Time for Growth*

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Abstract

This paper studies the impact of the early adoption of one of the most important high-technology machines in history, the public mechanical clock, on long-run growth in Europe. We avoid endogeneity by considering the relationship between the adoption of clocks with two sets of instruments: distance from the first adopters and the appearance of repeated solar eclipses. The latter instrument is motivated by the predecessor technologies of mechanical clocks, astronomic instruments that measured the course of heavenly bodies. We find significant growth rates between 1500 and 1700 in the range of 30 percentage points in early adoptor cities and areas.

Keywords: technological adoption, cities, mechanical clocks, information technology.

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1 Introduction

This paper investigates the impact of the early adoption of high-technology machines on long-run growth. Various studies have widely discussed the possible benefits and drawbacks of the role of hi-tech innovation on firms and nations economic success. On the one hand, a well-established literature of various scholars (e.g., Ricardo (1821), Leontieff (1983), Samuelson (1988), and Zeira (1998)) has claimed that the impact is negative because advanced machines lower wages, which in turn reduce population and income growth. On the other hand, in the last twenty years, which coincide with the introduction of new innovations in information technology (IT, henceforth), new research has found a more differentiated picture of this relationship. In a 1987 article published in the *New York Times*, Robert Solow underlined a productivity paradox (also known as Solow Paradox) that highlights that the American productivity slowdown in the 1970s concurs with the adoption of computers (*"You can see the computer age everywhere but in the productivity statistics."*). However, other scholars have found the advantage and the positive effects of the spread of computers on society: Bresnahan, Brynjolfsson, and Hitt (2002) underline the positive role of hi-tech capital and the complementarity with skills and innovations at the firm level; Caselli and Coleman (2001) use country data and find a strong and positive relationship between human capital, computers and productivity; Andersen, Bentzen, Dalgaard, and Selaya (2012), examining the negative role played by lighting in IT diffusion, explain the higher economic growth across American states due to digital technologies. Contrarily, more recently Acemoglu, Autor, Dorn, Hanson, and Price (2014) confirm a Solow Paradox in IT-intensive sectors, where an increase in labor productivity is associated with a decline in employment. Some main problems with these types of studies is that they have to address several empirical challenges. First, it is difficult to identify the adoption of IT at the micro level and to create a representative aggregate picture at the macro level. Second, the identification of adoption does not necessarily guarantee the accurate use of the new technology. Finally, the time series for potentially identifying growth are relatively short.

To find an answer to question concerning the relationship between technology and economic performances, cases studies based on the introduction of innovative machines can be useful. In an early reply to Solow, the economist and economic historian Paul David (David (1990)) suggests resolving the study of the Solow Parodox from a historical perspective. Examining the innovation of the dynamo

in the late 19^{th} century he argues that it simply takes time until the use of such a general purpose technology (GPT, henceforth) results in economic growth rates. Crafts (2002) among other scholars took up this line of argumentation and compared the impact of different GPTs, such as electricity and computers, on long-run economic growth. He finds comparably strong evidence for the effect of IT, but admits that there are problems in measuring and comparing such effects adequately. Another related technology study has been done by Dittmar (2011) who explains long-run pre-modern growth effects based on the invention of the printing press.

In this paper, we attempt to shed light on the productivity paradox from a new perspective. We study the impact of one of the most important technologies ever invented in history, i.e., the public mechanical clock, on economic growth. This technology was first introduced in Europe at the end of the thirteenth century and it spread across Europe during the following two centuries. Mechanical clocks have been identified as one of the greatest GPTs of the last millennium.[1] The importance of mechanical clocks has been discussed by several scholars in different fields. Landes (1983) claims that clocks were the technological sensation of the 14^{th} century, similar to computers today. Furthermore, he argues that the clock had a strong impact on productivity: it enabled increases in organizational skills in terms of coordination and division of labor and the monitoring of production processes. Very much in line with Landes, Mokyr (1992) argues that mechanical clocks was one of the most important technology inventions of the last millenium. Moreover, Thompson (1967) highlights that the mechanical clock changed the work culture and increased work discipline. Le Goff (1982) claims that the introduction of the public mechanical clock was a turning point for the Western society. It helped create a new epoch, "the time of the merchants", because it enabled business people to better frame and measure all types of economic activities in a timely manner. Dohrn-van Rossum (1996) finds that in addition to the already discussed points, also evidence for the improvement of various co-ordination activities in pre-modern towns such as market times, administrative meetings of the town governments, and school and university lecturing time. Other economic historians with a greater focus on the transition to modernity, e.g., Mumford (1934), Rosenberg and Birdzell (2008) and Voth (2001), argue that the clock had a profound impact on the processes of the Industrial Revolution. Mumford even describes the mechanical clock, and not the steam machine, as the key machine of

[1] Bresnahan and Trajtenberg (1995) define technologies according to three characteristics: first, they should be pervasive in most economic sectors; second, they should improve over time with lower costs for the consumers; finally, they should incentivize new products and processes.

the the modern industrial age, because the knowledge accumulated from the mechanical clock had a positive spillover during the Industrial Revolution. Finally, more generally, prominent social scientists such as Marx (1863), Weber (1905) and Sombart (1921) claim that clocks had a fundamental impact on the evolution of capitalism and rationality of societies.

Thus, examining this enumeration of findings and claims made by this great number of important scholars we should find some growth effects based on changes in organization, production, and work culture. Therefore, the introduction of clocks in medieval cities should have localized spillover effects in these towns and further affect growth at a more aggregate level.

To test the impact of clocks on economic growth, we construct a unique dataset collected from several historical sources. To study economic growth we use the dataset of European city sizes mainly collected by Bairoch, Batou, and Chevre (1988). We use the change of population size over time as a proxy to study pre-modern economic growth (Acemoglu, Johnson, and Robinson (2005a)). Our data set contains all cities for which we have population numbers from 1200-1800. As a main explanatory, variable we collect information on the construction of public mechanical clocks in all these cities. We identify a group of early adopting cities from the first adopters in 1283 until 1450. The end point is calculated based on the inflection point and hazard rate of the S-shaped diffusion curve of the technology we observe. Based on this identification we measure the impact of the implementation of clocks by early adopters compared to other cities. We study growth rates from 1300 until 1800. We control for a broad set of control variables, including institutional and geographical characteristics of cities and regions. Our dataset has several favorable characteristics. It is not affected by sample selection because the construction of clocks is rather well documented in the available source material. Therefore, we have a representative and rather complete sample on the date of the adoption and geographical location of this new GPT. Clocks also had relatively low maintenance costs and were rather robust. Thus, once implemented, clocks were used and maintained by the city population over many centuries. Furthermore, clocks were non-exclusive public goods that were easy to understand and use by the whole city population. Finally, our study allows us to have a very long run perspective on the effect of this GPT on economic growth.

Our empirical strategy includes various standard approaches used in the related empirical literature. We start with the estimation of a modified econometric growth equation derived by Mankiw, Romer, and Weil (1992) represented by a simple OLS regression as a benchmark. To prevent endo-

geneity problems between the growth variable and the implementation of clocks, potentially missing explanatory variables, and measurement errors of the main explanatory variable, in the next step, we introduce two-stage least squares procedures and related non-linear estimation approaches (Angrist and Pischke (2008)). Finally, we use a generalized difference-in-differences approach and propensity score analysis similar to the techniques adopted by Dittmar (2012) as further robustness checks.

We consider two different sets of instruments: the distance from the early adopters and the presence of eclipses in the previous centuries. The distance from a knowledge source has been already examined by other studies on innovation of product and culture and economic growth (Becker and Woessmann (2009) and Dittmar (2012)). Instead of a single geographical location of a city, as applied in these previous studies we use the first wave of adopters identified by Dohrn-van Rossum (1996). In the literature, this approach has been used in relation to education and labor economics (e.g., Card (1993)). Additionally, we consider a new type of instrument: solar eclipses. We collect data elaborated by the National Aeronautics and Space Administration (NASA, henceforth) on populated geographical area intensively covered by solar eclipses before the adoption of the first clocks. The use of solar eclipses as an instrument for clocks is motivated by two types of observations by science and technology historians: first, eclipses and other astronomic movements influenced the study of astronomy and triggered the construction of mechanical devices that aided in measuring these astronomic events, such as astrolabes and specially designed water and sun clocks (Turner (1911) and Dohrn-van Rossum (1996)); second, these machines have been identified as the predecessor technologies of mechanical clocks. Furthermore, this instrument also highlights the importance of human capital in the adoption of new technology. This is similar to the positive relationship between high levels of education and computer adoption highlighted by Caselli and Coleman (2001). The existence of universities is also included as a further control variable in the two-stage procedure.

Following the proposed methodology, we find that earlier adopters, compared to other cities, display significant growth differences in the range of 30 percentage points for the period of 1500-1700; these differences are robust for all specifications. These results indicate that public clocks as a GPT indeed localized spillover effects on various economic and economy-supporting activities and led to higher city growth rates. This approach explains economic growth from a micro perspective. As an extension and alternative approach, we study countries GDP growth rates. This allows us to estimate comparative growth effects between countries and create a macroeconomic perspective. Our main

explanatory variable is the adoption rate measured by the population rate of a country. Here, we follow the methodology of Czernich, Falck, Kretschmer, and Woessmann (2011). We use the share of the population of the country covered by the eclipses as an instrument. Again, we find significant growth effects based on the diffusion rate of mechanical clocks on economic growth.

Our results support the point of view that GPTs indeed have a strong impact on economic growth. However, it takes time for such fundamental new technological innovations to have an effect because the technology must be culturally and socially accepted and applied in related economic activities. In this way, our findings are in line with David (1990), who claims that it takes time to resolve the Solow Paradox. Thus, with this paper, we contribute to the discussion of the Productivity Paradox from a long-run historical perspective. More specifically, our results support the findings of the social scientists who claim that economic and cultural effects of the clock can only be found in the long run. Our paper is a unique quantitative study on economic growth effects, which has not been done thus far.

The paper is structured as follows. Section 2 illustrates the introduction and diffusion of mechanical clocks, and describes potential links to economic growth. In addition, the two types of instruments are explained. Section 3 describes the data collected. Section 4 introduces the empirical strategy for studying the impact of clocks at the city level. Section 5 studies the impact of this technology on Growth Domestic Product (GDP, henceforth) per person from a more aggregate level. Finally, Section 6 concludes.

2 The mechanical clock

2.1 Introduction of public clocks

The introduction of public mechanical clocks can first be observed during the late 13^{th} century. These clocks were typically built on church towers or the communal tower of the town, and they were mechanical devices that produced a weight-driven acoustic signal every hour. Thus, early mechanical clocks did not have a dial but worked only with a bell.[2] The day was typically divided into two units of twelve and the bells rang accordingly as many times.[3] In this way, the clocks were publicly

[2]The introduction of complementary dials is frequently documented from the beginning of the 15^{th} century.

