activity following the advent of brick technology. The coefficient of interest in column 4 is positive and highly significant, suggesting that cities endowed with natural resources suitable for brick production had a comparative advantage in church construction activity following the introduction of brick technology in Germany, as compared to the preceding centuries. The coefficient on *brick suitability* × *Post* presented in column 6 is close to 2,400, indicating that cities with a brick suitability index of 0.84 (such as Neubrandenburg) would experience an additional 1,990 square meters of church construction following the advent of brick technology compared to cities with a brick suitability index of 0.

## 5.2 Reduced Form Event Study

To verify whether brick suitability indeed conferred an advantage for church construction following the advent of brick technology in the 12th century, I present an Event Study in the subsequent step. Following the empirical strategy of Nunn and Qian (2011), I estimate the following model:

$$construction_{it} = \alpha_i + \delta_t + \sum_{j=800}^{1500} \beta_j(Brick\ Suitability_i \times I_t^j) + \sum_{j=800}^{1500} X_i' I_t^j \phi_j + \varepsilon_{it} \tag{3}$$

In this specification, the indicator for city-level brick suitability is now interacted with each of the time-period fixed effects, spanning from the 8th to the 15th century. This allows me to scrutinize the period in which the impact of having natural endowments conducive to brick production on church construction activity first became statistically discernible. Since the brick suitability index is constant over time and the model accounts for both city and time-period fixed effects, the $\beta_j$ coefficients are measured in relation to the 11th century as baseline time-period. Hence, the absolute level of the estimated coefficients only indicates the difference in the association compared to the arbitrarily chosen reference point (Nunn and Qian 2011, p. 619).
The coefficients are plotted in Figure 7. The figure compellingly illustrates that there was indeed a discontinuity precisely in the 12th century. In the centuries prior, a high brick suitability index had no significant effect on church construction. This changed dramatically in the 12th century, as the coefficient on the interaction term suddenly turned positive, and in the 13th and 14th centuries became statistically significant at the 95% level. Notable at this point is the surprising observation that the coefficient of interest declines following a peak in the 13th century. This could be attributed to a consolidation of church construction activity in the brick regions following a remarkable catch-up process.

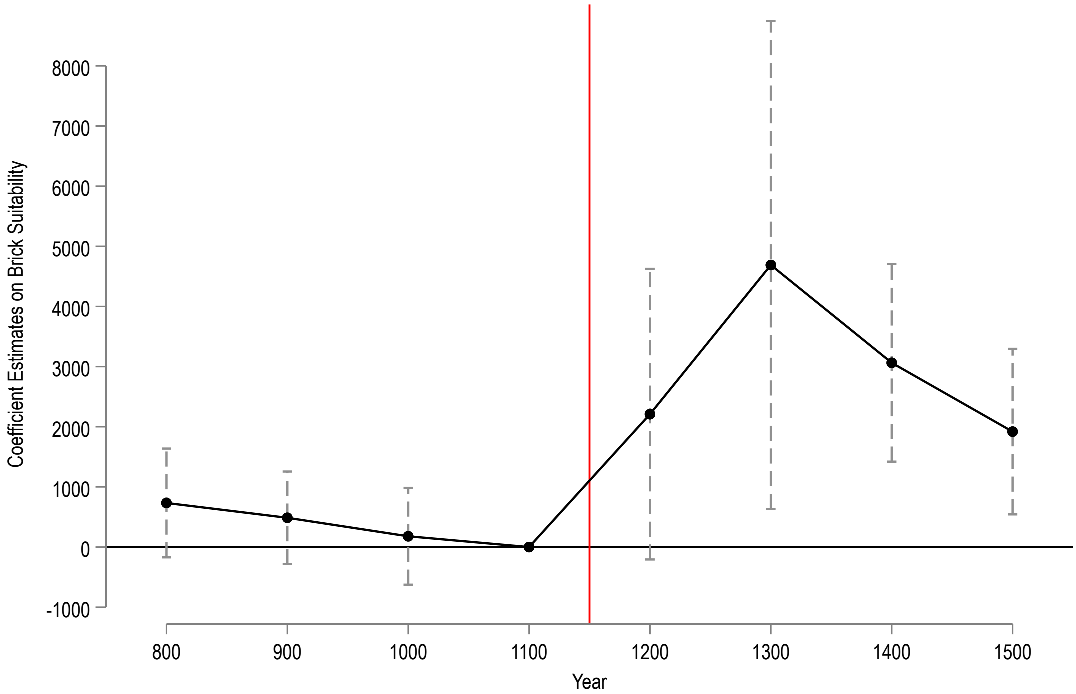
## 5.3 OLS and Second-Stage Results

OLS and Second-stage estimates are presented in Table 3. The corresponding regression equation is given by:

$$construction_{it} = \alpha_i + \delta_t + \beta\ adopted_{it} + \sum_{j=800}^{1500} X_i' I_t^j \theta_j + \varepsilon_{it} \tag{4}$$

The previously hypothesized pattern is confirmed: In both OLS and IV specifications, brick adoption had a positive and statistically significant impact on subsequent

Figure 7: 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.

