Trajectories in Physical Space out of Communications in Acquaintance Space: An Agent-Based Model of a Textile Industrial District

Fioretti, Guido
University of Bologna

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Guido Fioretti*
University of Bologna

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Abstract

This article presents an agent-based model of an Italian textile district where thousands of small firms specialize in particular phases of fabrics production. It is an empirical and methodological model that reconstructs the communications between firms when they arrange production chains. In their turn, production chains reflect into road traffic in the geographical areas where the district extends. The reconstructed traffic exhibits a pattern that has been observed, but not foreseen, by policy makers.

Keywords: Time-Geography, Agent-Based Models, Prato

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1 Introduction

Individual trajectories in physical space have been first investigated by Hägerstrand and his colleagues during the 1960s, under the label of "Time-Geography". Essentially, Hägerstrand suggested that geographers could figure out the occupation of space with time out of knowledge of (a) peoples' time schedules and (b) the opportunities for movement provided by roads or other transportation facilities [33] [66] [71] [67] [34] [35] [51]. So for instance by knowing that a certain person has to visit certain spots at certain times in order to work, to entertain herself and to meet other people, the space of her possible movements in the course of a day is contained within a specific volume in a 3-dimentional space — defined by two geographical coordinates plus time. This volume is called *space-time prism*; its projection on the 2-dimensional geographical space is called the *potential path area*, where actual trajectories unfold. Later scholars, unaware of Hägerstrand's Time Geography, re-invented the same concepts with the names of *lifeline bead* and *geospatial lifelines*, respectively [37]; henceforth, Hägerstrand's namings will be used for both streams of literature. In fact, after about two decades of partial neglect Time-Geography has returned to be quite an active research field, still undergoing theoretical development so far it regards the possibility of variable contraints on movement, the combination of space-time prisms and the evaluation of individual trajectories [78] [72] [41] [47] [58] [48] [46] [61].

This revival of interest has been spurred by recent developments among Geographical Information Systems (GIS) which, implementing previous suggestions [57] [31], have made available data on individual movements coupled with timings of meetings and other events [43] [76]. However, the development of Information and Communication Technologies (ICT) also brought to the front the problem that space-time prisms cannot only be delimited by physical movements, for communications may substitute or eventually generate physical movements.

Hägerstrand himself recognized that a phone call may substitute for physical deplacement in a very early publication [33]. Subsequent writers conceptualized the impact of ICT in terms of *extensibility* of human capabilities for movement across space [38] [1]. Eventually, empirical investigations reconstructed the time series of communications and their impact on space-time prisms [28] [2] [42]. In some of these applications, communications have been included in space-time prisms; however, communications and physical movements have always been sharply distinguished from one another albeit all these investigations had the purpose of highlighting their mutual influence. This is a key observation, for it suggests that understanding the impact of communications on travel decisions — as well as the impact of travel on communication — is essential to reconstruct spatial trajectories in contemporary societies.

However, this implies a movement away from objective features of the environment, such as physical distances or infrastructures, and into the realm of *perceived* distances, infrastructures, and opportunities [44] [70]. It amounts to shift from a concern with the set of all possible trajectories — the space-time prism — to a concern with single decisions and, therefore, single trajectories.

Models and GIS centered on autonomous, active "objects" have been advocated in order to reconstruct the physical movements of people or other actors in an artificial space [77] [69] [74] [59]. Spatial applications of cellular automata [6] foreshadowed this kind of models, known as Agent-Based Models (ABM) in order to stress that their actors are endowed with a degree of artificial "intelligence". Essentially, ABM recreate human characters in an artificial space endowing them with sufficiently complex behavioral algorithms to make their interactions non-trivial, and the outcomes of the model interesting, or even surprising [9]. In geographical applications, ABM generate all possible trajectories of the actors concerned, so the bundles of all trajectories generated by running an ABM several times in the limit tend to coincide with the space-time prisms that Hägerstrand derived from constraints on possible movements.

