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Time and Temporality as Categories of Connectedness

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Time as a Causal Factor and Network Analysis: The Circulation of Astronomy Knowledge and the Investment of Book Printers in the Early Modern Period

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Keywords Sphaera-Sacrobosco Dataset, Network Analysis, Circulation of Knowledge, Historical Time, Agent-Based Modelling, Time as Causal Factor

Abstract In this paper, we investigate the role of historical time in understanding causal relationships that can be formulated quantitatively, both in reconstructing an entire historical process and in examining the historical actors involved. Our focus is on the publication of Nicolaus Copernicus's *De revolutionibus orbium coelestium* in 1543. We analyze the interplay between the circulation of knowledge and the key figures responsible for this publication, Georg Rheticus and Johannes Petreius, considering the perspectives of both the historians and the actors themselves. Methodologically, we combine network analysis and agent-based modelling. The research utilizes the *Sphaera-Sacrobosco* dataset. Through network analysis, we identify different phases in the circulation of knowledge, particularly noting a phase of acceleration beginning in 1531. These findings are then used to simulate a dynamic early-modern book marketplace that allows for the investigation of book printers' behaviors based on shifting trends. Our results suggest a causal relationship between the dynamics of these networks and the actors' perception thereof in their decision, based significantly on economic incentives, to publish new and innovative texts, including Copernicus's work.

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1. Introduction

When the polymath Georg J. Rheticus decided to organize the publication of Nicolaus Copernicus's *De revolutionibus orbium coelestium* in 1543 by making use of his own institutional and private network of friends, lecturers, publishers, and printers, he did so because he believed in the work as a scientific contribution to astronomy. Copernicus was already old (he died shortly after the book was published), which certainly played a role in Rheticus's timing. Additional (or even determinant) encouragement concerning this undertaking might also have come from the printer of Copernicus's work, Johannes Petreius, as it is well known that Rheticus and Petreius planned and executed this step together.[1]

The year 1543 indeed fell at the beginning of a new era in the diffusion of astronomical culture. A completely novel dynamic in the circulation of astronomic knowledge had begun only a few years earlier. Starting in 1538, new astronomy textbooks – namely core knowledge[2] – with some variations in content were produced in Wittenberg. They became models imitated all over Europe, prompting a process of homogenization of scientific knowledge.[3]

These dynamics prompted an increase in the production of treatises in other centers, and in general nourished a boost of scientific knowledge production and circulation. Intervals between successive publications of the same treatise became shorter; distances between centers of book production influenced by the Wittenberg model became longer. Dissemination accelerated. Rheticus and Petreius, well established in this context,[4] must have perceived this compression of time, making them more prone to act. In this respect, we consider time to have been an inciting factor in Rheticus's and Petreius's work.

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Data accessibility: The data are available via the database that can be reached through the project website *The Sphere: Knowledge System Evolution and the Shared Scientific Identity of Europe* (https://sphaera.mpiwg-berlin.mpg.de)

1 Swerdlow and Petreius 1992.
2 Cole 1983.
3 Valleriani et al. 2019; Zamani et al. 2020; El-Hajj et al. 2022; Valleriani et al. 2022; Zamani et al. 2023.
4 Valleriani, Federau, and Nicolaeva 2022.

After introducing the historical sources on which this study is based and the dataset retrieved therefrom (see Section 2), we first conduct a network study focusing on the non-linear analysis of the dynamics of the circulation of knowledge (see Section 3). Thereafter, the discussion shifts to historical time, aiming to identify which aspects of historical temporality can now be quantified (see Section 4). We distinguish between *ex-post* historians' and historical actors' perspectives. In Section 5, we then introduce an agent-based model to attempt to quantify time perception in historical actors, and in the conclusion (Section 6) we discuss how the historian's overview can be integrated with the historical actors' perception on a formal network level.

2. Data and Network

The *Sphaera-Sacrobosco* dataset investigated in this research is a collection of 359 textbooks that were used to teach astronomy (geocentric cosmology) in all European universities during the early modern period between 1472 and 1650. Strictly speaking, we collected 359 editions of textbooks. For each edition or print run, we selected just one copy as representative of the entire run. In the following, therefore, we will refer to textbooks and editions interchangeably. The geo-temporal distribution of the production of these editions is displayed in Figures 1 and 2.[5]

All the editions have been selected because they include a specific treatise: Johannes de Sacrobosco's *Tractatus de sphaera,*[6] written during the 13th century and in use until the 17th. The editions of the *Sphaera-Sacrobosco* dataset are atomized into text parts, which are categorized as "original text parts," "translations," or "commentaries." The interacting networks between the editions are built based on shared text parts. If two editions contain the same text part, there is a link between them; the direction of the link is based on chronological order, from the older edition to the newer.

In the following analysis, we use precepts and approaches typical of the physics of complex systems.[7] To maintain full control of the interpretational framework, we also make use of multi-layer networks,[8] whose single layers correspond to different but temporally parallel phenomena that took place during the period under consideration.

5 This dataset is part of a wider collection of four datasets all constituted by university textbooks used for the teaching of astronomy in early modern European universities: https://sphaera.mpiwg-berlin.mpg.de. In previous publications, when the other datasets were not yet generated, the *Sphaera-Sacrobosco* dataset was referred to either as the Sphaera corpus or the Sacrobosco corpus.

6 Thorndike 1949; Valleriani 2017, 2020a.

7 El-Hajj et al. 2022; Siebold and Valleriani 2022.

8 Kivelä et al. 2014; Cozzo et al. 2018.

Fig. 1 Geographical distribution of the production of the editions of the *Sphaera-Sacrobosco* dataset (1472–1650).

We build a multiplex network that contains four different layers that are defined as follows:

- SOP (Same Original Part) Two editions are connected if they contain the same original text part (such as scientific innovations);
- SAP (Same Adaption Part) Two editions are connected if they contain exactly the same adaption part, such as the same commentary on the same original part. An adaption can also be a translation;
- TSOP (Translated Same Original Part) Two editions are related to each other if they both contain a translation, but not the same translation, of the same original part;
- ASAP (Annotated Same Adaption Part) Two editions have a connection if they both contain commentaries that are not the same but are on the same adaption.

Figure 3 shows the number of common nodes and links among the four layers. The values on the diagonal of the two matrices shown in Figure 3 reflect the number of nodes and links for each layer; the off-diagonal values show the number of shared nodes and links. Layers SOP and TSOP have the greatest and smallest numbers of nodes and links, respectively.

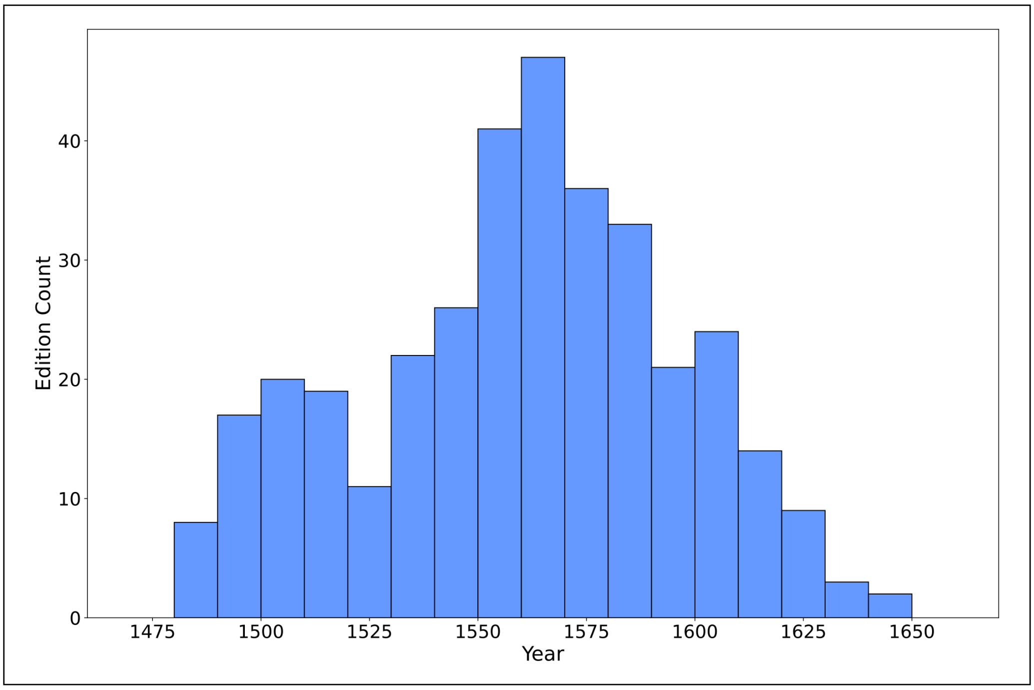

Fig. 2 Temporal distribution of the production of editions of the *Sphaera-Sacrobosco* dataset (1472–1650).