[3]In some cities, other formulas such as four units of six were used.

accessible and easy for everyone to understand. A person only had to listen to the chime and have the ability to count. The origin of these mechanical clocks cannot be precisely documented. However, two main hypothesis have been formulated. In one hypothesis, the innovation developed out of scientific curiosity and the need to keep time in the European monastic life (Landes (1983) and Dohrn-van Rossum (1996)). Time keeping was particularly important for the study and measurement of the course of the celestial bodies. The assumption of this approach is that the monks had a basic knowledge of water clocks, sun clocks, and the existing astronomic instruments, particularly the astrolabe. Such knowledge must have been transmitted either via old Roman and Greek sources or more recently from the pretty well-developed scientific body of knowledge of the Arabs, who were leading during the late middle ages. This body of knowledge was accessible to the European world. However, the critical step, the introduction of the weight-driven mechanism with an escapement and regulation was developed by the Europeans. A few sources indicate the imminent discovery during the second half of the 13^{th} century but do not reveal the crucial step of discovery. For example, Thorndyke (1941) reports the existence of an astrolabe that closely resembles the mechanical clock. The second hypothesis is that the technology had already been sufficiently developed by the Chinese in the form of astronomic clocks (which, however, were driven by hydraulic mechanisms) and that the information on their construction had been vaguely transmitted via the Indians or Arabs to Europe (Price (1956) and Needham (1986)). By using their knowledge, simplifying their astronomic instruments, and creating a different mechanical engine, the Europeans created the mechanical clock. The two hypotheses share the notion that the innovation was strongly driven by scientific curiosity in general and by the interest to better understand the constellations of the heavenly bodies and to further develop astronomic instruments in particular. We will consider this link in more detail when we discuss the appropriate instruments for the econometric analysis.

2.2 The diffusion of mechanical clocks between 1283 and 1450

Dohrn-van Rossum (1996) identifies the time interval from the first adoptions to 1450 as the period of the early adoption of public mechanical clocks. In addition, he divides these decades into three phases based on the areas and intensity of diffusion in Europe. The first adoption phase covers the period until 1350. During that time, the few public mechanical clocks were mainly built in cities in

Italy in the area of the Papal States and Northern Italy (which partly belonged to the Holy Roman Empire), in England, and in the Holy Roman Empire north of the Alps. In the second phase, 1350-1370, a stronger diffusion in the mentioned areas can be found. Further diffusion in French and Dutch cities can be observed. In addition, a few observations in Spain and Sicily are documented. Finally, in the third phase, 1370-1450, further and strongly booming diffusion in the already covered areas is documented. Furthermore, in neighboring eastern European areas and Scandinavia, the diffusion process also began.

The motivation for the diffusion of public clocks in late medieval towns (at least during the 14^{th} century) was mainly prestige (Bilfinger (1892), Sombart (1921), and Mokyr (1992)). The clocks were financed by worldly and ecclesiastical dukes and other wealthy noblemen of the towns. Clocks were the pride of the cities and showed the openness and progressiveness of a town. Economic motivations in terms of merchants needs, as suggested by Le Goff (1982) cannot be identified in corresponding source material during this early phase of adoption and only evolved over time (Dohrn-van Rossum (1996)).

Exploiting our dataset on the adoption of clocks (described in the next section) and the GIS national borders provided by Nuessli (2011), we construct Figure 1 showing all the cities that adopted at least one public mechanical clock until 1450.[4] Detailed maps on the above-mentioned stepwise process of diffusion can be found in Appendix A, where the dispersion of the mechanical clock technology in medieval Europe during the period of 1282-1450 is illustrated in periods of roughly thirty to forty years, i.e., 1283-1320, until 1350, until 1380, and until 1410. A similar pattern as that described by Dohrn-van Rossum can be found by further statistical analysis: The left part of Figure 2 shows the cumulative distribution of the proportion of technological adopters using our dataset for the period of 1283-1600. In this graph, we observe an S-shaped curve with a slow start in adopting the new technology and two structural breaks during the second half of the 14^{th} and 15^{th} centuries and beyond. This forms the typical diffusion curve of new technologies, as described in Rogers (2003)'s analysis of diffusion processes. Moreover, a more precise analysis based on the hazard rate (Young (2009)) the right part of Figure 1,[5] shows that early adopters of the mechanical clocks are the cities

[4]Please keep in mind that our total sample contains all the cities covered by Bairoch for which we have population data from 1300-1800

[5]More precisely, we consider the strategy applied by Young (2009) on Griliches (1957)'s dataset. We define p_t the proportion of adopters a time t, we define the hazard rate of adoption H_t, i.e. the conditional probability of adopting a mechanical clock as

that built this technology before 1450; the conditional probability, represented by the hazard rate, is almost equal to zero. Then, we can observe a strong acceleration in adoption. This result confirms the use of 1450 as an endpoint and defines the number of early adopters in our sample.

$$H_t = \frac{p_{t+1} - p_t}{p_t(1-p_t)}$$

Figure 2 shows the prediction of a cubic polynomial, $H_t = a + b_1 t + b_2 t^2 + b_3 t^3 + u$.

Figure 1: The diffusion of the mechanical clock in Europe in 1450. Source: Authors' calculations using the authors' dataset of clock and GIS border from Nuessli (2011).

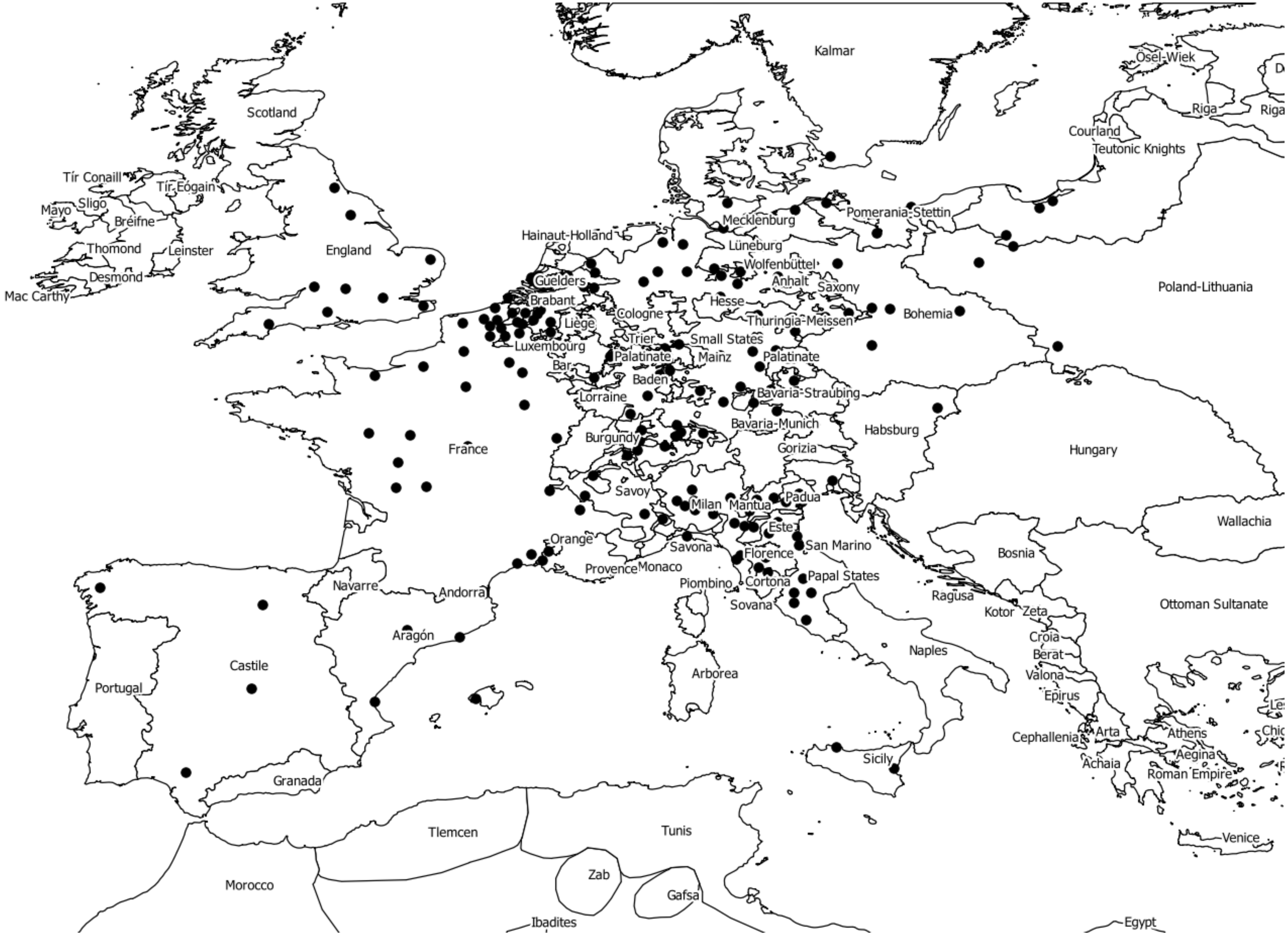
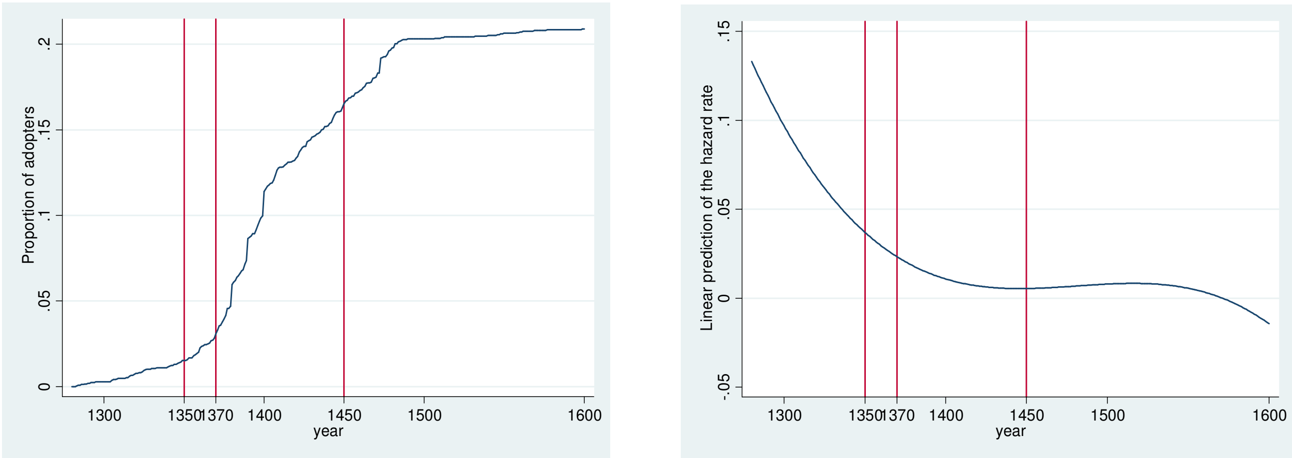


Figure 2: Cumulative distribution of mechanical clock (left part) and linear prediction of the hazard rate (right part)



2.3 Mechanical clocks and economic growth

As outlined in the introduction, a great number of scholars claim that clocks had strong and long-lasting effects on the growth and development of societies. However, most scholars also admit that it took time for societies to accept, adapt, and learn to use this new technology and transform it into corresponding growth rates. To better understand this process, we need to proceed in three steps. First, we need to understand what the introduction of the public mechanical clock potentially offered to the European cities. Second, we must determine how this means of keeping time was different from previous means. Finally, we have to identify the different channels of adoptions and applications that made the clock valuable and could result in higher economic growth rates.