Geographers quickly understood the potentialities of ABM [3] [21] [5], calling for GIS that would provide ABM with appropriate data [73] [23] [39] [15] [64]. Albeit this is still not the case, there are already a number of examples of ABM in geographical contexts.

This article presents an ABM that addresses the above reported issue of communications impacting on physical deplacements. It does so by resorting to an extreme means: a *space of acquaintances* is defined, where all communications take place; as a consequence of these communications, movements in physical space take place. Thus, the model presented herein reconstructs trajectories in physical space out of knowledge of behavioral algorithms of actors entertaining communications with one another.

The context is that of a famous cluster of small textile firms, that of Prato, Italy. Section (2) illustrates the features and challenges posed by this kind of agglomeration. Section (3) expounds an agent-based model of the formation of production chains in Prato. Before running the model, Section (4) explains what data it receives and Section (5) checks its sensitivity to parameters variations. Section (6) derives shares of traffic between the communes composing the Prato province out of the reconstructed production chains. Finally, Section (7) concludes.

2 Prato as a Prototypical Industrial District

Firms are not scattered uniformly on earth surface; rather, they generally concentrate at specific places. The reasons advanced for this state of affairs include the availability of specialized labor force, the possibility of sub-contracting excess demand, complementarities of local buyer-supplier relationships, knowledge spill-overs from other firms, faster innovation, specific cultural traditions as well as opportunities to avoid labor and environmental regulations when the firms involved are very small.

Alfred Marshall, the first scholar to investigate firm agglomeration at the end of the XIX century, based his observations on the huge number of small cutlery firms to be found in Sheffield at his time [54]. Marshall coined the expression "industrial district", somehow bound to the idea of geographical concentration of a large number of small firms operating in the same industry, and used the rather vague concept of "district atmosphere" to subsume the cultural and relational factors at work. These concepts have been widely used since then, but they also show serious deficiencies when coming under close scrutiny.

In particular, the notion of "atmosphere" understands the effects of geographical proximity on economic activities as a sort of beneficial halo emanating from firms; thus, to the extent that firms are clustered on a specific territory, a halo exerts its benefits to any economic activity in the area. Albeit this sort of accounts may be satisfactory for macroeconomic theory, they fall short of explaining the economic development of a particular area. Rather, it is often necessary to reconstruct the evolution of the network of relationships between firms and other institutions in order to understand why a local economy developed along a specific path [68] [22] [29]. In particular, several authors stress the relevance of the structure of the network of interactions for knowledge development [12] [40] [63].

In many instances, the network of relations is not homogeneous with respect to the outer world. Even where all firms are equally small, only a few of them have access to the outer markets; obviously, these firms take care not to diffuse this information among other firms [8] [60]. Likewise, only a few firms have the capability of developing knowledge and, therefore, lead the remaining ones on product and process innovation [30] [11] [53]. It is clear that the capability to innovate and the capability to relate to the outer markets, albeit conceptually distinct, may correlate with one another in practice.

These pure network effects are further enhanced by the size distribution of firms. Although the notion of industrial district refers to clusters of small firms, many industrial agglomerations labelled as "districts" are not composed only by small firms [49] [50] or, even if they are, many among these small firms are arranged into industrial groups [13] [16]. In many instances it appears that the emergence of a few large firms is a question of economic development, in the sense that industrial districts that were originally composed by a large number of micro-firms evolved into industrial structures where a few larger firms emerged as leaders [75] [10] [65].

Finally, the rationale for geographical concentration of firms is changing as well. Whilst Marshall observed a huge number of tiny family firms competing on price and exploiting a traditional technology as well as their own family members, the most interesting contemporary industrial agglomerations are rather based on the capability to develop innovative knowledge [56] [55] [52].