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 7 in the Appendix demonstrates that the coefficient estimates remain robust toward employing alternative Difference-in-Differences estimators proposed by Borusyak-Jaravel-Spiess (2024), Callaway-Sant'Anna (2021), DeChaisemartin-D'Haultfeuille (2020), and Sun-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 clearly indicates that OLS estimates in this scenario tend to be downward biased. 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 2,500 square meters. This is equivalent to the surface area of ten tennis courts or nearly the surface area of Westminster Abbey. These findings

Table 3: Instrumental Variable Regressions

| | Dependent variable: Church construction activity (in sqm) | | | | | |
|---|---|---|---|---|---|---|
| | OLS | | | IV | | |
| | (1) | (2) | (3) | (4) | (5) | (6) |
| *Adopted* | 909.61*** | 735.22*** | 744.50*** | 1664.16*** | 2503.08*** | 2435.18*** |
| | (180.01) | (173.34) | (174.29) | (331.11) | (870.79) | (836.65) |
| | [153.46] | [149.01] | [168.01] | [327.57] | [580.86] | [521.84] |
| Time-interacted controls | No | Yes | Yes | No | Yes | Yes |
| City fixed effects | Yes | Yes | Yes | Yes | Yes | Yes |
| Century fixed effects | Yes | Yes | No | Yes | Yes | No |
| Century × Region FE | No | No | Yes | No | No | Yes |
| Number of Cities | 163 | 163 | 163 | 163 | 163 | 163 |
| Number of Observations | 1,304 | 1,304 | 1,304 | 1,304 | 1,304 | 1,304 |

Notes: In both specifications, 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. 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 ***".

remain robust even when considering solely within-region and century variation, addressing concerns about specific regions driving the results. Parameter estimates reported in column 6 remain practically unchanged. Moreover, the results are robust to using alternative definitions of the brick suitability index based on different cutoff radii. Table 8 in the Appendix replicates the estimates presented in column 6 of Table 3, instrumenting brick adoption using the share of brick-suitable soils within alternative cutoff radii of 10 km and 40 km. The coefficient estimates remain positive, large in magnitude, and highly significant.

An intriguing question emerges regarding the impact of brick technology: Was the effect of adopting brick technology purely a development effect, enabling cities without natural stone resources to start building significantly? Or was there also an advantage of brick architecture over traditional natural stone-based architecture? To test this, I re-estimate Equation 4 on a subsample of German cities with nearby natural stone resources.[4] Table 9 in the appendix shows regression results indicating that brick adoption provided an additional advantage even to cities that had previously been capable of large-scale construction using natural stone.

## 5.4 Robustness

Several factors could potentially distort the effects presented in the previous section. One concern is that regions inherently suitable for brick production may exhibit

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

Table 4: Sample Restrictions

| | Dependent variable: Church construction activity (in sqm) | | | | |
|---|---|---|---|---|---|
| | w/o High Yields | w/o Large Cities | w/o Late Settled | w/o Coastal | w/o After 1150 |
| | (1) | (2) | (3) | (4) | (5) |
| *Adopted* | 2929.22*** | 1667.24*** | 2428.04*** | 1972.83*** | 2474.34*** |
| | (825.56) | (468.41) | (769.50) | (605.31) | (698.11) |
| | [525.99] | [511.22] | [519.01] | [449.70] | [455.91] |
| Time-interacted controls | Yes | Yes | Yes | Yes | Yes |
| City fixed effects | Yes | Yes | Yes | Yes | Yes |
| Century fixed effects | Yes | Yes | Yes | Yes | Yes |
| Number of Cities | 122 | 146 | 127 | 144 | 117 |
| Number of Observations | 976 | 1,168 | 1,016 | 1,152 | 936 |

Notes: This table presents IV estimates. The dependent variable is 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. 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 "***".