Answering the first question is rather straightforward. The clock offered an accessible and audible signal that divided the day into equally long units (Landes (1983)). To answer the second question a more sophisticated answer is needed. The concept of dividing the day into measurable subunits existed before the clock (Lippincott, Eco, and Gombrich (1999)). The division of the day into twelve parts dates back to ancient times. However, the length of the hour depended on the length of the day and was a fixed proportion of the sunlight hours (so-called temporal hours). Thus, an hour could vary during the summer and winter periods. In line with this concept, the hour could be measured by sun clocks. However, because this measurement technique depends on time of the year and the weather

conditions, the length of the hour varied and the technology was less reliable. Therefore, it was not intensively used in societies. Rather, people followed simpler indications such as the position of the sun, i.e., the sunrise, noon, and sunset, as guidelines. The concept of the division into twenty-four equally long hours (so-called equinoctial hours) also dates back to ancient times. However, it was rather complicated to measure and could not be directly derived from the constellation of the sun; it had to be derived by calculations. This division of time was mainly used to follow the course of the heavenly bodies. Astronomic instruments, so-called astrolabes, or specially calibrated water clocks were employed to measure these activities. The use of astrolabes to measure daily time was overly complicated, and the use of water clocks required additional calculations and a very precise calibration of the clock.[6] Therefore, the introduction of the mechanical clock improved the quality of time keeping dramatically.[7]

The use of bells as signals existed before the introduction of mechanical clocks (Dohrn-van Rossum (1996), chapter 7). In late medieval cities, it became popular to indicate and coordinate all types of social and economic activities with various bells, fanfares or flags. These signals were approved by the city government and were used for specific tasks and groups of people. Therefore, what was new with respect to the public mechanical clock was the introduction of a regular, repetitive, precise, and common signal for the urban society that could be used for all types of signaling purposes. In this way, the multiplicity of signals, which in some cities reached their limits by the late Middle Ages and created chaos rather than order, could be replaced by one abstract signal.

Finally, the remaining question that needs to be answered is how the clock affected the daily life of the population and was transformed into higher economic output. Clocks had an effect on the organization and coordination of daily life activities with respect to economic, administrative and educational tasks. There exists broad evidence from the 15^{th} century onwards that the public clocks were used to coordinate such activities in many cities (Dohrn-van Rossum (1996)). The organization of markets neatly documents this change. Whereas prior to public clocks, the market time typically started with sunset and ended at noon, with the introduction of clocks, market times were deter-

[6] The use of water clocks can only be documented in a few sources in ancient Europe. There are references for ancient Rome, but the clock was likely calibrated based on the length of the day. Furthermore, we have some evidence that such mechanisms potentially existed in the neighboring Arabic world in the form of water clocks, which produced regular repeating sounds. However, according to the source material available, these machines were rather automates for entertainment and admiration. Finally, it is documented that medieval monasteries used water clocks.

[7] For a more detailed discussion of the quantification of this improvement, see Cipolla (1967).

mined by the stroke of the hour. Furthermore, market time was shortened and market access was granted to different groups of people at different times. For instance, market regulations offered time-differentiated access to consumers, retailers, and wholesalers, and in some cases, a differentiation between foreigners and locals or religious groups was made. Furthermore, we find evidence for the tight organization of administrative meetings of town officials following the signals of the public clock. Finally, schools and universities started using the public clocks to determine the starting and ending time of lectures. There were several economic benefits of such improvements of organization and coordination. First, the precise public indication of time reduced the urban populations search, match, and waiting time. This enabled people to better plan activities and have more time to do other tasks. In this sense, the clock is an information technology that improves coordination and reduces transaction time, as discussed by Hayek (1945). However, it could also improve the coordinating task itself. The concentration of the market time created thicker markets and could improve the allocation quality between the demand and supply sides. The precise separation of different groups of buyers and sellers allowed towns to create a more powerful market policy. Towns particularly intended to avoid commodity hoarding and speculation. A precise meeting time in markets, the town hall, or educational institutions could create better human capital spillover effects within the meeting groups. The division of education into single hours allowed to create schedules with alternating easier and more difficult subjects, making the learning experience more productive.

Furthermore, clocks enabled the coordination and monitoring of production activities by (Landes (1983) and Dohrn-van Rossum (1996)). The public clock created an "objective" measurement for the employer and employee or any cooperative group of productive agents. Whereas the use of church clocks and special work clocks as signaling devices had previously been used to determine the starting and ending time of the day for specific working groups, the public mechanical clock could now precisely measure the working time and breaks and enable payment by the hour or the payment of overtime hours. The public mechanical clock was particularly introduced for simple tasks, for which monitoring and payment by the hour were meaningful. For instance, Landes argues that it must have been particularly useful in the booming textile "industry" of the time. Another well-documented sector was large construction sites, such as those for domes or cathedrals, where many workers had to be coordinated and monitored at the same time. More differentiated uses of time to precisely define and synchronize work tasks evolved over time. The late 17^{th} century law book of the "Crowley Ironworks",

the biggest ironwork in Europe at that time, further illustrates this development (Thompson (1967)).

However, the use of the clock as a control function did not automatically translate into measures to increase productivity. In a dispute between different guilds in late 14^{th} century France, the public clock was used to coordinate working activities to restrict working time to limit the amount of output produced and create less competition (Fagniez (1877)). This example shows that the use of the clock as a productivity supporting device is related to the work culture of a society. Thompson (1967) documents how the work culture indeed changed over time. Based on case studies, he shows that after the implementation of the clock, a new perception of work discipline evolved slowly and gradually. Building on Thompsons insights, Glennie and Thrift (1996, 2009) develop this perspective further and argued that along with the implementation and the further development of the clock a new culture of work coordination, regularity, and repetition evolved. In a different strand of research McClelland (1961) finds empirical evidence for a developing "achieving society" during the early modern times. Further supporting evidence for such a change can be found in the cultural movements of the 16^{th} and 17^{th} centuries (Macey (1979) and Wendorff (1980)). Protestantism of the 16^{th} century identified time as a scarce product that had to be used wisely to achieve moral values and goals during individuals worldly life (Engamarre (2009)). Seventeenth century scientists and philosophers such as Robert Boyle and Thomas Hobbes used the clock as a metaphor for the functioning of the world and to explain how institutions, such as the state, should work. Finally, this broad penetration can also be reflected in wealthy peoples acquisition of home clocks and watches during the 16^{th} and 17^{th} centuries, which was triggered by the early implementation of public clocks during the 14^{th} and 15^{th} centuries (Cipolla (1967)).

This short presentation of the application of the clock in a broad range of sectors and areas, with an impact on the economic and social structure of the society, clearly indicates that the closck is a GPT (Bresnahan and Trajtenberg (1995) and Comin, Easterly, and Gong (2010)). In addition, it is important to mention that the technology was not for production and the application was not dependent on the local geographic amenities. Thus, this technology can be compared, for instance, with modern computers.

2.4 Distance and solar eclipses as instruments

In our empirical analysis, we will use two types of instruments. The distance from the first adopters and solar eclipses. The use of an instrument is valid if it correlates with the explanatory variable (in our case, the clock) but is not related to the dependent variable, the growth rate in terms of the city population size or the estimated GDP of a country. In this section, we aim to support this claim by historical narratives and stylized facts. Further quantitative evidence will be provided later.

As previously outlined, the adoption of mechanical clocks occurred in a few cities in a first wave in different regions in Europe. Then, diffusion in these and neighboring regions can be observed. The diffusion pattern can be explained by the fact that only a few experts had clock making skills. These clock makers traveled from city to city to sell their expertise by building mechanical clocks, and their expertise was shared slowly (Cipolla (1967), Landes (1983) and Dohrn-van Rossum (1996)). Thus, the likelihood of the implementation of a clock in a town depended on distance from one of the first adopters. However, this distance is not endogenous to the growth rate of a city before the implementation of the clock. We later show this empirically in the regression analysis. Thus, we can follow an established research methodology that has been used in related empirical historical studies (for instance, see Becker and Woessmann (2009) and Dittmar (2011)).

The use of solar eclipses as an instrument for the implementation of public mechanical clocks requires a more detailed two-step analysis. The observation and documentation of the course of the celestial bodies and specific astronomic events date back to ancient times (Lindsay (1858) and Steele (2000)). Solar eclipses have elicited a special fascination. They could be observed by everyone, and due to their rare appearance, they were perceived as sudden and irregular events. Furthermore, coincidental political and religious events created curiosity and speculation on the origin and causal relations of these astronomic phenomena. For instance, the death of the son of Mohamed in 632 and the death of the emperor Louis and the Treaty of Verdun in 840 coincided with solar eclipses. In another example, in one of the Gospels, the evangelist Luke reports a total solar eclipse during the crucifixion of Jesus. To study these heavenly bodies and astronomic events, various instruments were developed and applied. In particular, so-called astrolabes were developed, which date back to Ancient times and were transmitted from the Arabs to medieval Europe (Turner (1911)). An astrolabe was

able to measure and simulate astronomic constellations and to measure time in equinoctial hours.[8] Furthermore, the sun and, in particular, water clocks were used to measure astronomic activities. The creation of advanced astronomic water clocks can be particularly observed in China, where astronomic water clocks were constructed by the Middle Ages. In Europe, water clocks can be observed in medieval monasteries, where they were also used to study astronomy. Therefore, we can establish a link between the observation of astronomic events and the creation of instruments and basic machines to measure these events. The use of solar eclipses not only appears to be a strong motivation for the development of intellectual curiosity and astronomic instruments but also enables us to separate Europe into both areas with and without eclipses and, consequently, areas with a stronger and weaker motivation to study astronomy. The second link is between astronomic instruments and the development of public mechanical clocks. Cipolla (1967) states that medieval scholars were only interested in the development of machines that were related to astronomy. Cipolla takes the clock as a prime example of such a machine. Whereas the precise sequence and evolution from earlier clocks and astronomic instruments to the creation of public mechanical clock have been widely debated, there are no doubts that a clear correlation can be established, which was outlined in Section 2.1. Consequently, we can use the appearance of solar eclipses via the curiosity, invention and application of related astronomic machines as an instrument for the implementation of public mechanical clocks. More precisely, we consider regions and cities where solar eclipses appeared as places with a higher likelihood of building clocks.[9]

3 Data

This section contains an overview of the city- and country-level variables considered in the empirical analysis. Tables A.1 and A.2 in Appendix A contain the descriptive statistics of these variables.

We collect the presence and the year of adoption of public mechanical clocks during the period of

[8] The places where these astrolabes were found in Europe (King (2011)) seem to overlap with areas where solar eclipses frequently appeared. However, due to the fragmented nature of the source material, further quantification is not possible

[9] The reader might wonder why we use cities and regions rather than the location of monasteries as the crucial geographical point and connection. First, we are interested in the implementation of public mechanical clocks in cities and their related growth path. Second, most medieval cities that we study had at least one monastery inside their town walls and all of them had one in their immediate neighborhood. Finally, in some monasteries, there existed opposition against the study of astronomy because it was not willed by God. Therefore, the use of cities as geographical loci of potential human capital accumulation and adapters of the clock can be justified.

our analysis mainly from four different sources: Bilfinger (1892), who analyzes the introduction of city clocks in France, Germany, England and Italy; Ungerer (1931), who provides a list and description of mechanical clocks in Europe; Dohrn-van Rossum (1996), who historically describes the adoption process, and Glennie and Thrift (2009), who concentrate their attention on the use of time in England. This initial dataset is integrated with an additional and non-published list provided to us by Dohrn-van Rossum with other information from other sources (e.g., Cipolla (1967) and Landes (1983)). In addition, when possible, we confirm the date of adoption with the original historical sources. Our final list contains 182 clocks adopted between 1283, the date of adoption of the first mechanical clock in Dunstable, England, and 1450, when it is assumed that the period of yearly adoption concluded.[10] Table 1 displays, at country level the aggregate number of clocks adopted, the number of cities with more than 5,000 inhabitants in 1500, and the percentage of adoption, computed as the ratio of the first two columns.[11] We can observe the adoption rate has an average of 20%, covering both areas with low diffusion (e.g., Spain with 3%) and more intense adoption (Switzerland with 90%).