Prato, a small town in central Italy with a tradition in the production of cloths out of regenerated wool, has been presented to the world as a prototypical industrial district composed by small family firms specialized in tiny fractions of the whole production process [7]. In reality, Prato is an area where textiles are produced since the Middle Age, which, for a few decades in the second half of the XX century, approximated the Marshallian district reasonably well. In fact, at the end of World War II a few woollen mills found it profitable to fire some of their workers, providing them with an option to take at home the loom on which they used to work in order to subcontract to them at production peaks [17]. The Marshallian district was born; at its peak in the 1970s, it arrived to include about 10,000 firms, many of them composed only by their owner or, at most, one or two employees. The number of firms started to decline with the 1980s, although the district recovered in the 1990s when it switched from a price-based to a variety-based competitive advantage [62] [26]. The beginning of the XXI century is charaterized by such a sharp competition from abroad, and such an extent of industrial concentration and non-local relations that the classification of Prato as a Marshallian industrial district is at least problematic [36] [18].

The model presented in this article reconstructs movements of goods between firms in the classical Prato, the one that very closely approximated a Marshallian industrial district. The data used by the model cover the timespan 1975–97. While the employed database is unavailable before 1975, the restriction to 1997 makes sense because it stops at a point where Prato still roughly behaved as a Marshallian industrial district.

Obviously, a few deviations from the prototypical Marshallian district occurred in this period as well. They are handled as follows:

- The fact that only a few firms entertain relationships with the outer market and that only these firms are able to arrange the production cycle, is included in the model. Indeed, this is a depature from the Marshallian ideal that was recognized even by the most extreme purporters of of Prato as a Marshallian industrial district [7].
- The fact that even in the considered period firms were to some extent heterogeneous in size is handled by the assumtion that, so far it concerns the number of shipments, larger sizes are partially compensated by larger production lots. This assumption is both supported by empirical observations and numerical simulations — see § (4).
- In this period, innovation generated a larger variety of textiles by incresing the extent of both “finishing” operations and purchases of semi-finished products outside the district [50] [26]. The model takes account of these developments by reading the number of finishing agents and external procurements each year, which increase with time.

The ensuing § (3) illustrates the model. Although it seeks to employ all available data, the reader is asked to understand it as a methodological, rather than a realistic model.

3 The Model

Several reconstructions of industrial districts by means of ABM have been made [27]. This model distinguishes itself in that it makes use of empirical data on the number of firms, besides qualitative data on their behavior (s. § (4)); therefore, some claims on possible usages of ABM for policy-making will be made. [1]

The model reconstructs the communications and related shipments between Pratese firms. By crossing reconstructed shipments with geographical location of firms, it reconstructs traffic along roads between the main settlements in the Prato province.

For each year, 1975 to 1997, the model takes as input the number of firms specialized in ten production phases: The number of (1) Traders of Raw Materials, (2) Rags Collectors, (3) Carded Spinnings, (4) Combed Spinnings, (5) Warpers, (6) Weavers, (7) Dyeing Plants, (8) Finishers, (9) Traders of Finished Products and (10) Middlemen. Population dynamics is external to the model: each year, the model reads the number of firms that the empirically observed population dynamics generated.

At the beginning of each year, firms are placed on a torus that represents the space of acquaintances in the district. This is the space where communications occur, by any

[1]The same software was also used in a previous publication, but it was fed with a different dataset [26]. Furthermore, the outcomes of those simulations were not crossed with data on the geographical location of firms in order to esteem traffic shares.

means ranging from physical meetings to phone calls, e-mail, and so on. The definition of an acquaintance space, independent of physical space, attempts to solve the difficulties that arise when communications are introduced into Hägerstrand's space-time prisms (s. § (1)). Movements on physical space will be determined by communications in the acquaintance space.

This model makes use of all available data, but does not rest on an independent empirical investigation. Thus, since no data regarding communications between Pratese firms has ever been collected, ignorance of the initial structure of the acquaintance space is assumed. At the beginning of each simulation year 1975–97, firms are dropped randomly on the space of acquaintances. Subsequently, during the year firms move in the space of acquaintances, eventually forming chains of production.

All production chains end up with fabrics, the typical product of Prato. Economic equilibrium is implicitly assumed, in the sense that demand is assumed to match supply.

Of all firms that can be found in the Prato district, middlemen are the most crucial. Middlemen arrange the operations of other firms. Thus, Middlemen are the only Pratese firms that have contacts with international buyers.