higher agricultural productivity. To address this concern, all cities in the sample with agricultural productivity in the upper quartile, measured as log rye yields under rain-fed agriculture, are dropped. As indicated in column 1 of Table 4, the estimate remains positive, highly significant, and even increases in magnitude compared to the full sample. Another potential concern is that the results may be driven by large cities such as Bremen, Lübeck, and Hamburg. To mitigate this issue, the next step involves dropping all cities that reached a population of 10,000 by the 15th century. Results are presented in column 2 of Table 4. While the coefficient is slightly smaller, it remains positive and significant at the 1%-level. Empirical results could also be influenced by the German territorial expansion east of the Elbe River. This region, predominantly pagan around the year 1000, was subsequently christianized, leading to increased church construction activity. Furthermore, the regions east of the Elbe lacked natural stone resources but were highly suitable for brick technology. To address this concern, the regression is re-estimated with a sample restriction that excludes cities in previously Slavic regions that were colonised by Germanic peoples after the 8th century. Results, presented in Table 4, column 3, demonstrate robustness to this exclusion. Another potential concern is that regions close to the North and Baltic Seas, characterized by high brick suitability indexs, may have benefited from an expansion of maritime long-distance trade in the 12th century, leading to increased church construction budgets. To address this, the IV models are re-estimated, excluding all cities located within 50 kilometers of the sea. The findings, presented in column 4 of Table 4, show a slightly smaller estimated coefficient, but it remains highly significant. Notably, these regions were centers of medieval brick architecture, highlighting the remarkable persistence of the coefficient.

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.

## 5.5 Alternative Outcomes

The analysis so far has focused on newly built church surface area. However, did brick adoption also impact other aspects of construction activity? To test this, I consider alternative outcomes. First, I examine whether brick adoption increased newly built church volumes in addition to surface area. Coefficient estimates, using the specification that relies solely on within-century-region variation, are presented in column 2 of Table 5. The coefficient suggests that the adoption of brick technology resulted in an increase of nearly 50,000 cubic meters in church volume construction. The next step involves analyzing the impact of brick technology on per-capita construction activity in German cities. Since brick technology can be described as a pre-industrial high-economies-of-scale technology, I anticipate that city-level brick adoption not only increased overall construction activity but also unlocked additional per-capita construction potential. The outcome variable *area p.c.* is defined as city-century level newly built church surface area (in square meters), divided by the population of that city at the beginning of the given century. Data on historical city sizes is based on the revised Bairoch estimates of urban populations in Europe between 800 and 1850 (Buringh 2021). Especially for the early centuries (before 1100), population estimates often include zeros even for settlements known to have had construction activity. These zeros prevent calculating per-capita construction activity in some cities in certain centuries. To address this issue, I take the following approach: First, I assume that cities undertaking major church construction in a given century must have had a minimum population of 500 inhabitants. Subsequently, the remaining city-century observations with reported populations of zero are excluded from the analysis. Column 3 of Table 5 reports the relevant regression results. Indeed, brick adoption appears to have unlocked additional per-capita construction potential. The coefficient of interest suggests that cities experienced an increase in church construction activity per capita by 0.8 square meters following brick adoption.

Finally, I now turn to secular construction activity. While church construction serves as a useful proxy for urban building activity, it is crucial to verify that the adoption of brick technology not only boosted church construction but also influenced broader aspects of construction activity. Note that data on secular construction events is coarser than the data on church construction activity. The variable *secular* captures

Table 5: Alternative Outcomes

| | IV | | | |
|---|---|---|---|---|
| **Dependent Variable:** | **Area (m²)** | **Volume (m³)** | **Area per capita** | **Secular** |
| | (1) | (2) | (3) | (4) |
| Adopted | 2435.18*** | 47801.7*** | 0.8155*** | 0.5542*** |
| | (836.65) | (16406.9) | (0.2509) | (0.1631) |
| | [521.84] | [10495.1] | [0.2451] | [0.1344] |
| Time-interacted controls | Yes | Yes | Yes | Yes |
| City fixed effects | Yes | Yes | Yes | Yes |
| Century fixed effects | No | No | No | No |
| Century × Region FE | Yes | Yes | Yes | Yes |
| Number of Cities | 163 | 163 | 163 | 163 |
| Number of Observations | 1,304 | 1,304 | 966 | 1,304 |

Notes: This table presents IV estimates using alternative outcome variables: Volume (in $m^3$) represents the approximate newly built church volume in cubic meters. Area p.c. indicates city-century level newly built church surface area per-capita. Secular is an indicator variable set to 1 if a city experienced a significant secular construction event in a given century. *adopted* equals 1 for cities following brick adoption. 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 "***".

only whether a city experienced a significant secular construction event in a given century, but not the magnitude of the construction activity. As shown in column 4 of Table 5, the likelihood that a city experienced a significant secular construction event increased by 55 percentage points following the adoption of brick technology.