Table 1: The Diffusion of the Mechanical Clock in Europe before 1450.

Country	**Cities adopting the clock**	**Cities available in Bairoch in 1400**	**Percentage of adoption**
Austria	1	8	13
Belgium	14	33	42
Czechia	1	5	20
France	27	74	36
Germany	45	301	15
Italy	39	101	39
Malta	1	2	50
Netherlands	13	35	37
Poland	5	19	26
Spain	8	262	3
Sweden	8	18	44
Switzerland	10	11	90
Ukraine	1	2	50
United Kingdom	9	60	20
Total (all sample)	**182**	**931**	**20**

Source: Authors' calculation based on the clock's dataset.
Population data drawn from Bairoch, Batou, and Chevre (1988) and Malanima (1998).

In addition, we collect population data from Bairoch, Batou, and Chevre (1988) and De Vries (1984)

[10]In addition, we build a more extended list to 1600 to compute the penetration rate at the country level.

[11]In Section 7, we compute the penetration rate weighted by the population.

and integrate those data with Italian data from Malanima (1998). The union of these sources allows us to consider the population in all cities with more than 5,000 inhabitants for seven periods (i.e., 1200, 1300, 1400, 1500, 1600, 1700, and 1800). Following De Long and Shleifer (1993) and Acemoglu, Johnson, and Robinson (2005b), we assume that population is a good proxy for urban income because data on urban GDP are not available before 1500. We do not have precise information on population before 1100 and, thus, use the five-folded classification provided by Nuessli (2011). We also identify the capital of each country by century. We proxy this variable as the most populated city at the time.

Furthermore, we can construct a measure of productivity at a more aggregated level, considering GDP per capital measured in 1990 PPP International Dollars and the total population of 8 countries (Austria, Belgium, Denmark, Finland, France, Germany, Italy, Sweden, Switzerland, and United Kingdom) from Maddison (2007) and Colin and Jones (1978), respectively.

Data on the geographical positions (longitude and latitude) of cities, the locations of both big and small rivers and the presence of cities on sea coasts, and altitude are derived by Colin and Jones (1978), Nuessli (2011), Nunn and Puga (2011) and historical and geographical atlases. Data on Atlantic and Mediterranean port are taken from Acemoglu, Johnson, and Robinson (2005a). We construct our own data on ports related to the Baltic area, based on different geographical and historical atlases.

In terms of institutional settings, we consider two different sets of variables: one set related to the freedoom of institutions and one related to the presence of universities. Freedom data are taken from De Long and Shleifer (1993). The variable takes the value of one if the institutions were relatively free and zero if, instead, they were ruled by an autocratic prince. Information on the opening of university sites in Europe are taken from the composition of three different sources, i.e., Sheperd (1911), Darby (1970), and Verger (1992).

3.1 Instrumental variables

The data on solar eclipses are taken from the National Aeronautics and Space Administration (NASA) website.[12] We consider both total and annular solar eclipses: during a total solar eclipse, the sun is completely obscured by the moon, while during annular eclipses, the moon seems smaller than the sun. Table 2 shows the entire list of eclipses that have covered the European area from 800 to 1200.

[12]Espenak (2015), website:`http://eclipse.gsfc.nasa.gov/eclipse.html`

We consider the land territory in Europe[13] (reported in bold in the table) following two criteria, which can be rationalized based on the intensity of the perception of the eclipses. First, the geographical area should be overlapped by the umbral pattern of at least two eclipses within 100 years during the period 800-1284, the year of the first adoption of the mechanical clock.[14] Second, the eclipse should last more than one minute. Figure 3 displays the umbral pattern of both total and anular eclipses and the main town and city centers during the IX, X, XI, and XII centuries. The yellow color highlights the areas where the eclipses overlap. In addition, Figure 4 compares the above-mentioned areas in Europe with more than one total or anular solar eclipse, the main population areas with (in black) and without (in grey) mechanical clocks. In addition, in this figure. we can see a relationship between the astronomical events and the adoption of the new technology.

As an additional instrument, we consider distance from the first innovators. These measures are computed using GIS data from Nuessli (2011) using the nearest neighbor analysis technique. The maps on the upper part of Appendix A display the cities that are considered the first innovators.

[13]Unfortunately, for the period 800-1000 we do not have detailed data on population level from Bairoch, Batou, and Chevre (1988). We consider instead the classification contained in Nuessli (2011), who ranks the populated centers in five different categories according to their importance. We considered the centers enlisted in the two most important categories.

[14]We do not observe any relevant overlapping eclipse activities during the period of 600-800.

Table 2: Total and Anular Eclipses during the Medieval Period in Europe.

Date	Type	Duration in Seconds
May 5^{th}, 840	**Total**	**346**
March 3^{rd}, 852	**Anular**	**313**
October 29^{th}, 878	**Total**	**110**
August 8^{th}, 891	**Anular**	**342**
July 19^{th}, 939	**Total**	**342**
May 17^{th}, 961	**Anular**	**114**
December 22^{nd}, 968	**Total**	**148**
October 21^{th}, 990	Anular	489
January 24^{th}, 1023	Total	180
June 29^{th}, 1033	Anular	0.4
August 22^{nd}, 1039	Anular	0.1
April 19^{th}, 1064	Anular	238
February 16^{th}, 1086	**Total**	**288**
September 23^{rd}, 1093	Anular	123
December 25^{th}, 1098	**Anular**	**533**
May 31^{st}, 1109	Anular	311
August 11^{th}, 1124	Total	199
August 2^{nd}, 1133	Total	278
October 26^{th}, 1147	Anular	251
January 26^{th}, 1153	**Anular**	**413**
September 13^{th}, 1178	Total	238
May 1^{st}, 1185	Total	310
September 4^{th}, 1187	Total	245
June 23^{rd}, 1191	Anular	268
November 27^{th}, 1201	Anular	376
February 28^{th}, 1207	**Anular**	**272**
June 3^{rd}, 1239	Total	318
October 6^{th}, 1241	**Total**	**218**

Source: Espenak (2015). The eclipses marked in bold are the ones selected for constructing our instruments.
Section 4 contains the criteria for our selections.

Figure 3: Total and Anular Solar Eclipses during IX, X, XI and XII century. Source: Authors' calculation using Nuessli (2011)'s and Espenak (2015)'s data.

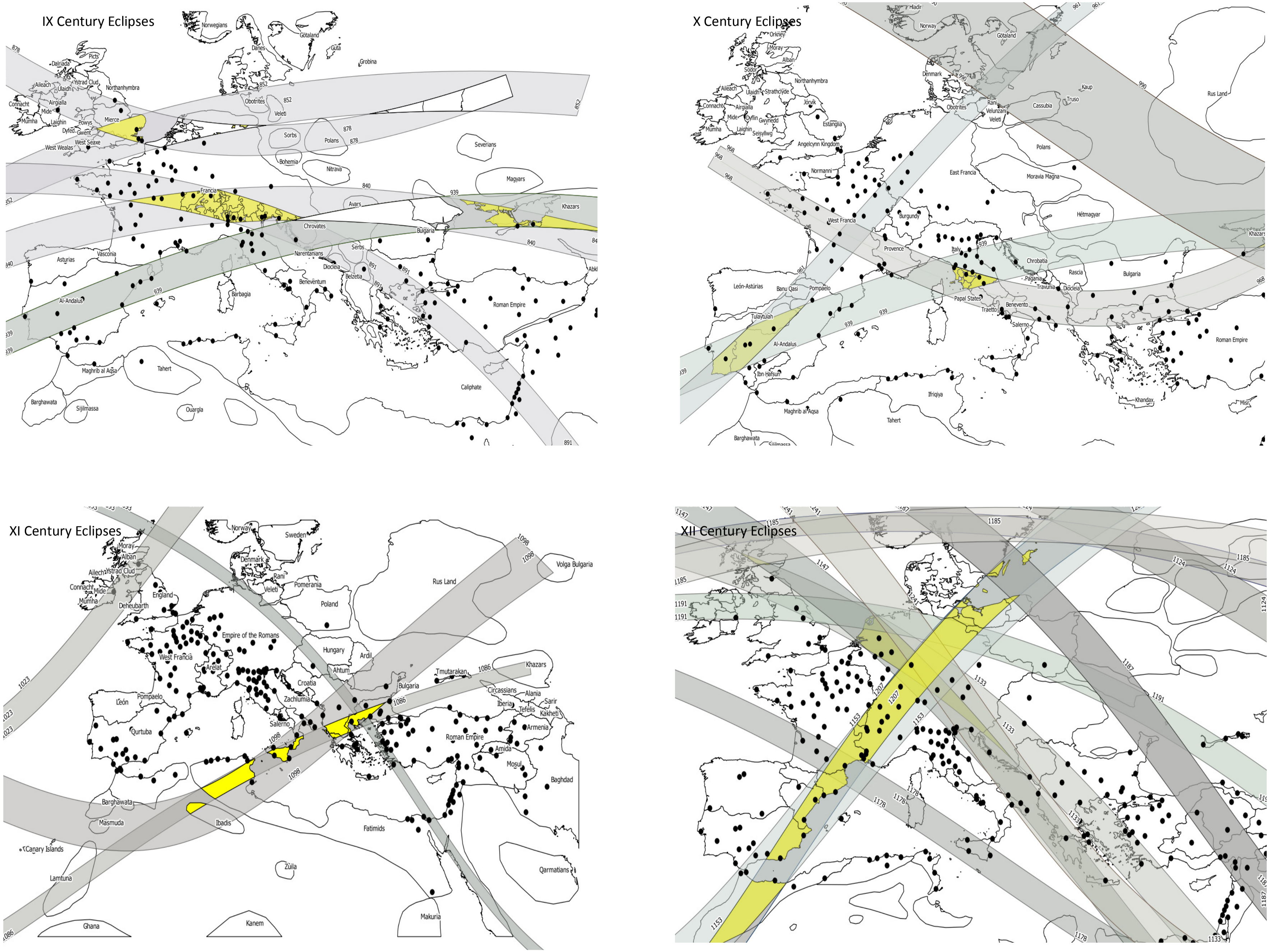
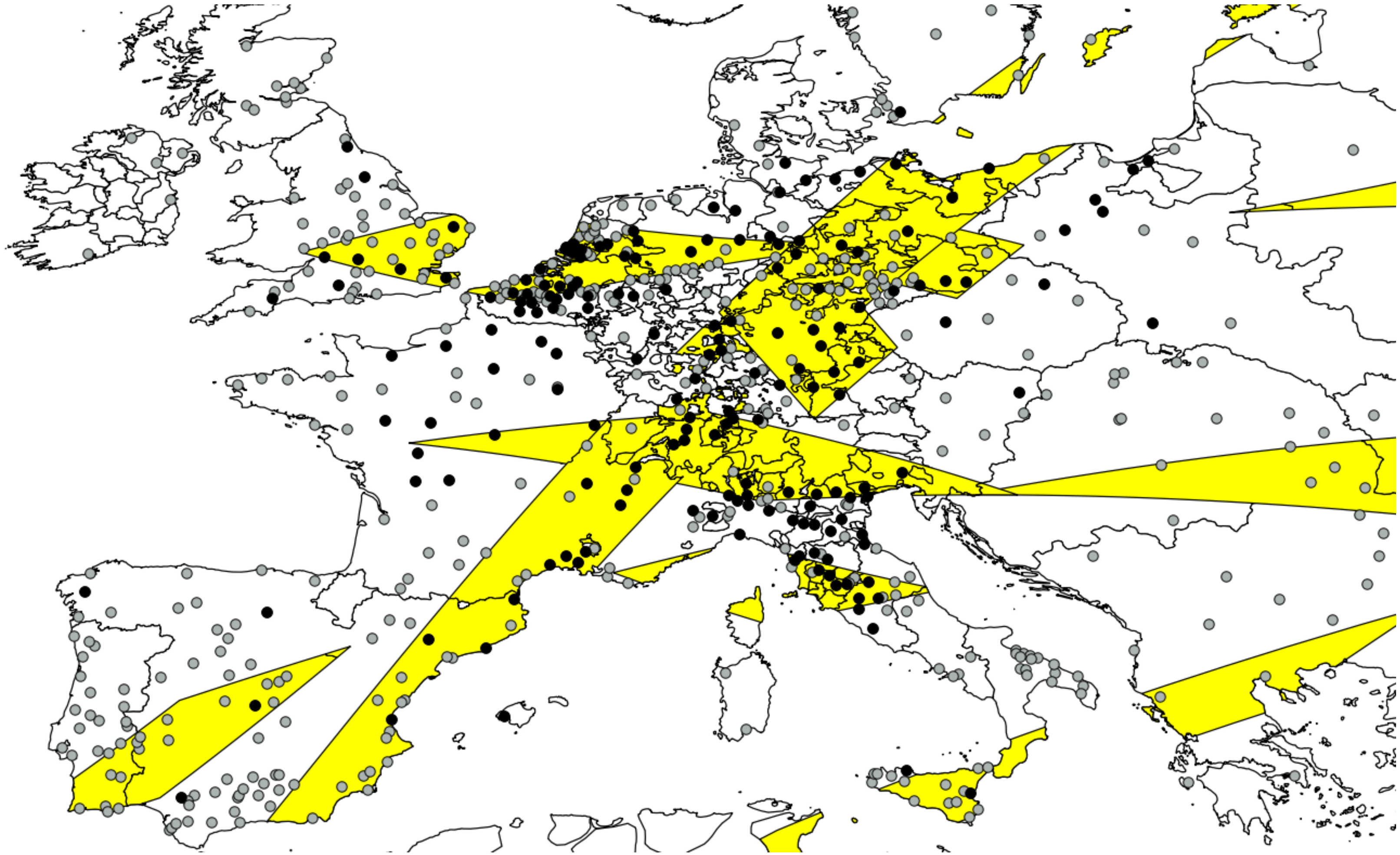