The history of each year (1975, 1976, etc.) is reconstructed by means of a large number of simulation steps. At the beginning of each year, the historically given number of each type of firm (Traders of Raw Materials, Rags Collectors, etc.) is placed randomly on the space of acquaintances. Middlemen stay fixed; all other firms move around randomly.

In particular, the Traders of Finished Products observe the surrounding space while they move around. As soon as they detect a middleman in their visual range, they move to it and place an order. In its turn, the Middleman starts to explore the acquaintance space around its position – its acquaintees – looking for firms that are able to carry out the production phases that yield the goods requested by the Trader of Finished Products. By default, all firms (except Middlemen) move around randomly in acquaintance space. However, as soon as they are reached by the command of a Middleman, they immediately move close to it and form a production chain – indeed, firms collaborating in a production chain are necessarily well acquainted with one another.

Appendix (A) illustrates these processes with the aid of flux diagrams. Figure (1) illustrates a snapshot of the model. Dots represent firms in the space of acquaintances. Stripes of firms represent production chains, i.e. a set of firms that are carrying out a sequence of operations yielding the final product. The Middleman is at the beginning of a stripe; eventually, two or more stripes may depart from the one single Middleman.

Middlemen cannot arrange firms in any order when they form a production chain. There are ten types of firms differing from one another according to the production phase that they carry out (Traders of Raw Materials, Rags Collectors, Carded Spinnings, Combed Spinnings, Warpers, Weavers, Dyeing Plants, Finishers, Traders of Finished Products and Middlemen). Technological requirements impose a sequencing on certain phases: Spinning must precede Warping, which must precede Weaving, which must precede Finishing operations. On the contrary, Dying may take place either before Spinning, or between Spinning and Warping, or between Weaving and Finishing [4].

Furthermore, although all production chains yield the same final product – fabrics – they may employ different phases. In particular, spinning may be carded or combed.

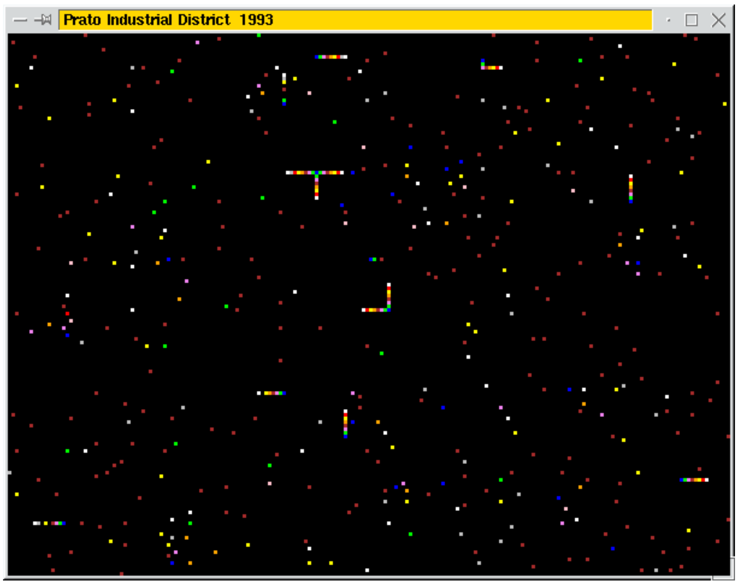

Figure 1: The space of acquaintance and the firms on it, at a particular step in the year 1993. Firms are colored dots (Carded Spinnings: yellow; Combed Spinnings: pink; Dyeing Plants: red; Finishers: purple; Middlemen: blue; Rags Collectors: grey; Warpers: orange; Weavers: brown). Lines are production chains. Production chains start with a Middleman; if a Middleman is arranging several production chains, several lines depart from him.