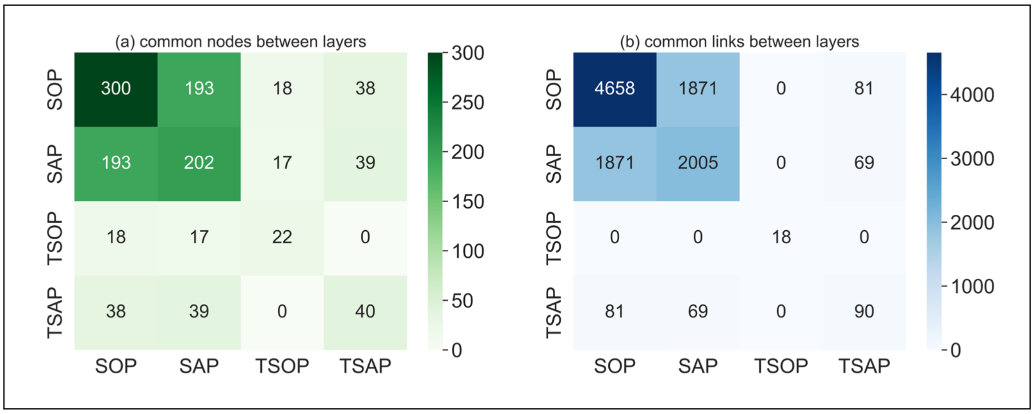

Fig. 3 Matrices of shared nodes and links between the four layers of the *Sphaera-Sacrobosco* dataset.

Fig. 4 Overlapping frequency matrix: the diagonal elements refer to the fraction of the links in the aggregated graph that are present in the layers; the off-diagonal elements represent the percentage of the links shared by the layers pairwise (pair: row and column).

3. Dynamics of Circulation

3.1 Entanglement between the Layers

The multiplex network of the *Sphaera-Sacrobosco* dataset with its four layers indicates that their corresponding entities (editions) could be relevant to each other according to different aspects. To understand the relation between the layers and their level of connectivity, we investigate the Layer Interaction Network (LIN). Each layer is simplified into a node. A new weighted network is built where the nodes are layers and the links between them represent the overlapping edges in the layers; the weights of the links in LIN represent the number of overlapping links between layers.[9]

The purpose of such a study is to better understand the coupling between the layers themselves and to represent such coupling by a well-defined quantity. This in turn results in a value of influence of each layer on the others. If a multiplex network is considered with V_M number of nodes and E_M number of links in each layer M, where $M = 1, 2, \ldots, L$, and L is the total number of layers, then the LIN network has L number of nodes, and there is a connection between two nodes of LIN if there is at least one common link in the corresponding layers.[10]

9 Renoust, Melançon, and Viaud 2014.
10 Škrlj and Renoust 2020.

Figure 3-b shows the LIN matrix, where the diagonal values are the number of links in each layer and the off-diagonal values show the overlapping links between the layers. Based on the LIN matrix, we can find the "overlapping frequency matrix," where the off-diagonal values correspond to

$$\frac{n_{l,\ l'}}{n_{l',\ l'}}$$

and the diagonal values refer to

$$\frac{n_{l,\ l'}}{E}.$$

$n_{l,l'}$ is the number of overlapping links between layers l and l'; E is the total number of links in the aggregated network of all the layers without considering the weight of the links (repeated connections).[11] In the four layers of the *Sphaera-Sacrobosco* dataset, the total number of links in the aggregated graph (E) is 4819.

Figure 4 shows the overlapping frequency matrix. This matrix represents the percentage of the number of links in a layer that overlap with the other layers. For example, the first row of Figure 4 shows that 93 % of the links in SAP are shared with SOP and 90 % with TSAP. Layer TSOP does not share any link with any other layer, and the value of 0.0037 in the diagonal of this matrix means that 0.37 % of the total links of the aggregated graph refer to this layer, whereas 97 % of the links of the aggregated network are present in layer SOP.

The entanglement of each layer with the other layers can be found from the eigenvector that corresponds to the maximum eigenvalue of the "overlapping frequency matrix." The entanglement value (γ) for each layer is presented in Table 1. Layer SOP has the maximum entanglement (coupling) with the other layers, and layer TSOP has none. These relations of influence can be easily captured by looking at the LIN matrix in figure 3-b, as it shows that SOP shares the greatest number of links with the other layers, and TSOP does not share any links. However, having a well-defined quantity such as γ gives us a general quantitative understanding of the level of connectivity between the layers and shows to what degree a layer influences the others.

The other standard technique to find the most influential layer is by calculating the maximum eigenvalue of the *supra-adjacency* matrix and comparing that to the maximum eigenvalue of the adjacency matrix of each layer.[12] The layer whose adjacency matrix has the maximum eigenvalue equal to the eigenvalue

11 Ibid.
12 Cozzo et al. 2016.

Layers	
Entanglement (γ)	
SOP	0.91
SAP	0.39
TSOP	0
TSAP	0.02

Tab. 1 Entanglement value of each layer

of the supra-adjacency matrix is considered the dominant layer in the multiplex network. The diagonal blocks of the supra-adjacency matrix are the intra-layer adjacency matrix, and the off-diagonal blocks refer to the coupling adjacency matrix, which can be found by connecting the overlapping nodes between layers.[13] Our analysis points out that the maximum eigenvalue of the adjacency matrix of layer SOP is 3.99, which is equal to the maximum eigenvalue of the supra-adjacency matrix, emphasizing that SOP is the dominant layer in the multiplex network.

3.2 Network Analysis of the Dominant Layers

In the previous section, we saw through different techniques that the layer SOP is the dominant layer in the multiplex network, as it has the greatest number of nodes and links, while layer SAP is the second most important. Therefore, the transformation process of astronomical knowledge mostly concerns these two layers (original parts and adaptions). In the following, we therefore focus on the network analysis of these two layers.

3.2.1 *The Structure of the Network*

Figure 5 shows the network structure of the connections in the layers SOP and SAP. The network consists of 35 components. Some components only have two nodes. The giant component (shown in pink) contains 91 editions, and there are 58 different text parts that propagate through the editions in this component. Note that the text parts of each component are different from those of other components; otherwise there would have been a link between them. This is one of the most important features of the *Sphaera Sacrobosco* dataset: the semantic knowledge is categorized into different non-overlapping groups of editions.[14]

13 Ibid.
14 The non-overlapping groups of editions are discussed and analyzed in detail in Zamani et al. 2020; Valleriani et al. 2019.

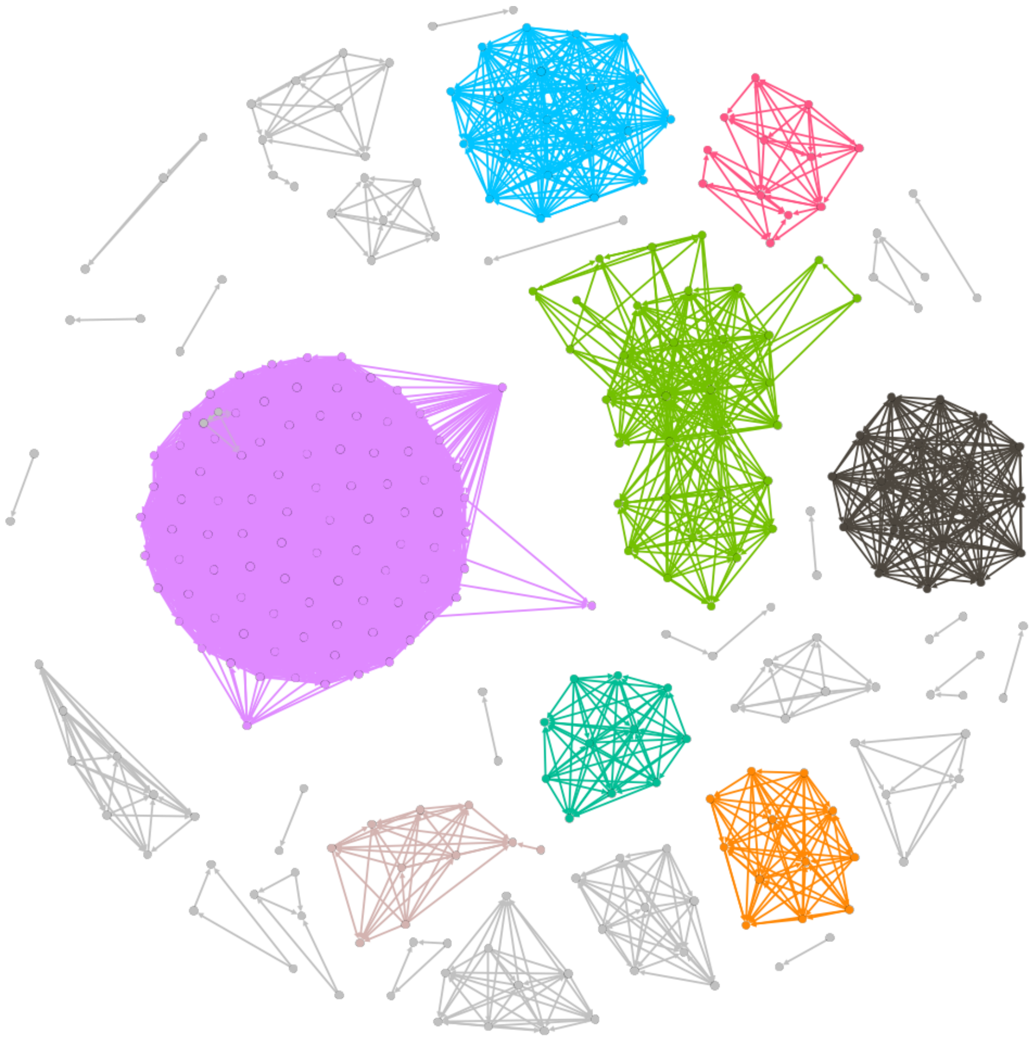

Fig. 5 Network of connections between editions of layers SOP and SAP; it contains 35 components.