Figure 4: Area in Europe with more than one total or anular solar eclipse.



4 Empirical strategy

In this section, we test whether the early adoption of the clock has an impact on cities population growth. As a starting point, we use the classical equation formula derived by Mankiw, Romer, and Weil (1992), whose original formula is considered in the last part of the empirical exercise, where economic growth is explained by a set of variables related to the input of production and human capital and the initial economic condition of the period studied (Barro (1991)). In our case, given the information available for the empirical exercise, we consider a modified version of the standard econometric growth equation, i.e.,

$$\Delta Pop_{itx} = \beta_0 + \beta_1 CLOCK_i + \beta_2 X_{it} + \beta_3 \ln Pop_{i0} + \epsilon_{it} \tag{1}$$

where for each city i and time $t = 1400, 1500, 1600, 1700, 1800$ and $x = t-100, t-200, t-300, t-400$, $CLOCK$ is a dummy that takess value equal to 1 if the city has adopted a mechanical clock before 1450, and 0 otherwise, Pop is the level of population, $\Delta Pop_{it-x} = \ln\left(\frac{Pop_{it}}{Pop_{ix}}\right)$, $\ln Pop_{i0}$ is the initial level of population, and X is a set of control variables described in the previous section. In particular, we consider a set of institutional variables, such as the presence of a university ($university$) in the city, whether the city was the largest in the country during the century considered (*capital*), and whether the institutions were free ($freedom$). In addition, we consider several geographical variables, i.e., the presence of either a small or big river (*small river* and *big river*, respectively), whether the city was located on a sea coast (*sea*) and whether the locality was a Mediterranean (*mediterranean port*), Atlantic (*atlantic port*) or Baltic (*baltic port*) port after 1500 according to Acemoglu, Johnson, and Robinson (2005a)), the elevation of the city (*elevation*) and the geographical location of the city according to the longitude and the latitude.

The OLS estimates of (1) are reported in Table 3. To study the long run effects, we consider six different intervals of time: 1200-1300, 1300-1400, 1400-1500, 1500-1600, 1500-1700, and 1500-1800. We consider the initial populations of 1200, 1300, and 1400 for columns (1), (2), and (3), respectively. The other columns consider has starting population the one measured in 1500.[15] We assume that a mechanical clock has an impact during a century if it is adopted for more than 50 years.

[15]We also run regressions considering population in 1300 for columns (2)-(6), obtaining similar results. Output available upon request.

Column (1), which considers a century growth rate for which the clocks have no impact, displays the placebo exercise, rejecting the hypothesis that cities that had adopted the new technology were already following an independent growth pattern. In column (2), instead, we check whether cities introducing a public mechanical clock during the first phase, i.e., during the period of 1280-1350, had an impact on growth during the following century: in this case, as in columns (3) and (4), we do not observe any effects. On the other side, the coefficients based on the introduction of the mechanical clock display both positive and significative results for the periods of 1500-1700 and 1500-1800, suggesting a positive effect of new technology on population growth in the long run. Finally, similar to the findings of other contributions in the literature (e.g., Acemoglu, Johnson, and Robinson (2005a) and Dittmar (2011)) our findings indicate that other geographical and institutional variables have a relevant effect on population growth, e.g., the presence of a university and a port improve the population growth.

Table 3: The effect of mechanical clock on population growth: OLS Regressions

	Dependent variable:					
	(1)	(2)	(3)	(4)	(5)	(6)
	$\Delta Pop_{1200-1300}$	$\Delta Pop_{1300-1400}$	$\Delta Pop_{1400-1500}$	$\Delta Pop_{1500-1600}$	$\Delta Pop_{1500-1700}$	$\Delta Pop_{1500-1800}$
CLOCK	0.13	-0.02	0.03	0.10	0.29***	0.28***
	(0.08)	(0.15)	(0.09)	(0.07)	(0.07)	(0.09)
university	0.33	0.30	0.02	0.19***	0.33***	0.32***
	(0.29)	(0.16)	(0.05)	(0.04)	(0.07)	(0.11)
capital	0.23**	0.18	0.19	0.03	0.12	0.12
	(0.08)	(0.15)	(0.12)	(0.10)	(0.18)	(0.19)
freedom	0.26	0.07	-0.11	0.56***	0.84***	0.64***
	(0.38)	(0.27)	(0.28)	(0.07)	(0.10)	(0.08)
$ln\ Pop_0$	-0.39***	-0.18***	-0.28***	-0.24***	-0.36***	-0.53***
	(0.13)	(0.04)	(0.04)	(0.06)	(0.07)	(0.06)
sea	0.51***	-0.24***	-0.00	-0.11	0.15	0.17
	(0.15)	(0.07)	(0.18)	(0.15)	(0.17)	(0.19)
big river	0.09	0.15	0.13	0.09	0.08	-0.00
	(0.20)	(0.21)	(0.10)	(0.19)	(0.18)	(0.15)
small river	-0.03	-0.01	0.01	-0.15***	-0.20***	-0.17**
	(0.16)	(0.11)	(0.09)	(0.04)	(0.06)	(0.06)
mediterranean port	0.20	0.23**	0.22	0.22*	0.28***	0.28
	(0.21)	(0.09)	(0.21)	(0.12)	(0.09)	(0.22)
atlantic port	0.17	0.35***	-0.07	0.44***	0.64***	0.93***
	(0.33)	(0.10)	(0.22)	(0.14)	(0.20)	(0.18)
baltic port	-0.14	0.28*	-0.01	0.38*	0.31	0.00
	(0.23)	(0.15)	(0.23)	(0.21)	(0.20)	(0.22)
elevation	0.01	0.02	0.01	-0.01	-0.07**	-0.06
	(0.05)	(0.02)	(0.03)	(0.02)	(0.02)	(0.04)
constant	2.14	1.01	3.61***	2.53***	5.19**	5.63***
	(2.23)	(1.46)	(1.20)	(0.84)	(1.93)	(1.48)
R^2	0.44	0.21	0.22	0.23	0.31	0.41
N. of observations	118	274	292	471	491	588

Country fixed effect, *longitude*, *latitude*, and $longitude * latitude$ included.
Heteroskedasticity-robust standard errors are clustered at the country level.
$ln\ Pop_0$ is referred to year 1200 in column (1), 1300 in column (2), 1400 in column (3),and 1500 in other columns.
Significance at the 90%, 95%, and 99% confidence levels are indicated by *, **, and ***, respectively.

The OLS results displayed in Table 3 might be affected by several biases. First, reverse causality can be problematic. Endogeneity issues of the variable $CLOCK$ on the dependent variable can arise because cities' growth may drive the early adoption of the mechanical clock. In addition, equation (1) can be mispecified: institutional and other city characteristics (e.g., cities' policies and institutional quality), which are not observable, might also play a role. Finally, the historical variables we use in the specification might be affected by measurement errors.

For these reasons, we consider a two-stage-least-squares (2SLS, henceforth) model based on two different equations:

$$CLOCK_i = \alpha_0 + \alpha_2 \ln DISTANCE\ FIRST_i + \alpha_2 \sum ECLIPSE_i^j + \alpha_3 \tilde{X}_i + \alpha_4 \ln Pop_{1300,i} + u_i \quad (2)$$

and

$$\Delta Pop_{itx} = B_0 + B_1 \widehat{CLOCK}_i + B_2 \tilde{X}_i + B_3 \ln Pop_{1300,i} + E_{it} \quad (3)$$

where $DISTANCE\ FIRST_i$ is the distance, measured in kilometers, from the first adopters, i.e., the cities that introduced a mechanical clock during the period of 1280-1350, $ECLIPSE_i^j$ is a dummy that takes the value of one if the city is covered by one of the combination of j eclipses and zero otherwise, $\widehat{CLOCK}_i$ is the predicted adoption obtain by the estimates of (2), and $\tilde{X}_i$ is a set of geographical and institutional controls, measured before 1300, and also used in equation 3. We consider two different types of strategies. One strategy is that use of a 2SLS estimation with an OLS estimation in the first stage. Alternatively, a second procedure is inspired by Angrist and Pischke (2008), where, instead of using the nonlinear fitted values in the second stage, we use this prediction as an instrument.[16]

Table 4 provides the estimates both considering a linear probability model (LPM) and a different set of logit estimates ($LOGIT$). The use of the logistic distribution is motivated by the best representation of the S-shape curve of adoption, as in Geroski (2000). While the LPM displays significant signs for both distance from the first adopters and eclipses, the logit estimate suggests that the astronomical events play a more relevant role in the adoption of clocks.[17] In addition, we can observe that the

[16] A third case, also known as "forbidden regression" (see, e.g., Angrist and Pischke (2008)), based on a non-linear estimation of (2), is not consistent (Greene (2011).