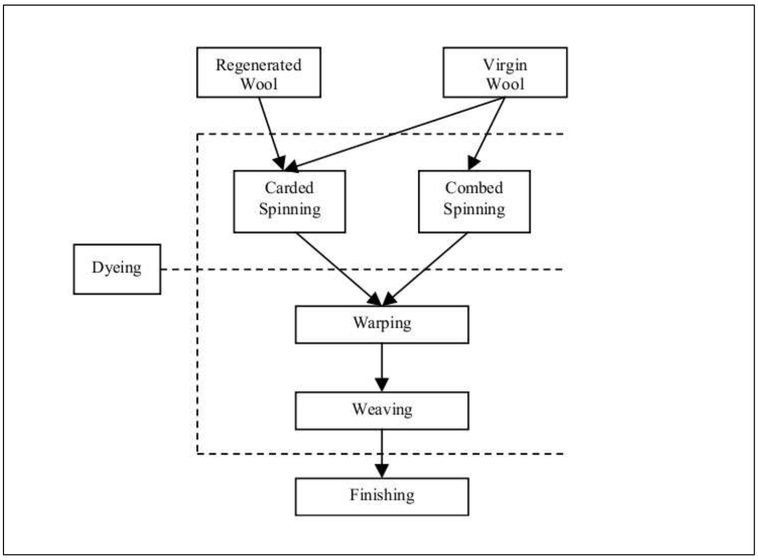

Figure 2: A scheme of the production processes to be found in Prato, rough enough to be considered invariant with time. Dyeing can either take place before spinning, or before warping, or just before finishing operations. Spinning can be either carded or combed. Carded spinning may either make use of virgin wool or regenerated wool obtained from rags and old clothes. On the contrary, combed spinning necessarily requires virgin wool.

While Combed Spinnings require virgin wool, Carded Spinnings can take as input both virgin wool and regenerated wool. In the first case, the Traders of Raw Materials provide wool; in the second case, they provide rags and old clothes. Finally, certain semi-finished goods may be purchased by a supplier or they may be produced within the chain.

Figure (2) subsumes the above considerations in a general scheme of the production processes to be found in Prato [4]. Wool (either virgin or regenerated) must be spun (either carded or combed), warped and then woven. Dyeing can be carried out at one of three different stages. Finally, fabrics are refined by a series of finishing operations. Since technical innovations either concern machinery or details that at this level of generality do not show up, we can safely assume that this scheme did not change in the 1975–97 time interval.

The technological constraints of figure (2) restrict the set of possibilities to the 11 production chains illustrated in figure (3). Figure (3) should be read top to bottom, from a Trader of Raw Materials (TRM) to a Trader of Finished Products (TFP). For instance, the leftmost production chain entails the following sequence: Trader of Raw Materials $\rightarrow$ Combed Spinning $\rightarrow$ Warper $\rightarrow$ Weaver $\rightarrow$ Dyeing Plant $\rightarrow$ Finisher $\rightarrow$ Trader of Finished Products.

The choice of one among the 11 possible production chains illustrated in figure (3) depends on which firms are closest to a Middleman in its acquaintance space. As