Figure 6 provides a matrix illustrating how different text parts in the giant component are responsible for the temporal evolution of the component. Each row refers to a text part with its unique part-ID; each column shows the year. Each color-coded element of the matrix indicates how many editions published in the year shown on the x-axis contain the respective text part on the y-axis. As shown in the figure, part-IDs 206 and 203 are the most repeated among the editions in the giant component. They start to shape this component from the very beginning, in 1531, and start to decay around 1585. Some of the text parts have very short lives – they appear in the middle of the timespan of the giant component and only last for a couple of years. This suggests that one way of considering

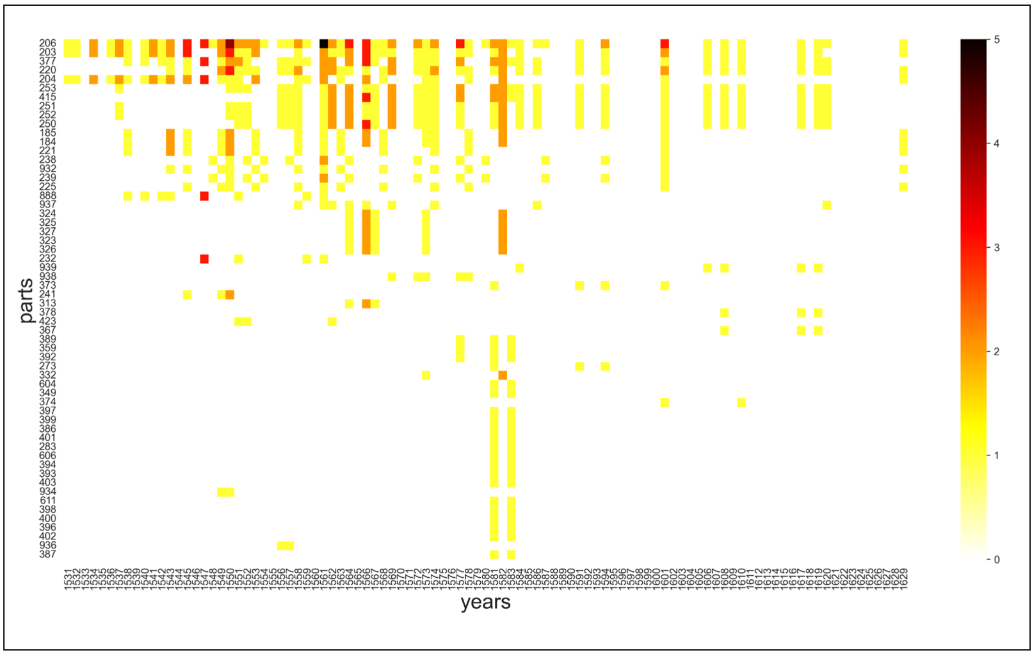

Fig. 6 Existing text parts in the giant component (y-axis) and their propagation in time (x-axis). Color code: the number of published editions that contain the corresponding text part.

the influence of each edition on later ones is by studying their out-degrees and lengths of influence in time.[15]

We can therefore investigate how the connections inside each component are built and ask if influence (having a high value of out-degree) depends on the number of text parts inside a given edition. Figure 7-a shows the in-degree value of each edition versus its out-degree, which in turn is shown for the different components displayed in Figure 5. It is evident that while the out-degree value increases, the in-degree decreases, and that the slopes of decrease for all components are the same. The reason behind this behavior is that all the editions of each component are almost fully connected, except from the second component (green).

We can now reproduce the same slope for the giant component with a very simple model (red circles). We consider the same number of nodes of the giant component sorted in chronological order and make a fully connected directed graph whose direction is from the oldest to the newest editions. Figure 7-a shows that the slope of the graph based on the "toy model" is the same as the giant

15 Zamani et al. 2020.

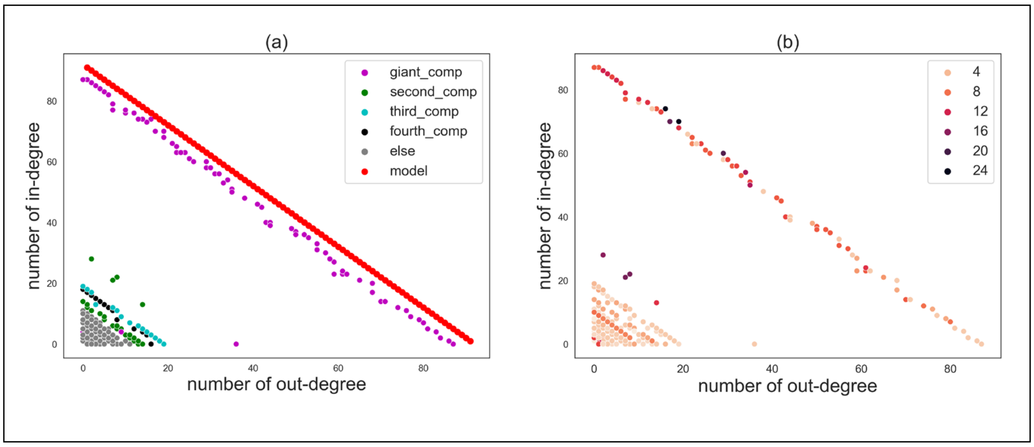

Fig. 7 (a) Change of values of in-degree versus out-degree for each edition in the network shown in Figure 5; (b) color code based on the number of text parts contained by the editions. The plots show that high-impact editions with a high out-degree and a low in-degree are those editions constituted by a lower number of text parts.

component since they have the same number of nodes and the network in the giant component is almost fully connected. We can see in this figure that the second big component (green) is sparser and that the ratio between the in-degree and out-degree values does not decrease monotonically for all the editions of this component. Figure 7-b shows the same plot color-coded based on the number of existing parts in each edition. Interestingly, the more influential editions with high out-degrees and low in-degrees contain a smaller number of text parts.

3.3 Phase Transition and Change of Dynamics

We measure the duration of influence for each edition by the age of its outgoing links to the other editions. In Figure 8, the x-axis refers to the age of the outgoing links from editions published in the respective year indicated on the y-axis. This figure shows a clear transition in 1531, as attested by the relevant increase in size of the giant component. The editions published in or after this year are connected to the editions published thereafter until the end of the period. The lifetime of the second big component (shown in green in Figure 5) ends before this year. In fact, most of the connections that shape the triangle before 1531 in Figure 8 belong to the second component. From this plot it becomes evident that, from 1531, at the time of the emergence of the giant component, all the editions in this component connect to almost every edition published thereafter.