[17] The variables *eclipses* $1133 - 1147$ and *eclipses* $1153 - 1207$ do not appear in the last specification because they perfectly predict the adoption of the clock.

size of the city; the presence of a river, especially small rivers; and the presence of a university in 1300 have positive effects in explaining the adoption of the new technology, while sea has a negative sign. Finally, similar to the findings of Caselli and Coleman (2001), who show that the adoption of computers in OECD countries is positively associated with the level of human capital, we note that the presence of a univeristy in a city increases the probability that a public mechanical clock is introduced.

Table 5 displays the second stage of the IV regression with the variable $\widehat{CLOCK}_i$ predicted using column (1) of Table 4. The results are very similar to those obtained by the OLS estimates, especially for the positive and significant effects of the mechanical clock on population growth between 1500 and 1700, confirming the delay of the benefits of the technological adoption. In addition, different sets of tests confirm the different effects of mechanical clocks on population growth. First, the F test largely rejects the hypothesis that our set of instruments is weak. In addition, the Hausman test rejects the hypothesis of endogeneity of clocks, confirming the historical insight that the early adoption of clocks is not driven by economic growth but by other factors such as prestige.[18]. Finally, the Sargan test rejects the hypothesis of overidentification of the instruments in all five specifications.[19]

An alternative to the instrumental variable technique is to consider a linear regression with endogenous treatment effects (Angrist and Pischke (2008)). In our case, we follow the procedure suggested by Adams, Almeida, and Ferreira (2009), which is based on three stages. In practice, first, we consider the estimation of the logit model in column (2) of Table 3; second, we compute the fitted probabilities $\widehat{CLOCK}$; and finally, we estimate the population growth using $\widehat{CLOCK}$ as an instrument.[20] In this case, we find that mechanical clocks have positive and significant effects on population growth.

[18]In addition, the coefficients of Table 5 are very similar those obtained by OLS regressions using the same controls and the dummy $CLOCK$, confirming the exogeneity of the variable

[19]We also examine whether our set of instruments had an influence on population growth before 1400. A simple OLS regression displays non significant impacts of the instruments. Output available upon request.

[20]We also run a standard linear regression model using the Stata command *etregress*, obtaining similar results. The main difference is that a probit is run in the first stage. Output available upon request.

Table 4: Determinants of clock adoption: First stage of 2SLS regression.

Dependent Variable: *CLOCK*				
	(1)	(2)	(3)	(4)
	LPM	*LOGIT*		
ln *distance*	-0.01***		-0.34	-0.75
	(0.00)		(0.40)	(0.71)
eclipses 840 − 891	0.20		-0.33	0.74
	(0.16)		(0.45)	(0.98)
eclipses 852 − 878	0.04		-0.48	-1.05
	(0.08)		(0.81)	(0.71)
eclipses 840 − 939	0.01		.	.
	(0.14)		.	.
eclipses 861 − 939	-0.05		0.60**	0.45
	(0.11)		(0.29)	(0.33)
eclipses 939 − 968	0.26***		0.52	2.92***
	(0.08)		(0.42)	(0.96)
eclipses 1086 − 1098	-0.06		-0.32	-0.44
	(0.08)		(1.26)	(1.52)
eclipses 1133 − 1147	0.20***		-0.06	-0.78
	(0.05)		(0.35)	(0.48)
eclipses 1153 − 1207	-0.32***		.	.
	(0.11)		.	.
same state 1200				-4.11***
				(1.00)
same state 1300				-2.01
				(1.65)
ln Pop_{1300}	0.16***	1.05***	1.24***	1.38***
	(0.04)	(0.19)	(0.36)	(0.48)
university 1200				-1.87***
				(0.52)
university 1300	0.09	0.86**	0.84	1.81***
	(0.08)	(0.35)	(0.58)	(0.50)
capital 1200				0.44
				(0.62)
capital 1300	0.04	0.19	-0.08	-0.86
	(0.11)	(0.52)	(0.72)	(0.84)
freedom	0.06	0.22	1.05	0.42
	(0.12)	(0.67)	(2.08)	(1.94)
sea	-0.11*	-0.88**	-0.41	0.00
	(0.06)	(0.36)	(0.53)	(0.71)
bigriver	0.19	1.89**	0.96	1.77
	(0.16)	(0.87)	(1.43)	(1.10)
smallriver	0.16***	1.13***	0.89***	1.00***
	(0.05)	(0.31)	(0.30)	(0.18)
elevation	-0.01	-0.06	0.01	-0.10
	(0.02)	(0.15)	(0.23)	(0.21)
constant	-1.92**	-18.64***	-29.48***	-21.98***
	(0.88)	(4.43)	(5.88)	(7.89)
R^2	0.28	0.24	0.37	0.54
N. of observations	297	297	252	252

Country fixed effect, *longitude*, *latitude*, and *longitude* $*$ *latitude* included.
Significance at the 90%, 95%, and 99% confidence levels are indicated by *, **, and ***, respectively.

Table 5: The effect of mechanical clock on population growth: IV Regressions

	Dependent variable:				
	(1)	(2)	(3)	(4)	(5)
	$\Delta Pop_{1300-1400}$	$\Delta Pop_{1400-1500}$	$\Delta Pop_{1500-1600}$	$\Delta Pop_{1500-1700}$	$\Delta Pop_{1500-1800}$
$\widehat{CLOCK}$	-0.05	0.27	0.17	0.32**	-0.24
	(0.20)	(0.17)	(0.11)	(0.13)	(0.17)
$university$	0.45***	-0.12	0.24***	0.33**	0.49***
	(0.10)	(0.16)	(0.07)	(0.13)	(0.11)
$capital$	0.18*	-0.13*	0.22**	0.25***	0.23**
	(0.10)	(0.08)	(0.09)	(0.09)	(0.11)
$freedom$	0.11	0.09	0.03	0.03	-0.24
	(0.14)	(0.07)	(0.11)	(0.18)	(0.16)
$ln\ Pop_{1300}$	-0.21***	-0.18***	-0.19***	-0.31***	-0.28***
	(0.04)	(0.05)	(0.05)	(0.06)	(0.06)
sea	0.01	-0.03	0.04	0.38***	0.27**
	(0.11)	(0.12)	(0.10)	(0.10)	(0.12)
$big\ river$	0.28*	0.02	-0.11	-0.40**	-0.40**
	(0.17)	(0.11)	(0.14)	(0.18)	(0.17)
$small\ river$	0.00	-0.09	-0.14**	-0.25***	-0.10
	(0.11)	(0.11)	(0.06)	(0.09)	(0.11)
$elevation$	0.03***	-0.03	-0.02	-0.07**	-0.07
	(0.01)	(0.03)	(0.02)	(0.03)	(0.05)
$Constant$	1.06	2.19***	2.35***	2.98***	2.08
	(0.71)	(0.76)	(0.84)	(1.13)	(1.41)
R^2	0.12	0.06	0.10	0.20	0.22
$F\ test$	9.46***	9.69***	11.05***	9.91***	11.30***
$Hausman\ test$	0.04	0.23	0.28	0.15	0.17
$Sargan\ test$	0.09	0.21	0.24	0.31	0.09
N. of observations	274	228	288	293	330

longitude, *latitude*, and $longitude * latitude$ included.
Heteroskedasticity-robust standard errors are clustered at the country level.
p-values reported for Hausman and Saragn test
Significance at the 90%, 95%, and 99% confidence levels are indicated by *, **, and ***, respectively.

Table 6: The effect of mechanical clock on population growth: Linear regression with endogenous treatment effects

	Dependent variable:				
	(1)	(2)	(3)	(4)	(5)
	$\Delta Pop_{1300-1400}$	$\Delta Pop_{1400-1500}$	$\Delta Pop_{1500-1600}$	$\Delta Pop_{1500-1700}$	$\Delta Pop_{1500-1800}$
CLOCK	0.21	-0.08	0.21*	0.40**	0.26
	(0.17)	(0.16)	(0.13)	(0.19)	(0.20)
university 1200	-0.07	0.04	0.34	0.49	0.26
	(0.33)	(0.29)	(0.22)	(0.34)	(0.38)
university 1300	0.61**	-0.20	0.06	0.08	0.24
	(0.24)	(0.21)	(0.16)	(0.23)	(0.26)
capital	0.08	-0.09	0.16*	0.29**	0.32**
	(0.11)	(0.10)	(0.08)	(0.12)	(0.13)
freedom	-0.01	0.28	-0.04	-0.01	-0.37
	(0.32)	(0.27)	(0.22)	(0.33)	(0.38)
$ln\ Pop_{1300}$	-0.31***	-0.11**	-0.18***	-0.35***	-0.37***
	(0.06)	(0.05)	(0.04)	(0.06)	(0.07)
big river	0.22	0.04	-0.08	-0.28	-0.32
	(0.19)	(0.17)	(0.14)	(0.20)	(0.22)
small river	0.03	0.00	-0.15**	-0.28***	-0.20*
	(0.10)	(0.10)	(0.07)	(0.11)	(0.12)
sea	-0.05	0.10	0.09	0.30**	0.20
	(0.11)	(0.11)	(0.09)	(0.13)	(0.15)
elevation	0.02	0.01	-0.04	-0.10**	-0.10**
	(0.03)	(0.03)	(0.03)	(0.04)	(0.04)
Constant	1.16	1.22	2.39**	6.01***	5.17***
	(1.32)	(1.22)	(0.94)	(1.43)	(1.57)
R^2	0.18	0.18	0.16	0.29	0.31
N. of observations	232	185	236	241	268

longitude, *latitude*, and $longitude * latitude$ included.
Heteroskedasticity-robust standard errors are clustered at the country level.
Significance at the 90%, 95%, and 99% confidence levels are indicated by *, **, and ***, respectively.

5 Robustness checks

Similar to the approach adopted by Dittmar (2012), we construct a generalize difference-in-difference regression[21] as follows

$$\ln\left(\frac{POP_{ic,t}}{POP_{ic,t-100}}\right) = \theta_i + \omega_t + \sum_{\tau=1300}^{1700} \delta_{1,t} CENTURY_\tau CLOCK_{ic} + \delta_{2,t} CENTURY_\tau \tilde{\tilde{X}}_{ic} + \xi_{ict} \quad (4)$$

where θ_i and λ_t are time and city fixed effects, respectively; $CENTURY$ is a dummy equal to one if the observation belong to a particular century between 1300 and 1700, and 0 otherwise; and $\tilde{\tilde{X}}$ is a set of control variables. In particular, we consider whether the city is a Mediterranean or an Atlantic port and it is a capital. Other variables are not included because of perfect multicollinearity. Table 7 contains the estimates of the generalized difference-in-differences. In addition, in this case, we can observe an effect of the mechanical clock after 1600 for all samples (column (1)). We also control for the possibility that the results might be driven by particular location or geographical amenities. We exclude the cities located on the Baltic (column (2)), with big rivers (column (3)) and with all rivers in general (column (4)) from the sample. In all these cases, the effect of mechanical clocks in the later centuries remains positive and significant.[22]

[21]This approach is similar to a type of Granger-causality test (see, for example, Angrist and Pischke (2008).