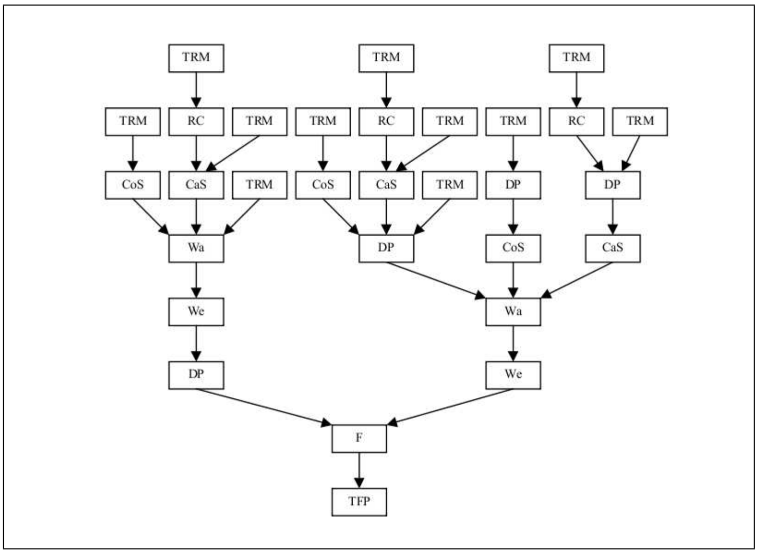

Figure 3: The eleven production chains that can be constructed with the ten given types of firms. Abbreviations are as follows: TRM = Trader Raw Materials; RC = Rags Collector; CaS = Carded Spinning; CoS = Combed Spinning; Wa = Warper; We = Weaver; DP = Dyeing Plant; F = Finisher; TFP = Trader Finished Products. Middlemen organize production chains but they are not really part of them.

soon as a Middleman receives an order from a Trader of Finished Products, it starts to construct a production chain beginning from its end. In the terms of figure (3), it looks for a path bottom to top from a Trader of Finished Products to a Trader of Raw Materials.

A production chain starts when a Trader of Finished Products moves close to a Middleman and makes an order. The Middleman looks first of all for an agent that can be added to the Trader of Finished Products. According to figure (3), this must be a Finisher. Thus, the Middleman explores the surrounding acquaintance space. As soon as he finds a Finisher, he attaches it to the Trader of Finished Products. At this stage, the production chain is composed by two elements (TFP and F). According to figure (3), the Middleman may either attach a Weaver or a Dying Plant to the Finisher. Thus, it explores the surrounding acquaintance space looking for one of these firms. What firms it will attach (We or DP) depends on what firm it finds first. Thus, it depends on how many firms of each type are closest in its acquaintance space. This process continues along several bifurcations until a Trader of Raw Materials is found: at that point, a production chain has been completed.

In the end, selection of one out of the eleven possible production chains depends on which firms are nearest to middlemen in acquaintance space. This depends on how many firms of each type are available in a particular year, as well as on which firms have been contracted by middlemen during the previous steps.

In fact, at the end of each step all production chains are destroyed and their component firms are set free to move randomly. However, if a Trader of Finished Products remains sufficiently close to a Middleman, in the subsequent step it will prompt the construction of a production chain attached to the same Middleman. So if also the other firms did not move too far in the meantime, it is quite possible that the very same production chain will be reconstructed.

Thus, the model is path-dependent because production chains are chosen depending on the position of firms in acquaintance space. However, we shall focus on stable properties achieved by performing a large number of simulation steps for each year and by running the model with many different initial droppings of firms.

Since the geographical location of each firm is known, the production chains thus obtained translate into traffic between and within the communes of the Prato province. Appendix (B) explains the details of this passage.

The number of steps in each year is chosen as follows. In order to obtain reliable results, the number of interactions must be kept nearly constant each year. Thus the number of steps in year y, denoted by $s(y)$, is chosen such that $s(y)n(y) = c$, where $n(y)$ is the number of firms in year y and c is a constant. It was observed that $c = 1,000,000 >$ is sufficient to yield smooth results. The code has been written in *objective C* on the *Swarm-2.2* platform. It is free software, available at ¡http://econwpa.wustl.edu/eprints/-prog/papers/0210/0210001.abs¿ under the terms of the GNU public license. Swarm is available at ¡http://wiki.swarm.org¿.

4 The Data

This model makes use of two sets of empirical data. The first one is qualitative data on what firms connect to what other firms in order to arrange production chains; this information has been expunged from [4]. The second dataset is quantitative: the number of firms carrying out each production phase in each year.

The data on the number of firms for each of the ten production phases have been collected by the *Istituto Nazionale per la Previdenza Sociale* (INPS), the Italian agency for social insurance. [2] These data cover all firms that have at least one employee, for whom they must pay social benefits to INPS. [3] From 1975 to 1997 INPS recorded all firms in the province of Prato, their names and addresses, a brief description of their activity and the number of their employees. From this description, and to a lesser extent from the names of the firms, I constructed a database that specifies in which phase of the production process a firm is specialized (warping, weaving, etc.).