Before 1531, 57 % of connections are between editions published in the same city, while this number decreases to 25 % for the connections after 1530. Meanwhile, 75 % of connections after this transition point (1531) are between editions

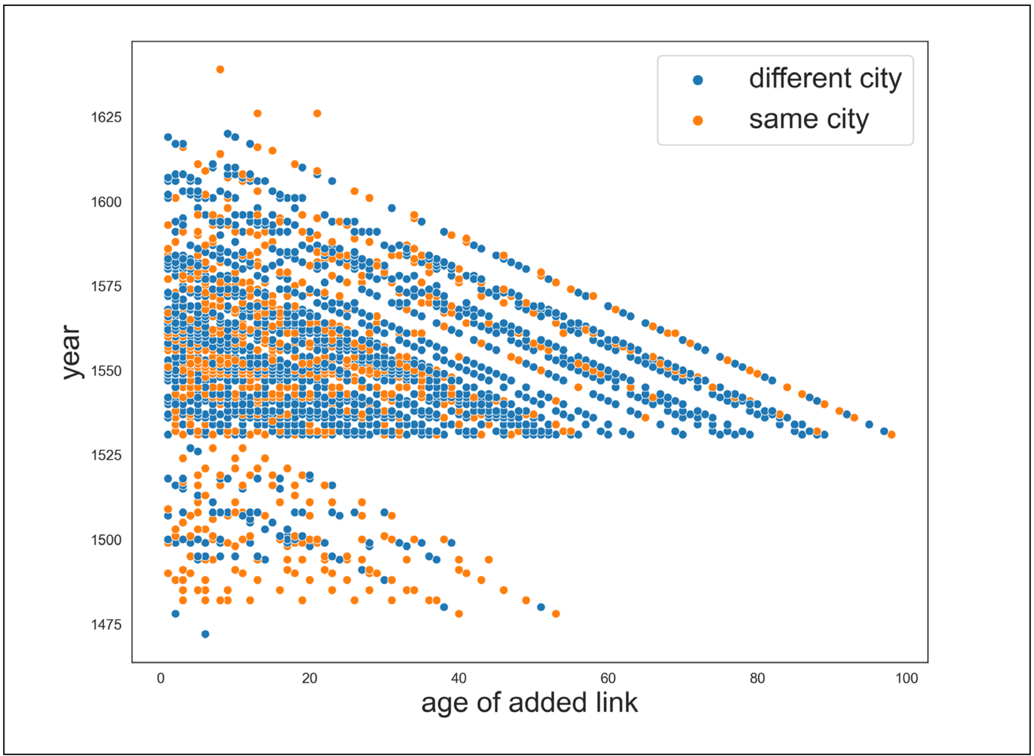

Fig. 8 The years of publication of each edition versus the age of outgoing links show two separate phases with different dynamics of the circulation of knowledge, one ending and one starting around 1531. In particular, it shows that before 1531, text parts were mostly re-published in the same city (local market). On the contrary, after that year, re-occurrences increasingly took place over a broader geographic area. The plot clearly shows a break in 1531 and an acceleration of dynamics just after.

published in different cities. Therefore, we can state that the dynamics of the circulation of knowledge radically changes in 1531 and continues until the end of the period of our study.[16]

Figure 9 shows the details of these inter- and intra-city connections in the *Sphaera-Sacrobosco* dataset. These are the most important and active cities (in terms of the production of printed books) among all the cities that appear in

16 Shortly before 1600, the dynamics began changing again through a deceleration of the circulation of knowledge. As the number of publications also decreased, probably due to the fact that textbooks were increasingly centered on different treatises, we have not analyzed this last phase in detail. In section 5, where the behavior of historical actors inside the network is simulated, we do distinguish between three phases.

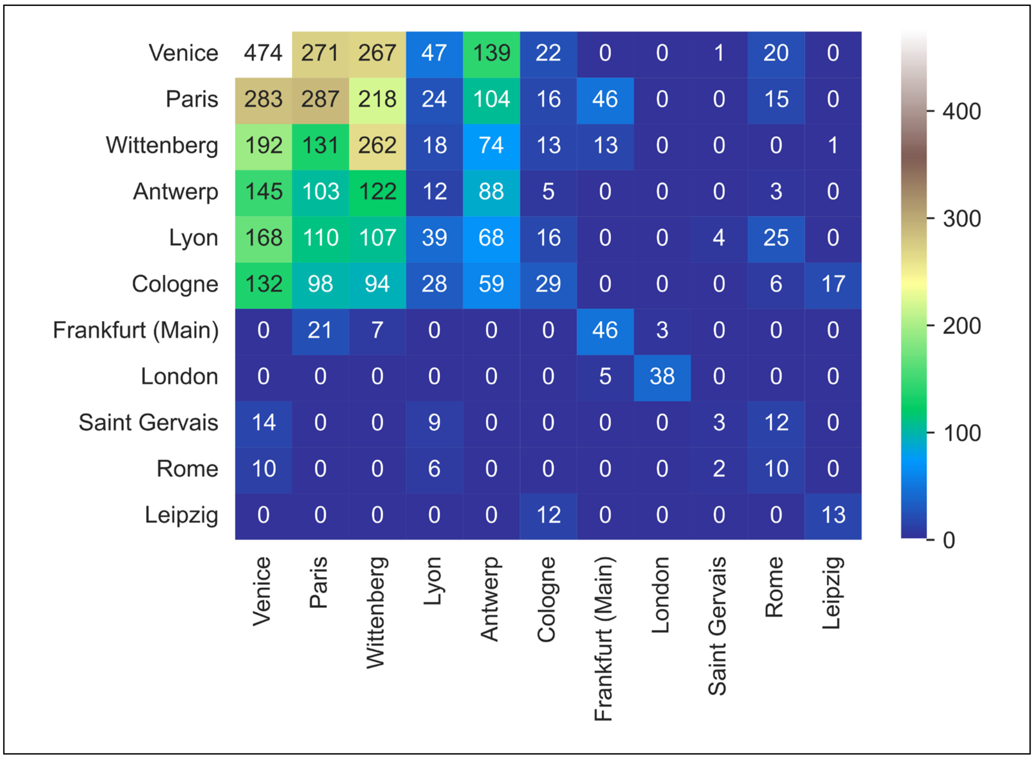

Fig. 9 Local and trans-regional interactions displayed by the number of links between editions published in the same city or in different cities. Venice, Paris, and Wittenberg are the most relevant global players in the trans-regional academic book market.

the dataset. If we look at the row related to Venice, the most active city, we see that there are 474 connections between editions published in Venice; but, on the other hand, Venice shows a higher number of connections to other cities altogether. Concerning Paris, there are 267 links whose source editions are published in Venice. Shifting perspective, there are 283 links from source editions published in Paris and whose targets are in Venice.

3.4 Historical Insights from the Network Analysis

The investigation of the entanglement of these layers has shown that two layers are particularly relevant: the layer in which editions are connected when they contain the same original parts, and the layer in which editions are connected when they contain the same commentaries on the original parts. This situation implies that the production of scientific knowledge in the period was due not only to the attempt to innovate (or even *radically* innovate) but also to the reflective work (commentaries) on those innovations produced by other scholars.

The component analysis and, more specifically, the analysis of the links of the giant component have shown that some text parts are particularly relevant. These are part-IDs 206[17] and 203.[18] Part-ID 206 is a specific chapter of a scientific work (but not the entire work) written by one of the most important mathematical astronomers of the 15th century, Johannes de Regiomontanus. The chapter deals with the multiple causes of the inequality of the length of solar days. Part-ID 203 is an introductory open letter by the Reformer Philipp Melanchthon, by means of which he wanted to motivate young people toward the study of astronomy. This letter was even reprinted many times in Catholic regions. The first part testifies to the increasing mathematization of astronomy as taught at the universities; the second to the great influence of the pedagogic program of Protestant Reformers all over Europe.

Analysis of the relationship between the rate of influence of the editions (out-degree) and the number of text parts that they contain shows that there is no correlation between the two values. This implies that, in the knowledge tradition of the *Sphaera-Sacrobosco* dataset, the quantity of text parts in an edition (and, therefore, the quantity of scientific content) was not a parameter that made an edition more or less influential or popular. Only specific text parts counted in this respect, and it was even better if those parts were in an edition that was not too voluminous. While the general historical meaning of this result needs further investigation, it can circumstantially be inferred that European universities were highly selective in deciding the works with which the pupils were to be trained.

Analysis of the circulation of knowledge has shown that the process of transformation in astronomy, as mirrored through the teaching at European universities, underwent two phases. The first ends in 1530, and the second begins in 1531. Matching this result with the metadata referring to places of publication immediately shows that these phases were characterized by a very different dynamic of the circulation of knowledge. While the first phase displays a development clearly characterized by the centrality of few locations, the second phase literally moves into a global dynamic between different European regions, territories, and political entities. Specific analysis of the roles of individual cities shows moreover that, for the most important centers of book production (such as Paris, Venice, and Wittenberg), while the local market remained relevant, half of each city's production circulated on the international market and influenced production abroad.[19]

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17 Valleriani, M., Kräutli, F. et al. 2019. Epitome of Ptolemy's Almagest by Regiomontanus. In Sphaera Database. Available at: hdl.handle.net/21.11103/sphaera.100087.

18 Valleriani, M., Kräutli, F. et al. 2019. Paratext: Letter by P. Melanchthon to S. Grynaeus. In Sphaera Database. Available at: hdl.handle.net/21.11103/sphaera.100077.

19 Valleriani and Ottone 2022b.

It is at this stage that we can return to the question we started with – whether Rheticus and Petreius moved toward the introduction of Copernicus's text in 1543 as a consequence of these new dynamics. To try to answer this question, we suggest working with an Agent-Based-Model (ABM). But before proceeding to this experiment, we first need to frame the temporality expressed by the ABM into a general picture concerning historical temporality and which of its aspects can be confidently quantified.