[22]As an additional robustness check, we consider an estimation based on propensity score analysis in Appendix C.

Table 7: The effect of mechanical clock on population growth: Generalized Difference-in-Differences

Dependent variable: Population Growth				
	(1) All sample	(2) excluding Baltic cities	(3) excluding big rivers	(4) excluding all rivers
Clock 1400	0.19	0.17	0.21*	0.15
	(0.12)	(0.12)	(0.12)	(0.14)
Clock 1500	0.01	0.07	0.02	-0.12
	(0.12)	(0.12)	(0.12)	(0.14)
Clock 1600	0.20*	0.22*	0.21*	0.24*
	(0.12)	(0.12)	(0.12)	(0.14)
Clock 1700	0.21*	0.22*	0.23*	0.16
	(0.12)	(0.12)	(0.12)	(0.14)
atlantic 1500	-0.42*	-0.32	0.03	0.46**
	(0.22)	(0.22)	(0.20)	(0.21)
atlantic 1600	0.17	-0.11	0.13	0.11
	(0.22)	(0.23)	(0.20)	(0.21)
atlantic 1700	-0.16	-0.21	0.00	0.16
	(0.22)	(0.23)	(0.20)	(0.21)
mediterranean 1500	0.20	0.21	0.20	0.20
	(0.17)	(0.17)	(0.18)	(0.19)
mediterranean 1600	0.27	0.26	0.27	0.26
	(0.17)	(0.17)	(0.18)	(0.19)
mediterranean 1700	0.49***	0.50***	0.50***	0.47**
	(0.17)	(0.17)	(0.18)	(0.19)
capital	0.10	0.10	0.08	0.09
	(0.07)	(0.07)	(0.07)	(0.08)
Constant	-0.57**	0.49	0.17	0.53
	(0.29)	(0.59)	(0.53)	(0.68)
R^2	0.20	0.18	0.19	0.45
N. of observations	1010	910	955	705

Overall, these results show robust significant growth effects for the period of 1500-1700. Such results support the hypothesis that it took time for the clock to have an impact on economic growth rates. The observation of significant growth rates during the 16^{th} and 17^{th}centuries supports the conclusion that changes in work organization and work culture were needed to create growth effects. Thus, there must have been a nexus between a change in technology and work culture. In general, economists claim that it is normal for the application of a GPT to take awhile[23] Nevertheless, we might ask the question of why we cannot find significant effects in the 15^{th} century. Based on our historical analysis, it is likely that improvements in coordination could be achieved first. However, the clock mainly replaced earlier signaling devices, and further coordination gains were too small to be visible in the data. More importantly, these gains freed time. However, this time needed to be used and invested in new tasks, translating into higher growth numbers during the next century. Another question that arises is why we can observe correlation effects during the 18^{th} century but no causal effects. This result may be related to the wide diffusion of other time instruments, e.g., portable watches (Thompson (1967)), which might be triggered by precedent economic growth (which in turn depended on the implementation of mechanical clocks (Landes (1983))).

6 Analysis at the State Level

This section allows us to test whether the adoption of public mechanical clocks had a direct impact not only on growth of towns but also on productivity in wider geographical areas. Such an aggregate study can be motivated by the fact that we consider GDP per capita as a measure of the aggregate performances, allowing us to make better comparisons with the related research on recent economic impact of the information technology discussed in the introduction.[24] To test this, we take inspiration from the empirical framework introduced by Czernich, Falck, Kretschmer, and Woessmann (2011), who analyze the effect of internet broadband on economic growth in European countries. The estimation is based on two stages: in the first stage, we study and predict the rate of penetration of the mechanical clock at the country level; in the second stage, we estimate the factors that are important

[23]Several theoretical models, e.g., Jovanovic and Nyarko (1996) and Jovanovic and Rousseau (2002), identify the role of adjustment costs on the diffusion of GPTs.

[24]Dale Jorgenson and associates deeply study the relationship between IT and productivity: for example, using growth accounting techniques Jorgenson (2005) and Jorgenson and Vu (2005) analyze ITs contribution to total factor productivity for the American and the world economies, respectively.

for economic growth and detect the importance of the new technology using the findings of the first stage. For our analysis, we consider a slightly modified version of the traditional growth regression model introduced by Mankiw, Romer, and Weil (1992), which is considered in the second stage, and study the different effects of physical factors and technology:

$$\Delta \ln y_{ct} = \ln A_c + \gamma_2 \Delta \ln POP_{ct} + \gamma_3 \ln y_{c0} + \xi_{ct} \tag{5}$$

where for country c at time t $\Delta \ln y$ is the gross domestic product (GDP, henceforth) per capita growth rate, $\Delta \ln POP$ is the population growth, $\ln y_{c0}$ is the initial level of GDP per capita and ξ is the error term. To study the effect of clocks, we decompose the country-level of technology A_c into a general technological effect, represented by the parameter γ_0 and the contribution of the clock B_{ct}, which is proxied by the penetration rate:

$$A_{ct} = exp(\gamma_0 + \gamma_1 B_{ct}) \tag{6}$$

Substituting (6) into (5), we obtain the modified growth equation

$$\Delta \ln y_{ct} = \gamma_0 + \gamma_1 B_{ct} + \gamma_2 \Delta \ln POP_{ct} + \gamma_3 \ln POP_{c0} + \xi_{ct} \tag{7}$$

Similar to the discussion in the previous section, here, an OLS estimate of (7) may be affected by two different endogeneity issues: first, a problem of reverse causality can arise because country economic growth can positively drive the adoption of the mechanical clock; second, there could be a problem of mispecification because particular government policies and different institutional quality, which is difficult to measure, can play a role in the adoption of the mechanical clock. For these reasons, we imitate the strategy introduced by Czernich, Falck, Kretschmer, and Woessmann (2011) considering an instrumental variable approach, which is also useful for studying the pattern of diffusion.and consider an instrumental variable approach, which is also useful for studying the pattern of diffusion. Following the previous contributions to adoption rate (Griliches (1957), Geroski (2000), and Comin, Easterly, and Gong (2010)) which are also motivated by the S-shaped diffusion of technology, we model the impact of the clock B following a logistic distribution

$$B_{ct} = \frac{\phi_c}{1 + exp\left[-\tilde{\beta}\left(t - \tau\right)\right]} + e_{ct} \tag{8}$$

where ϕ_c is the saturation level, i.e., the maximum amount of adoption, $\tilde{\beta}$ is a parameter displaying the double amount of maximum growth rate, τ provides information on the inflexion point of the curve and e is the error term. To provide a value to ϕ, we assume that the saturation can be positively related to the percentage of population living in area covered by the combinations of eclipses studied in the previous section, *eclipse share*$_c$

$$\phi_c = \phi_0 + \lambda_1 eclipse\ share_c \tag{9}$$

The availability of yearly population data described in Section 3 allow us to study the diffusion using more than 7,000 observations. More precisely, we consider population data for eight countries (Austria, Belgium, Denmark, Finland, France, Germany, Italy, Sweden, Switzerland, and the United Kingdom) for the period of 1250-1750. Table 8 shows the results of the regression of the equation obtained substituting (9) into (8) providing several information. We can observe that the parameter of eclipses (λ_1) enters in a positive and significative way, with a a penetration rate of approximately 20%. In addition, while the parameter τ suggests that the inflation rate is situated at the year 1470, a period which is similar to those analyzed in the empirical analysis in Section 2, $\tilde{\beta}$ indicates a maximum growth rate of approximately 1.5% In addition, Figure 5 compares the actual rate and the the fitted adoption rate generate by the first stage estimates and suggests a prevalence of logistic distributions in the countries analyzed.

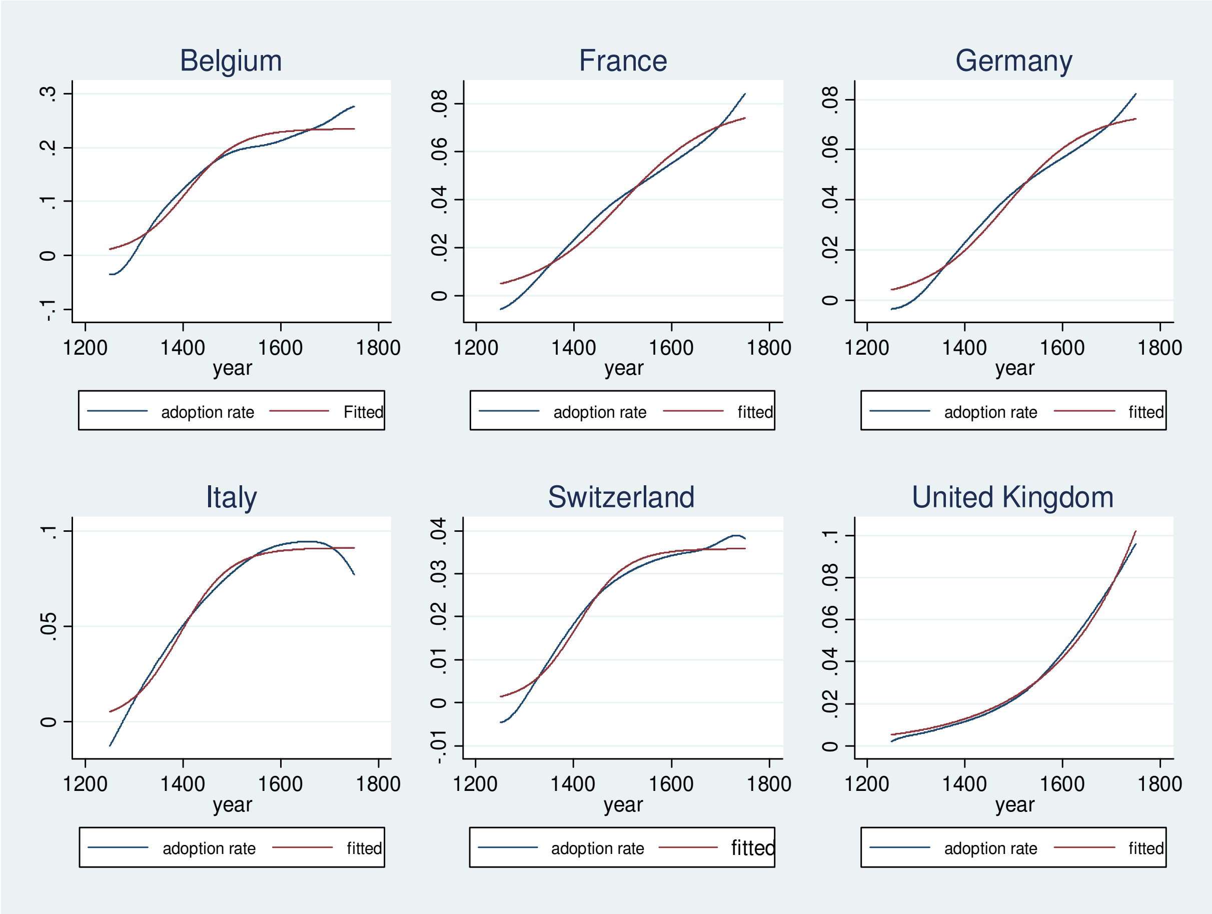
Table 8: NLS estimation for the diffusion curve

	λ_1	ϕ_1	$\tilde{\beta}$	τ
	0.03*** (0.00)	0.20*** (0.00)	0.03*** (0.00)	1470.89*** (8.50)
R^2	0.12			
N. of observations	7,014			

Significance at the 90%, 95%, and 99%
confidence levels are indicated by *, **, and ***, respectively.