## 5.6 Brick Technology and Resilience to Demographic Shocks

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, claiming the lives of approximately one third of the population and profoundly reshaping social, economic, and cultural landscapes. Labor became a scarce production factor, significantly increasing the bargaining power of workers, thereby ushering a "golden age of labor" (Postan 1972, Voigtländer and Voth 2013)). While rural populations flowed into cities, craft guilds regulated access to training and trades, exacerbating the scarcity of skilled workers (Bergoldt 2000).

The scarcity of skilled craftsmen also affected the 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, 310-13). It has been noted that during the plague centuries, the focal point of church construction activity shifted to Northern Europe, including several regions known for their use of brick. The resilience of these regions has been attributed to institutional characteristics (Buringh et al. 2020). However, I propose that this resilience was primarily a result of the labor market characteristics of brick technology.

Unlike the processing of natural stone, brick production did not require skilled stonemasons. Moreover, brick production operated outside the confines of guild regulations, fostering an environment of free enterprise. Therefore, cities that relied on brick technology in construction were less susceptible to local plague outbreaks, as the loss of workers involved in brick production could be easily filled by unskilled rural migrants. Table 6 offers insights into the interactions between the adoption of brick technology and local plague outbreaks. Estimates are based on the following regression model:

$$
\begin{aligned}
construction_{it} = \alpha_i + \delta_t + \beta_1 \ adopted_{it} + \beta_2 \ plague_{it} + \beta_3 \ (adopted \times plague)_{it} \\
+ \sum_{j=800}^{1500} X_i' I_t^j \phi_j + \varepsilon_{it}
\end{aligned}
\tag{5}
$$

Again, the dependent variable is the city-century level newly built church surface area (in sqm). In addition to the explanatory variable *adopted*, the variables *plague* and $brick \times plague$ are included. *plague* is a dummy variable indicating whether city $i$ experienced a plague outbreak in century $t$. $adopted \times plague$ is an interaction term between the two aforementioned variables, indicating city-century level plague outbreaks in cities that had adopted brick technology. All specifications rely solely on within-region-century variation.

Surprisingly, when initially considering the effect of plague outbreaks independent of brick adoption, plague outbreaks do not appear to have had a significant impact on church construction activity in both OLS and IV specifications (columns 2 and 5, respectively). However, when the interaction term between brick adoption and plague outbreaks is included (columns 3 and 6), a different picture emerges: the effect of plague outbreaks becomes negative and significant. Interestingly, this negative impact is not observed in cities that had adopted brick technology prior to experiencing a plague outbreak. These cities maintained very high construction levels even during plague centuries. In fact, the magnitude of the coefficient on $adopted \times plague$ is so large that it overcompensates for the negative effect of plague outbreaks.

These findings suggest that adopting brick technology made medieval cities more

Table 6: Interactions with Local Plague Outbreaks

| | Dependent variable: Church Construction Activity (in sqm) | | | | | |
|---|---|---|---|---|---|---|
| | OLS | | | IV | | |
| | (1) | (2) | (3) | (4) | (5) | (6) |
| *Adopted* | 744.50*** | 687.54*** | 442.72*** | 2435.18*** | 2342.41*** | 1758.37** |
| | (174.29) | (161.69) | (151.34) | (836.65) | (697.51) | (772.23) |
| | [168.01] | [159.12] | [147.62] | [521.84] | [397.90] | [557.98] |
| *Plague* | | 62.49 | −451.07** | | −75.96 | −853.09** |
| | | (198.53) | (219.52) | | (249.07) | (363.56) |
| | | [184.43] | [140.49] | | [187.92] | [252.51] |
| *Adopted* × *Plague* | | | 1288.46*** | | | 2047.82** |
| | | | (393.56) | | | (835.21) |
| | | | [279.41] | | | [653.15] |
| Time-interacted controls | Yes | Yes | Yes | Yes | Yes | Yes |
| City fixed effects | Yes | Yes | Yes | Yes | Yes | Yes |
| Century fixed effects | No | No | No | No | No | No |
| Century × Region FE | Yes | Yes | Yes | Yes | Yes | Yes |
| Number of Cities | 163 | 163 | 163 | 163 | 163 | 163 |
| Number of Observations | 1,304 | 1,304 | 1,304 | 1,304 | 1,304 | 1,304 |