4. Historical Time

In this section, we consider "historical time" as distinct from both "natural" and "social" time.[20] We consider natural time an objective phenomenon (the flow of time measured in connection with a regular natural phenomenon) independent of historical actors' perception of their past, present, and future, as well as from the historian's perspective of past events. We consider social time as one specific aspect of the whole conceptual framework that defines historical time, as will be shown in the following.[21] Without attempting to delineate any exhaustive theory of historical time or to enter into the philosophy of history, in the next section we constrain ourselves to a schematic framework that allows us to determine which aspects of historical time can be quantified and further investigated. The schematic framework is rendered in Figure 10, where the top section represents the historian's perspective and the bottom section represents the historical actor's (agent) perspective. These two sections are separated by a horizontal line representing the passing of natural time, which, as mentioned, flows independent of any event or human intervention.

Focusing first on the historian's perspective – and based on the works of Fernand Braudel and Ernst Bloch[22] – we identify three forms of historical explanations differentiated by their time scales. The first is the "Time of Events," which roughly corresponds to Braudel's "Time of Agents." From a network point of view, the "Time of Events" involves known events connected by historians based on a specific historical hypothesis dependent on the research question at hand. An example of this kind of research in the frame of network-based history writing is given in Section 3, where we have connected all historical sources that we consider relevant to the research question at hand. The "event" in this case is the appearance of each source: the publication of the textbooks.

20 Sorokin and Merton 1937; Rosa 2013; Koselleck 2004.
21 In Section 5, we simulate an agent-based model in which the agents are the printers and publishers of textbooks and therefore historical actors. For this reason, in this work, we interchangeably use historical actors and agents.
22 Braudel 1972–1973; Bloch 1973.

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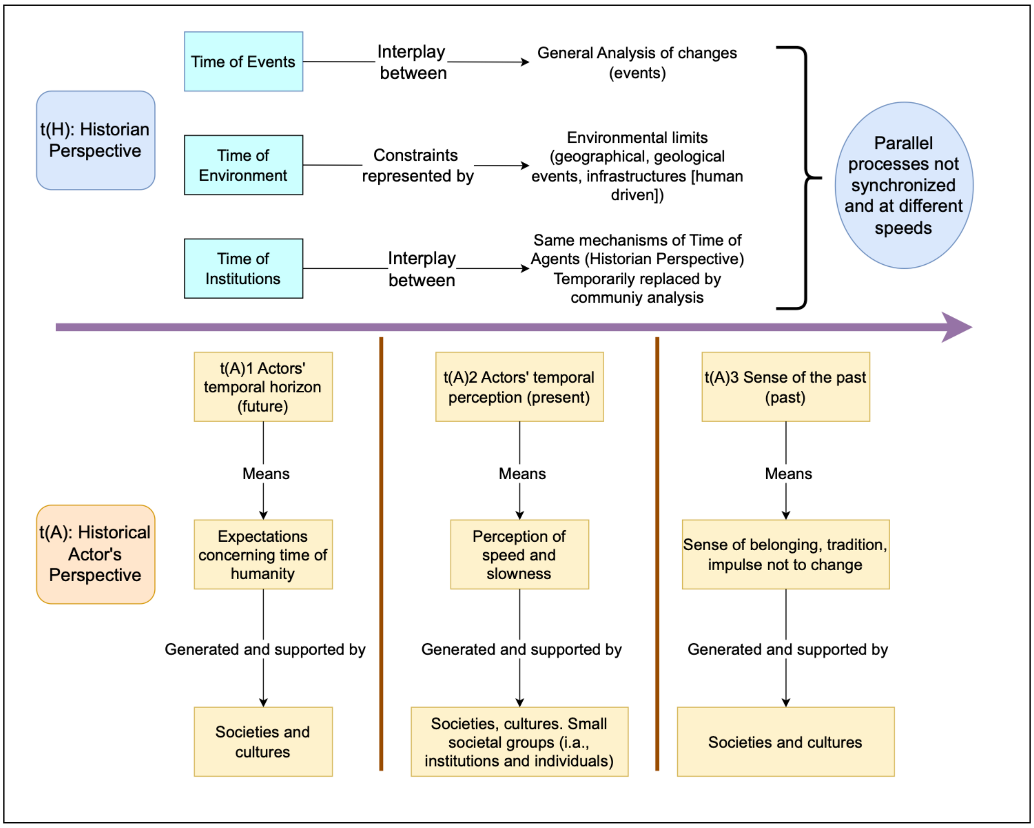

Fig. 10 Schematic representation of all aspects of historical temporality that are relevant in historical reconstructions. The central arrow pointing right displays the regular flow of natural time. The upper part displays the three major aspects of historical time as considered by historians who consider a past process or phenomenon in its entirety. The lower part shows the aspects of historical temporality related to the historical actors, particularly their perception of past, present, and future.

The major difference between Braudel's conception and the one presented here is in reference to the time scale. With "Time of Agents," Braudel directed attention to the time scale of individual humans. While we consider the appearance of the sources as the product of human agents, we nevertheless connect (or can connect), in a single graph, events that supersede the time interval of a human lifespan. If the research question requires it, we can compensate for such a change by creating additional graphs in the same multi-layer network in which links among sources (textbooks) produced by individuals who did not live contemporaneously are not allowed.[23]

23 Zamani et al. 2023; Valleriani et al. 2022.

With "Time of Environment" and "Time of Institutions," we refer to the same events (i.e. textbook publications); but in this case such events are connected on the basis of aspects that follow different, longer, time scales. If, for example, textbooks were connected because they were produced by the same printing workshop or printing brand, then the ages of their links might exceed the lifespans of the owners of the workshop. Print workshops, for instance, were often inherited within the families over generations during the early modern period. In this respect, such a workshop would be the institution in the "Time of Institution." "Time of Environment" (or environmental time) refers to longer time scales. The definition of *environment* can also be seen as more abstract than its immediate meaning. It could be the shores of the Mediterranean Sea (as in Braudel's case) as well as the use of a specific language within a large societal group in a given spatial region. Depending on the research question, one, two, or all these time scales (or graphs) can be considered at the same time, although their flow is not synchronized.

On a formal, network-based level, the current methods used in the frame of the historical research allow us to consider all these levels and their various time scales in one and the same network, for instance by making use of multi-layer networks … at least in principle.

According to the conception outlined here, the historian's perspective fully corresponds to the external view – looking at the whole forest as a single entity rather than inspecting individual trees. While this view is fully legitimate, it does not imply any form of historical inevitability.[24] It leaves fully open the question about the roles and agency of the individuals involved in the network and the way the network influenced them and vice versa. We want to suggest here an approach led by the concept of *histoire croisée,* an expanded meso-history that combines not only the diachronic and synchronic approach but also the historical actors' perspective within the same formal mathematical object.[25] This means investigating the whole network, the way it changes, and the reasons behind those changes, all at the same time and in a quantitative manner.

The advantage of such a holistic approach is that it allows us to pose the question of individual determination and agency. Using the words of Christopher Rundle, "can individuals' actions, in different circumstances, be more – or less – determined, with actors feeling free at certain points and constrained at others?"[26] The possibility of seeing the actors in the network opens the door to the investigation of the constraints that might have affected the agents and, in turn, the

24 Berlin 1954.
25 Werner and Zimmermann 2006; Little 2010; Rundle 2018.
26 Rundle 2018, p. 92.

evolution and transformation of the network. Finally, what if time itself is seen as such a constraint, as neurology suggests?[27]

The lower section of Figure 10 displays a scheme that represents the multifaceted meanings of time considered from the historical actors' perspective. For these historical actors, time is not only seen as the natural, measurable flow of time (represented in Figure 10 as the central arrow, the point of reference for the whole conception of historical time). For the actors, as for every human being, time is also a vision related to future expectations, a perception of the present, and a sense of the past.

The legal historian Andreas Thier was able to show that the structure of promulgated laws inherently depends on the expectations concerning their time of validity, and therefore on the temporal expectations of the actors involved in the process of law making. In particular, such differences appear when laws are compared between cultures that adhere to different conceptions of time. Looking at antiquity and, specifically, at the Roman Empire, he showed the link between their belief in an eternal world and the structure of their laws, a structure that is not to be found in laws promulgated by societies characterized by the belief in an end of the world, like the medieval one.[28] Inspired by this insight, we define one of the three temporal dimensions of the historical actors as the *future expectation of time,* namely an expectation rooted in the collective in which they live (rather than an individual one), an expectation that supersedes individuals' lifetimes.