Table 9 contains the results of the second stage. The first four columns show the impact of the

Figure 5: Mechanical adoption rate: Actual (blue line) and predicted (red line)



contemporaneous adoption of mechanical clock ($\widehat{B}_{ct}$) on economic growth, while columns (5)-(8) consider a lag of a century ($\widehat{B}_{ct-100}$). In all the cases, we consider both cluster and bootstrapped standard errors errors based on 50 replications. Our estimates are based on the GDP per capita every 100 years collected by Maddison (2007)), and confirm the findings of the regressions based on city-level data, i.e., the penetration of the GPT has a positive and significant impact on GDP per capita growth. We find that an increase of 10 percentage points in the diffusion of mechanical clocks can raise the GDP per capita growth approximately 30 percent in a century.

Table 9: The effects of mechanical clocks on GDP per capita: second stage.

	(1)	(2)	(3)	(4)		(5)	(6)	(7)	(8)
			Bootstrapped Std. Errors	Bootstrapped Std. Errors				Bootstrapped Std. Errors	Bootstrapped Std. Errors
$\widehat{B}_{ct}$	3.13***	2.74**	3.13***	2.74	$\widehat{B}_{ct-100}$	3.30***	2.88**	3.30***	2.88
	(0.78)	(1.13)	(0.81)	(1.69)		(0.84)	(1.23)	(0.86)	(1.82)
$\ln y_0$	-0.00	-0.00	-0.00	-0.00	$\ln y_0$	-0.00	-0.00	-0.00	-0.00
	(0.00)	(0.00)	(0.00)	(0.00)		(0.00)	(0.00)	(0.00)	(0.00)
$\Delta \ln POP$	-0.11	-0.10	-0.11	-0.10	$\Delta \ln POP$	-0.11	-0.11	-0.11	-0.11
	(0.11)	(0.12)	(0.33)	(0.33)		(0.11)	(0.12)	(0.31)	(0.31)
T		0.00		0.00	T		0.00		0.00
		(0.00)		(0.00)			(0.00)		(0.00)
Constant	1.21*	1.23*	1.21*	1.23*		1.19*	1.22*	1.19*	1.22*
	(0.63)	(0.65)	(0.62)	(0.67)		(0.64)	(0.66)	(0.62)	(0.67)
R^2	0.65	0.64	0.65	0.64		0.65	0.64	0.65	0.64
N. of observations	36								

Significance at the 90%, 95%, and 99%
confidence levels are indicated by *, **, and ***, respectively.

7 Conclusion

This paper studied the impact of public mechanical clocks on economic growth in pre-modern Europe. The study was motivated by the widely debated role of the influence of GPT on economic growth and, in particular, by the discussion of the role of computers in the well-known Solow Paradox concerning productivity. This study found long-run growth effects at the city and country levels. These growth effects were caused by indirect spillover effects, created by improvements in coordination, increases in productivity, and changes to work culture.

To achieve these results, we collected information on the introduction of public mechanical clocks in late medieval European cities. We identified a group of early adopters from 1286-1450 and compared this group with the remaining cities in Europe. We studied the population growth rate (which we used as a proxy for economic growth) of these two groups of cities and found strong significant differences: cities that adopted public mechanical clocks early had higher growth rates (30 percentage points higher) than other cities between 1500 and 1700. We found similar results for countries when we measured the impact of the aggregate adoption/ penetration rate on the estimated GDP of a country. We used various estimation strategies to receive this robust result. To avoid endogeneity problems between the dependent variable of economic growth and the main explanatory variables, the building of mechanical clocks, we introduced several instruments. In particular, we used the distance from the first adopters and solar eclipses as instruments for the likelihood of the implementation of public mechanical clocks. Our results contribute to a better understanding of the effect of GPTs on long-run economic growth. They support the strand of literature that claims that fundamental technological changes cause strong growth effects. However, we show that it takes time for the new technology to translate into economic growth via spillover effects. The penetration not only takes place in different sectors but also fundamentally changes the organization, structure, and culture of a society. Furthermore, our study contributes to the specific study of clocks as a new key technology in late medieval and early modern Europe. To the best of our knowledge, this study is the first quantitative exercise that investigates economic growth and mechanical clocks. Our results support the strand of literature that attributes strong but delayed effects to clocks.

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Appendix A: Descriptive Statistics

Table A1: First part

Variable	**Mean**	**Standard deviation**	**Min**	**Max**	**N. of observations**
$CLOCK$	0.28	-	0.00	1.00	621
$\Delta \ln POP_t$	0.40	0.57	-2.83	2.63	515
Pop 1200	20090.91	20062.81	1000.00	1.5e+05	121
Pop 1300	14779.76	18893.55	1000.00	1.5e+05	336
Pop 1400	14753.42	23752.61	1000.00	2.8e+05	292
Pop 1500	10805.15	15937.85	1000.00	2.2e+05	621
Pop 1600	16765.31	27020.18	1000.00	3.0e+05	490
Pop 1700	18330.10	41508.88	1000.00	5.7e+05	515
Pop 1800	22869.56	54691.81	1000.00	9.5e+05	621
Institutional variables					
$university$ 1200	0.02	-	0.00	1.00	621
$university$ 1300	0.04	-	0.00	1.00	621
$university$ 1400	0.07	-	0.00	1.00	621
$university$ 1500	0.10	-	0.00	1.00	621
$university$ 1600	0.13	-	0.00	1.00	621
$university$ 1700	0.14	-	0.00	1.00	621
$university$ 1800	0.14	-	0.00	1.00	621
$freedom$ 1200	0.38	-	0.00	1.00	621
$freedom$ 1300	0.38	-	0.00	1.00	621
$freedom$ 1400	0.38	-	0.00	1.00	621
$freedom$ 1500	0.17	-	0.00	1.00	621
$freedom$ 1600	0.17	-	0.00	1.00	621
$freedom$ 1700	0.14	-	0.00	1.00	621
$freedom$ 1800	0.14	-	0.00	1.00	621

Table A2: Second part

Variable	**Mean**	**Standard deviation**	**Min**	**Max**	**N. of observations**
		Geographical variables			
sea	0.24	-	0.00	1.00	621
mediterranean port	0.04	-	0.00	1.00	621
atltantic port	0.04	-	0.00	1.00	621
baltic port	0.10	-	0.00	1.00	621
big river	0.05	-	0.00	1.00	621
small river	0.32	-	0.00	1.00	621
longitude	6.97	8.82	-15.63	49.10	621
latitude	47.50	5.72	27.90	63.43	621
$elevation(inexp)$	349.32	6.05	0	1130.03	621
		Instrumental variables			
same state 1200	0.25	-	0.00	1.00	621
same state 1300	0.18	-	0.00	1.00	621
eclipses $840-891$	0.04	-	0.00	1.00	621
eclipses $852-878$	0.13	-	0.00	1.00	621
eclipses $840-939$	0.01	-	0.00	1.00	621
eclipses $961-939$	0.03	-	0.00	1.00	621
eclipses $968-939$	0.03	-	0.00	1.00	621
eclipses $1086-1098$	0.02	-	0.00	1.00	621
eclipses $1133-1147$	0.10	-	0.00	1.00	621
eclipses $1153-1207$	0.02	-	0.00	1.00	621
$DISTANCE\ FIRST$ $(in\ km)$	14.47	75.18	0.00	358.73	621

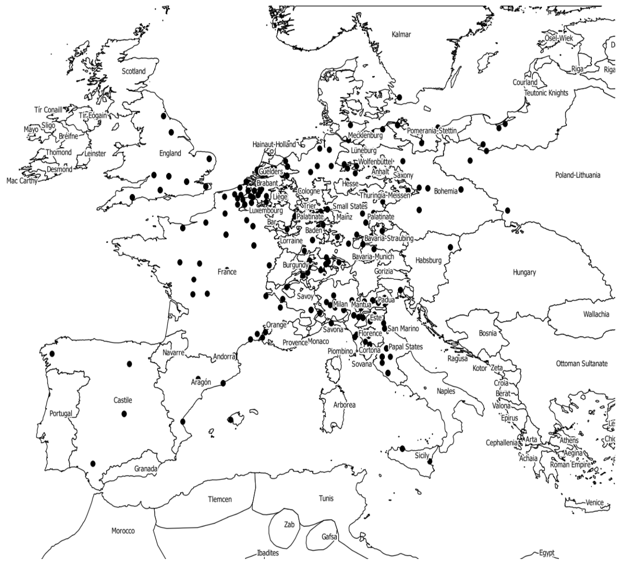
Appendix A: Different moment of diffusion process between 1283-1410

1283-1320

1320-1350

1350-1380

1380-1410



Appendix C: Propensity Score

In this appendix we consider the propensity score technique following procedure suggested by Wooldridge (2010). We first estimate the probability of adopting the mechanical clock, $Prob\,(CLOCK_i)$ from column (4) of Table 4. Then, we run

$$\Delta Pop_{it} = \theta_0 + \theta_1 CLOCK_i + \theta_2 Prob\,(CLOCK_i) + u_i \tag{10}$$

The effect of the early adoption of technology is given by the estimates of θ_1 in Table A3.

Table A3: Propensity Score: 1^{st} part

	$\Delta Pop_{1400-1500}$	$\Delta Pop_{1500-1600}$	$\Delta Pop_{1500-1700}$	$\Delta Pop_{1500-1800}$
	m1500	m1600	m1700	m1800
	none	none	none	none
$CLOCK$	-0.01	0.10	0.27***	0.25**
	(0.12)	(0.08)	(0.08)	(0.12)
$Prob\,(CLOCK)$	-0.17	-0.25**	-0.71***	-0.87***
	(0.23)	(0.10)	(0.12)	(0.14)
$Constant$	0.22*	0.31***	0.51***	0.88***
	(0.11)	(0.05)	(0.09)	(0.14)
R^2	0.01	0.01	0.04	0.05
N. of observation	217	275	280	317

In addition, we also consider an alternative estimation taking into account the problem of sample selection (Table A4):

$$\Delta Pop_i = \theta_0 + \theta_1 CLOCK_i + \theta_2 Prob\,(CLOCK_i) + \tag{11}$$

$$\theta_3 \left[CLOCK_i * Prob\,(CLOCK_i) - MEAN\,(Prob\,(CLOCK_i))\right] + u_i$$

In both case, the propensity score estimates confirms a significative and positive effect of early adoption of mechanical clocks on population growth during the period 1500-1700.

Table A4: Propensity Score: 2^{nd} part

	$\Delta Pop_{1400-1500}$	$\Delta Pop_{1500-1600}$	$\Delta Pop_{1500-1700}$	$\Delta Pop_{1500-1800}$
$CLOCK$	0.03	0.08	0.22***	0.26*
	(0.09)	(0.07)	(0.08)	(0.14)
$Prob\,(CLOCK)$	0.01	-0.32**	-0.88***	-0.85**
	(0.36)	(0.14)	(0.25)	(0.31)
$Constant$	0.18	0.33***	0.54***	0.87***
	(0.13)	(0.06)	(0.09)	(0.17)
R^2	0.01	0.00	0.04	0.05
N. of observations	217	275	280	317