Notes: In both specifications, the dependent variable is *construction*. *construction* measures church construction (in sqm) at the city-century-level. *adopted* equals 1 for cities following brick adoption. *plague* indicates city-century-level plague outbreaks. *Adopted* × *plague* is an interaction term between the above variables, taking the value 1 if city *i* experienced a local plague outbreak following brick adoption. 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 ***".

resilient to demographic shocks. The unique characteristics of brick technology – namely, that bricks could be produced by unskilled workers – meant that even during significant population declines, unskilled rural migrants could replace the deceased workers. Consequently, the construction sector in brick cities was less vulnerable to decreases in the (skilled) workforce, allowing these cities to maintain high construction levels.

# 6 Conclusion

This paper investigates the effects of the re-introduction of brick technology to the regions north of the Alps in the 12th century. This technology shock acted as a significant catalyst in the medieval construction sector, fundamentally altering the capability of certain regions to undertake large-scale construction projects. The advent of brick technology presented cities lacking natural stone resources with an alternative to importing natural stone at extremely high costs. In addition, brick offered several advantages over natural stone as a building material, such as the low cost of raw materials, the ability to produce bricks according to standardized formats, and the fact that brick production did not require skilled stonemasons. This implied economies of scale in construction for cities that adopted the new technology. To examine whether such cities actually benefited from these advantages, I assemble a novel dataset on city-level brick adoption in Germany based on the most comprehensive architectural directory covering the German-speaking region.

To analyze the impact of brick technology on construction activity, I utilize detailed data on city-level church construction compiled by Buringh et al. (2020) as well as data on significant secular construction events provided by Cantoni and Weigand (2020). Through examining variation in the availability of construction materials, I offer descriptive evidence suggesting that cities lacking natural stone resources lagged in construction activity before the introduction of brick technology in the 12th century. The adoption of brick technology allowed cities without natural stone resources but with clay and sand deposits to utilize these materials for construction purposes. These cities experienced a significant construction boom from the 12th century onwards.

Since the adoption of brick technology was likely not exogenous, I constructed an index of city-level brick suitability. This indicator represents the share of soils within a 20-kilometer radius of each city containing the ideal mix of clay and sand necessary for brick production. In the empirical analysis of the effect of brick adoption on subsequent construction activity, this index is used to instrument brick adoption. The key identifying assumption is that brick suitability did not have a time-varying effect on other drivers of medieval construction activity. As indicated by first-stage regression results, my brick suitability index is a strong predictor of brick adoption in medieval German cities. Second-stage results indicate that cities adopting brick technology experienced a significant construction boom following adoption. According to my preferred specification, which includes an extensive set of geographical and institutional controls and only relies on within-region-century variation, brick adoption led to an increase in church construction activity by 2,500 square meters. This is almost equivalent to the surface area of Westminster Abbey. Furthermore, as a pre-industrial high economies of scale technology, brick adoption boosted church construction activity per capita. These effects were not limited to church construction; cities also saw a rise in the likelihood of significant secular construction events following brick adoption.

However, concerns may arise that highly brick suitable areas were auspicious independent of the availability of construction materials. For instance, brick suitable areas may have higher agricultural productivity. To address this concern, I not only control for two indicators of agricultural productivity but also re-estimate the model by dropping cities with particularly high potential rye yields. Results remain

unchanged. Additionally, the results could be driven by large cities, cities influenced by the German territorial expansion east of the Elbe River, cities in coastal areas, or cities in newly urbanized regions. Even under the corresponding sample restrictions, the coefficient of interest remains positive, large in magnitude, and highly significant. As an additional step, I delve deeper into the labor market characteristics of brick technology. I show that cities adopting brick technology were more resilient to plague-induced demographic shocks. Brick production, not requiring skilled stonemasons and free from guild constraints, allowed unskilled rural migrants to replace workers lost to the plague. Consequently, the construction sectors of brick cities were less susceptible to significant declines in the (skilled) construction workforce.
The paper contributes to the understanding of technological change in the construction sector, which was arguably the only sector of the pre-modern economy that exhibited industrial characteristics. The findings suggest that the introduction of new technology alleviated constraints on construction activity in suitable regions. This research has significant implications for understanding medieval regional development, highlighting how technological progress can drive development in previously underdeveloped regions by overcoming constraints. Specifically, the study demonstrates how the adoption of brick technology allowed cities to bypass the high costs of natural stone imports, and reap the economies of scale associated with standardized, modularized construction processes. By shedding light on these mechanisms, the research contributes to our understanding of the broader processes driving economic and social change in the medieval period.