When it concerns the present, the time of the historical actors is best defined as the perception of the speed and slowness of time, namely the perception of the velocity of changes affecting the context in which individuals are networked. The maximal temporal horizon in this case is related to individuals' life length expectation, or slightly beyond if direct descendants are considered. This aspect of time corresponds to what is defined as social time, namely a time that is *not* divided into equally long time-steps but by the number of events. Looking back at the temporal production rate of the historical sources analyzed in this work (Figure 2), social time implies that the time-step would be divided by the number of publications and not by the number of years, as in Figure 11. This information would finally provide a proxy to speculate about the time perception of the historical actors. Based on the results shown in Section 3, we can infer that those authors, printers, and publishers who were active between the 1530s and the 1550s perceived a radical change of dynamics in book production and knowledge circulation. Finally, moving a step forward in this conceptual map, we can plausibly formulate the hypothesis that such historical actors, being influenced by this context, felt a pressure to act and a need to change their own context, and

27 Tverski and Kahnemann 1974; Wu et al. 2022.
28 Thier 2017.

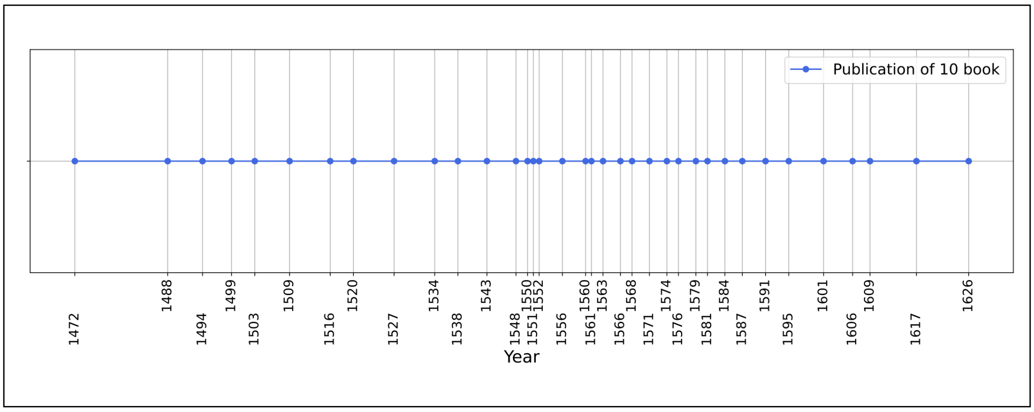

Fig. 11 Social time. The timeline displays the publication frequency within the *Sphaera-Sacrobosco* dataset, determined by steps based on the number of events rather than regular intervals of natural time, as shown in Figure 2. In this plot, each step represents the publication of 10 editions. The plot clearly shows how social time can be used to display the phenomenon of time compression (acceleration) that historical actors perceived around the publication year of Copernicus's work, 1543.

thus to publish a new book, giving rise to a kind of Matthew Effect in the academic book market, a phenomenon that looks like a self-feeding loop.

Coming to the last aspect of time in the frame of the historical actors' perspective, we define the sense of the past as the perception of individuals who belong to a more or less traditional society and culture, *traditional* in this case meaning "less inclined to change." The temporal horizon expands in this case to the time before an individual's life; and belonging, for instance, to a highly traditional society transmutes into the influence of the society on the individual, an influence that operatively acts as a constraint *against* actions, meaning against changes in the context (and the network). Religions that act in societies through powerful, stable, and *longue-durée* institutions (such as the Catholic Church) might represent good examples of how a sense of the past influences individuals' decisions. The time of the historical actors is here defined as the interplay of these three perspectives, where each of them embeds the potential of influencing the actors' decisions and therefore their active roles in network evolution. It is in this respect, especially, that we think of time as a causal effect.

As mentioned at the beginning of this section, our goal here is to investigate which aspects of historical time can be quantified in the frame of a network-based historical investigation. We have already mentioned that the historian's perspective can now be easily quantified using multi-layer networks, which include the different time scales along which historical processes unfold. Much remains, however, before we can quantify the interplay of the three temporal perspectives that define the time of the historical actors. Besides such interplay, moreover, there is no suitable method currently available that can quantify historical time in reference to future expectations while retaining a sense of the historical actors' past. As for the time perception of the actors concerning their present, however, in the next section we would like to suggest an approach based on agent-based modelling as a way to move toward the integration – on a mathematical level – between the historian's and the actors' perspectives, which will be then discussed in Section 6.

5. Historical Actors' Present Time Perspective: An Agent-Based Model

The "events" considered here are the publications of the editions of the textbooks. It has already been demonstrated that the key role in managing the production and distribution of academic books during the early modern period was not that of author but rather of printer and publisher, eventually in cooperation or through a dialogue with the author.[29]

Book producers were entrepreneurs, which means they were interested in publishing books in order to gain money and increase their profit. These producers invested their own capital by putting it at risk for each individual print run. This capital exposure period was relatively long, as books were considered "as new" for a time between 50 and 80 years.[30] The early modern book market was a highly competitive market, and economic growth fundamentally dictated what could be printed and what could not.[31] The choice to focus on only the figures of the printers and publishers (considered together as "producers") of the textbook editions turns out, therefore, to be the most logical on the basis of our historical insights. Moreover, it also simplifies our experiment. In the following, therefore, the producers are referred to as *agents*.

In this section, our goal is to create a simulation concerning the behavior of the book producers and analyze whether it fits with the results obtained through the network analysis. In particular, we refer to the dynamic of the circulation of knowledge as it results from the analysis of the dynamic of the re-occurrence of text parts, as plotted in Figure 8.

In order to reach this objective, we rely on Agent-Based-Modelling (ABM) to simulate an environment that can lead to a known output. Such ABMs have been

29 Zamani et al. 2023; Valleriani 2020b; Valleriani and Ottone 2022a; Valleriani et al. 2022; Pantin 1988.
30 Nuovo 2013.
31 Zamani et al. 2023.

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employed in numerous historical research projects to test hypotheses and model social and economic interactions in past societies.[32] In this case, we set out to create an ABM to simulate and test hypotheses relating to the economic situation in the early modern period; more specifically, we set out to investigate the book market and attempt to simulate the market conditions inferred through rigorous historical and complex network analysis conducted from a *historian time* perspective (see Section 3). Through this analysis, we simulate a variable market condition based on the findings in Section 3.3, and set out constraints that encourage economic gains by the agents in order to validate the hypotheses obtained through our network studies.[33]

5.1 Simulation Setting

The market moves between three different production phases, which are reflected in different perceived temporal speeds on the agents' level. The first production phase [**Phase I: Initial**] takes place between 1472 and 1530. It is characterized by high text part reprint activities, with a slowly increasing tendency to publish novel work. The second production phase [**Phase II: Acceleration**] is a phase of accelerated activity and takes place between 1531 and 1600. In this phase, a larger number of new text parts are introduced into the market, initially published almost exclusively separately from previously published text parts, followed by a sub-phase in which book producers started re-introducing older work alongside the new text parts. The last phase [**Phase III: Decline**] is characterized by a general decline in new text part production due to the emergence of a new paradigm in astronomy (see Figure 12). These three phases reflect the publication dynamics of the *Sphaera-Sacrobosco* dataset as shown in Figure 11. In this case study, the geographic location of actors and the appearances of text parts are not taken into consideration. However, future studies will address these factors and add them to the simulation.

5.1.1 *Agent Setting*

The main agents in our simulation are the book producers, who aim to publish books for financial gains at every single time-step. These m agents start the simulation with the same initial financial balance (capital) from which they have to buy text parts from the market by solving a knapsack problem, which involves selecting a subset of items (in this case text parts), each with a specified weight and value, to maximize the total economic value of the output (in this case the

32 Brughmans and Poblome 2016; Carrignon, Montanier, and Rubio-Campillo 2015; Carrignon, Brughmans, and Romanowska 2020.
33 Zamani et al. 2023; Eberle et al. 2024. For the code in order to repeat the analysis, see Valleriani et al. 2025.