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# 8 Appendix

Table 7: Alternative Difference-in-Differences Estimators

| | **Dependent variable: Church construction activity (in sqm)** | | |
|---|---|---|---|
| | Point Estimate | Standard Error | 95% Confidence Interval |
| Borusyak-Jaravel-Spiess | 901.93*** | 179.94 | [549.25; 1254.62] |
| Callaway-Sant'Anna | 700.09*** | 218.11 | [272.58; 1127.59] |
| DeChaisemartin-D'Haultfeuille | 703.94** | 307.64 | [100.96; 1306.91] |
| Sun-Abraham | 824.47* | 451.15 | [-71.43; 1720.38] |

Notes: This table presents the robustness of my baseline estimate using alternative difference-in-differences estimators introduced 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, and standard errors are clustered at the territory level. Statistical significance at the 90%, 95%, and 99% confidence level denoted '*", **", and ***".

Table 8: Instrumental Variable Results Using Alternative Radii

| | **Dependent variable: Church construction activity (in sqm)** | | |
|---|---|---|---|
| | 10 kilometers | 20 kilometers | 40 kilometers |
| | (1) | (2) | (3) |
| *Adopted* | 1802.73*** | 2435.18*** | 2450.69*** |
| | (551.14) | (836.65) | (865.12) |
| | [385.90] | [521.84] | [582.43] |
| Time-interacted controls | Yes | Yes | Yes |
| City FE | Yes | Yes | Yes |
| Century FE | No | No | No |
| Century × Region FE | Yes | Yes | Yes |
| Number of Cities | 163 | 163 | 163 |
| Number of Observations | 1,304 | 1,304 | 1,304 |

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. 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 ***".

Table 9: The Impact of Brick Adoption in Cities with Stone Resources

| | **Dependent variable: Church construction activity (in sqm)** | | | | | |
|---|---|---|---|---|---|---|
| | OLS | | | IV | | |
| | (1) | (2) | (3) | (4) | (5) | (6) |
| *Adopted* | 838.28*** | 680.07*** | 763.85*** | 2181.53*** | 2198.65*** | 2386.15*** |
| | (242.64) | (189.28) | (235.19) | (783.96) | (672.40) | (774.80) |
| | [201.97] | [183.79] | [213.57] | [711.60] | [562.99] | [595.90] |
| Time-interacted controls | No | Yes | Yes | No | Yes | Yes |
| City fixed effects | Yes | Yes | Yes | Yes | Yes | Yes |
| Century fixed effects | Yes | Yes | No | Yes | Yes | No |
| Century × Region FE | No | No | Yes | No | No | Yes |
| Number of Cities | 124 | 124 | 124 | 124 | 124 | 124 |
| Number of Observations | 992 | 992 | 992 | 992 | 992 | 992 |

Notes: Results presented in this table are based on the subsample of German cities that have at least some nearby natural stone resources. In both specifications, 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. 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 ***".

Table 10: The Impact of Brick Adoption in Cities with Brick Adoption Unrelated to Church Construction Projects

| | **Dependent variable: Church construction activity (in sqm)** | | | | | |
|---|---|---|---|---|---|---|
| | OLS | | | IV | | |
| | (1) | (2) | (3) | (4) | (5) | (6) |
| *Adopted* | 1098.16*** | 822.24*** | 807.51*** | 1600.67*** | 1846.83*** | 1921.33*** |
| | (246.12) | (226.45) | (266.17) | (349.18) | (510.10) | (710.99) |
| | [176.38] | [180.79] | [210.94] | [277.05] | [507.92] | [535.48] |
| Time-interacted controls | No | Yes | Yes | No | Yes | Yes |
| City fixed effects | Yes | Yes | Yes | Yes | Yes | Yes |
| Century fixed effects | Yes | Yes | No | Yes | Yes | No |
| Century × Region FE | No | No | Yes | No | No | Yes |
| Number of Cities | 134 | 134 | 134 | 134 | 134 | 134 |
| Number of Observations | 1,072 | 1,072 | 1,072 | 1,072 | 1,072 | 1,072 |

Notes: Results presented in this table are based on the subsample of German cities that adopted brick technology in the context of non-clerical construction projects. In both specifications, 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. 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 ***".