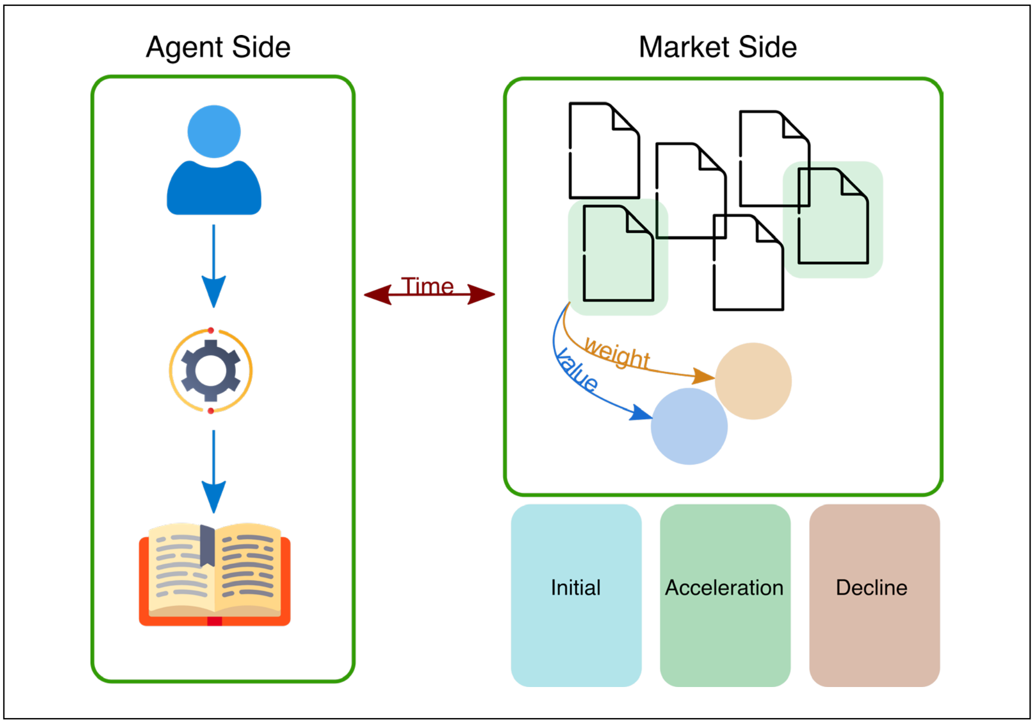

Fig. 12 Diagram to highlight the structure of the proposed simulation. Left (Agent Side): agents, who have to optimize their book publication strategy based on the market (Figure 13). Right (Market Side): different sorts of text parts available on the same shared market; some are reprinted text parts (white), others original text parts (green). Each text part has a weight and value. The weight (orange circle) represents the amount of capital needed by the agent to print a specific text part, while the value (blue) represents the attractiveness of printing this part, be it innovation or profit. The market behaves in three different ways along the three chronologically ordered phases symbolized in the lower right corner.

printed book) without exceeding the total capital at the agent's disposal[34] (see Section 5.2 for a more detailed look at the problem). At each time-step, the agents have access to a randomized subset of the available text parts in the market to simulate the fact that historical actors did not have access to every text part at every time-step. They must optimize their own knapsack problem by choosing which text parts to buy from those that are randomly available to them. At this stage of research, we do not consider the geographic information or the movement of the agents.

34 Cormen et al. 2022.

5.1.2 *Market Setting*

The market, on the other hand, behaves differently. We model its behavior according to the results shown in Section 3. In **Phase I: Initial**, the market produces a limited amount of new text parts compared to previously printed text parts; in **Phase II: Acceleration**, the market produces a large number of new text parts at each time-step to simulate the increase in the number of text parts within the *Sphaera-Sacrobosco* dataset, likely resulting in the increased speed of time perception for the agents. Finally, in **Phase III: Decline**, the number of new text parts declines sharply, which means that, at each time-step in Phase III, the actors have more restricted access to new text parts, especially as those new text parts that appeared in Phase II begin to lose value.

Each text part within the market has (1) a class, (2) a value, and (3) a weight. The class shows whether the text part is a reprint or an original text part. Text parts are original at the time-step when they are printed and appear on the market for the first time, after which their class becomes a reprint. The value and weight of each text part represent the profit or novelty and the cost of printing, respectively. An original text part that appears on the market for the first time has a high value due to the novel content it introduces, as well as a high weight; since there are not previously printed versions, the agents have to invest a higher amount of capital to incorporate these parts into their books – an event that is attested historically since the historical book producers needed to spend a higher amount of capital to account for typesetting, for example.[35] With each time-step, both value and weight decay at various rates, simulating both the loss of the novelty factor and the possibility of printing that text part by copying it from another printer (reducing costs such as typesetting), and thus reducing the cost of including that text part in the book.

5.2 The Knapsack Problem for Agent Book Creation

At each time-step, the agents aim to solve a *1-0 knapsack problem* to create their books. The knapsack is a well-known optimization problem and can be briefly explained for our case as follows.[36] At each time-step, the m agents are exposed to n text parts, with each of those characterized by a value v_i and a weight w_i (orange and blue circles in Figure 13). An agent's goal is to optimize the impact of their published book V, which will positively impact their earnings by adding the text parts with the most value v_i while being limited by their budget W, which can only accommodate a limited number of text part weights w_i. In this case, the agent cannot print a fraction of a text part. A schematic representation of this problem is shown in Figure 13.

35 Valleriani et al. 2022.
36 Cormen et al. 2022.

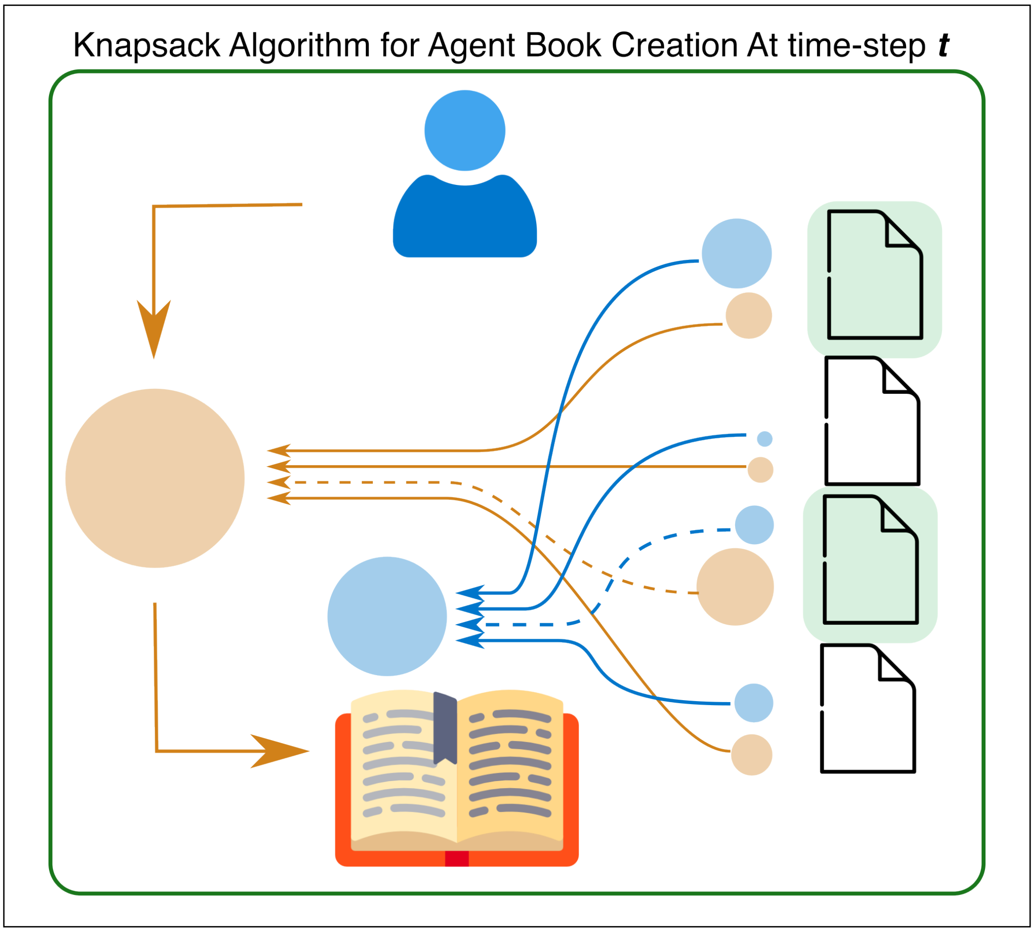

Fig. 13 Schematic representation of the knapsack problem for the Agent-Book-Creation at each time-step. An agent must choose from a subset of available text parts, which are generally composed of new (green) and previously printed (white) text parts. The agent is constrained by a budget, represented by the large orange circle on the left, and must choose carefully which text parts will finally constitute the edition. Each text part has its own cost that the agent must consider (represented by the smaller orange circles on the right). The agent is motivated by the goal to maximize the impact of her or his book by increasing its values and the financial gain at production time (represented by the blue circle on the right); the agent tries to realize this goal by adding text parts with the best value for cost within the frame of the available capital (the value of each text part is represented by a blue circle on the right).

5.3 Preliminary Results

Despite the fact that this is a preliminary simulation, attempts to simulate the historically validated market environment and book producers' behavior at different phases have led us to some preliminary insights that fully correlate to the change of dynamics of the circulation of knowledge disclosed through the network analysis. As shown in Figure 14, the *m* agents present similar text part choices across the different phases. In Phase I, the agents favor older, reprinted text parts, presumably due to their low cost. In the acceleration phase, Phase II, the agents tend to pivot to new or only recently available parts and only marginally use the previously printed text parts. In the final phase, Phase III, the agents tend to balance their book with a choice of relatively recent text parts, as well as lean back into the traditional (text parts published in the early years of the simulation), which produces a "two-peak" plot in red.

Such behavior is observed within the *Sphaera-Sacrobosco* dataset, where the books produced in the historically attested Phase I rely heavily on traditional text parts, those already known, reprinted, and accepted by the scientific community. The disruption at the beginning of the historically attested Phase II – which witnessed an influx of new text parts carrying new and unpublished knowledge – lead the book producers to prioritize the publication of the new material. In the historically attested Phase III, they revert to a mixture of older, traditionally accepted, and reprinted text parts and recently produced text parts. This result is in line with the findings of the network analysis in Section 3.4, where it was shown that – at the beginning of the acceleration phase – the most influential editions timewise (whose influence extended far into the future) were not reliant on a high quantity of non-novel text parts. Instead, the influence of these editions stemmed from the careful selection of novel text parts.

While this simulation was able to reflect a certain aspect of the early modern market for astronomy textbooks, it is clear that the early modern market was regulated by complex forces that are not present in our simulation.[37] However, this approach, combined with what we already know about the *Sphaera-Sacrobosco* dataset, opens the door to a more complex and rigorous simulation to generate new historical insights on the *historical actors'* level as well as to the possibility of integrating the historian's perspective.

37 Zamani et al. 2020.

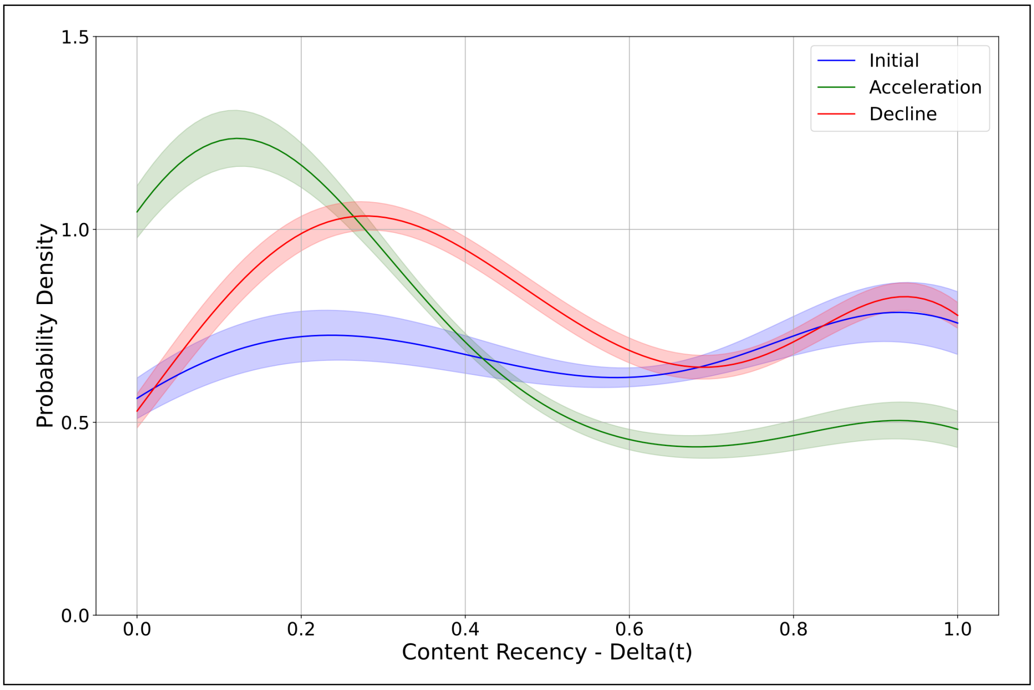

Fig. 14 Results of the average behavior of *m* agents across the different phases of the simulation with a 95 % confidence interval. The plot represents the types of text parts these agents chose to include in their editions along the phases of the simulation. The blue color represents Phase I: Initial, the green color represents Phase II: Acceleration, and the red color represents Phase III: Decline. The y-axis shows the probability density based on the edition content histograms, while the x-axis represents the "recency" of these text parts normalized between 0–1, with 0 [left side] being an original text part published for the first time, while a value of 1 [right side] represents a text part that has existed in the simulation since its initial time-step, thus considered an old reprint. The plot clearly shows a) that the editions of the initial phase are constituted by a mixture of new and reprinted text parts, b) that the acceleration phase displays the increased relevance of innovation (new text parts) while conceiving new products for the market, and c) that the final declining phase is characterized by a tendency back toward the behavior of the initial phase.

6. Conclusions

We began by questioning whether the timing of Rheticus and Petreius's 1543 publication of Copernicus's famous work can be explained by formulating a cause-effect relationship inherent in the interplay between the general dynamics of the circulation of knowledge and the way the historical actors perceived these dynamics. To investigate this, we first relied on network analysis of the dynamics of production of textbook editions, which we consider proxies for the circulation of knowledge. After having identified that both layer SOP (same original part) and layer SAP (same commentary) are the most influential, we identified the most influential textbooks – essentially those that have high out-degrees and low in-degrees – and we found that they are those containing a smaller number of text parts. All these influential editions were published around the time of the dramatic change in the dynamics of the circulation of knowledge (in this case, a dramatic acceleration) that can be observed starting in 1531 and that became particularly evident around the date of publication of Copernicus's work. Also particularly relevant here is the fact that the most re-occurring text parts testify to the increasing mathematization of astronomy as taught at the universities, and that one center of this change of dynamics and content was Wittenberg, where Rheticus was active.

With these quantitative results, we moved toward the formulation of historical temporality animated by the question of whether Rheticus and Petreius's incentive to publish Copernicus's work was motivated by the dynamic shift in the circulation of knowledge after 1531 and even more after 1538. To do so, we first needed to distinguish between the historian's perspective, which allows us to understand the entire process, and the perspective of the historical actors, experienced by the actors themselves. After an overview of all aspects of historical temporality, we asked which of these aspects can actually be quantified from a methodological point of view. Apart from the historian's perspective, we suggested a quantified approach for what concerns the historical actors' perception of the dynamics in their present time. To achieve this, we relied on the concept of social time and proceeded to analyze it utilizing an agent-based-model approach.

We produced an ABM simulation by dividing the period considered into three phases, the first coinciding roughly with the first phase indicated by our network analysis, the second with the initial phase of the second period (characterized by the acceleration of dynamics), and the third phase referring to the remaining time interval (see Section 3). Within the *Sphaera-Sacrobosco* dataset, we observed that book producers in Phase I produced editions by heavily relying on traditional text parts, those that have been already known, reprinted, and accepted by the scientific community. The disruption at the beginning of the historically attested Phase II (around 1531), which witnessed an influx of new text parts carrying new and unpublished knowledge, led the book producers to prioritize the publication of these new text parts. In the historically attested Phase III, finally, they start reverting to a mixture of older, traditionally accepted, and reprinted text parts and recently produced ones. Using the simple ABM model proposed in Section 5, we were able to show the plausibility of our hypothesis, which connects the change in general knowledge circulation dynamics with the historical actors' perception of these processes, driving them to gravitate toward publishing new, innovative parts in search of profit. This relation can be perceived as causal. As all these aspects are different components of what is defined as historical temporality, we define time itself as a causal parameter.

Our exploration of the historical timing of the publication of Copernicus's work by the likes of Rheticus and Petreius sheds some light into the interplay between the broad dynamics of knowledge circulation (as explored by the network analysis) and the subjective experiences of the historical actors who sought profit in times of knowledge acceleration. Using both network analysis and ABM approaches, we have shown the plausibility of the hypothesis that the changes in knowledge dynamics, namely the acceleration after 1531, led to changes in the behavior of the historical actors. The perceived causality between historical temporality and individual agency highlights the importance of considering *at the same time* the macro- (historian view) and the micro- (historical actor view) perspectives in historical analyses.

Our multi-disciplinary approach – which combines conceptions of historical temporalities on the one hand and mathematical-computational methods on the other, such as multi-layer networks and ABM – appears promising. However, at this stage of our research, the dynamics of knowledge circulation deduced from our networks and our simple ABM are disjointed. Some of our future work will be focused on integrating the network dynamics into a more complex ABM model where we aim to create richer simulation settings that allow for the integration of geographical encoding. The integration of system dynamics could be achieved using approaches such as exogenous emerging networks,[38] in which the network of text parts changes behavior based on the results of the system dynamics deduced from the network analysis discussed in Section 3; the agents would react at each step based on these changes. Such approaches inject empirical historical data into the simulation, allowing for a more refined testing of hypotheses. Such approaches are used to assess the impact of external factors, such as government institutions in ecology[39] or imposing specific economic constraints in forecasting problems.[40] Such methods hold promise to create more insightful ABM models using system dynamics from our multiplex, thus opening the door to further analyses using the *Sphaera-Sacrobosco* dataset.

38 Will et al. 2020.
39 Vallino 2012.
40 Poledna et al. 2023.

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