The details of these classification criteria are explained in Appendix (C). However, the following issues deserve some attention:

1. Almost no firm carried out more than one operation, except for a very limited number of dyeing plants that performed finishing operations as well. In these very few cases, a firm appears twice in the final dataset, e.g., both in the list of dyeing plants and in the list of finishers.

[2] Data have been kindly provided by Prof. Giuseppe Tattara of the University of Venice, who accessed them in the framework of MIUR 2001.20011134473.

[3] This is the most severe limitation of these data. In fact, many family firms employ family members without any legal registration. In the limit, a firm may declare no employee, for its owner does all the work.

2. A few large woolen mills have been added to the middlemen. One reason is that the model focuses on that part of their production that exceeds their productive capacity, for which they eventually contract other firms.

The size of firms may influence the formation of production chains if large firms process more orders than small firms, i.e., if large firms participate to a larger number of production chains. However, it is also possible that large firms are involved in the production of larger lots of fabrics. In this case, the two effects may balance out so the size of firms may have no influence on the formation of production chains.

Albeit no information on lot size is available, the size of the trucks employed by Pratese firms can been used as a proxy. Empirical research has shown that the average size of trucks increases from $1.0 \div 2.5$ tons among the smallest firms to an average of 3.5 t among medium-sized firms and up to $5.0 \div 9.0$ t among the largest firms [45]. These data suggest that we may assume that lot size is proportional to firm size and, consequently, that the size of firms does not influence the formation of production chains.

This is the assumption that will be made throughout the paper — henceforth, Hypothesis (1). However, it makes sense to evaluate in what direction this assumption may distort the final results. In order to do so, let us run the model by making the opposite assumption, i.e., that inter-firm communications and, consequently, the number of production chains that are formed, are proportional to firm size measured by the number of employees. Henceforth, this will be Hypothesis (2).

The main outcome of the model (s. § (6)) are the percentages of traffic due to wares movements within and between the seven communes that constitute the Prato province: Let $w_{ij}(YYYY)$ denote the percent of traffic between commune i and commune j in year $YYYY$. The differences between the traffic percentage between any two communes in 1997 and 1975 subsume the findings of the model: Let $\Delta w_{ij} = w_{ij}(1997) - w_{ij}(1975)$ denote these differences. Thus, the differences between these values calculated with Hypothesis (2) and Hypothesis (1) tell what would happen if Hypothesis (1) would be completely wrong:

$$\Delta w_{ij}\big|_{H2} \; - \; \Delta w_{ij}\big|_{H1}$$

Table (1) reports the values of the above indicators for all possible pairs between the seven communes that constitute the Prato province. Values have been rounded to the second decimal; net of approximations, the sum of all values by rows and columns is zero.

It appears that, if Hypothesis (2) would be made, the reconstructed traffic within the Prato commune would increase less than the amount reconstructed by making Hypothesis (1). This lower growth would be balanced by a greater increase of traffic within and between other communes.

In order to understand this effect it is necessary to remark that the largest firms in the district, notably a few old woollen mills, are located in the town of Prato. These firms do not exchange wares with one another, but with their subcontractors. Thus, if the activity of larger firms is enhanced, as Hypothesis (2) does, a larger share of traffic between these firms in Prato and their subcontractors in other towns results.

Cantagallo	-0.00						
Carmignano	+0.03	-0.01					
Montemurlo	+0.21	+0.24	+3.08				
Poggio a C.	-0.01	-0.02	+0.16	-0.00			
Prato	-0.14	-0.12	+5.38	+0.32	-11.13		
Vaiano	+0.01	-0.02	+0.96	-0.01	+0.96	+0.07	
Vernio	-0.02	-0.02	+0.03	+0.00	+0.04	+0.00	+0.00
	Cant.	*Carm.*	*Mont.*	*Poggio*	*Prato*	*Vaiano*	*Vernio*

Table 1: Differences between variations of traffic percentages from 1975 to 1997, calculated with Hypothesis (2), and the same variations calculated with Hypothesis (1). Values have been rounded to the second decimal; signs have been kept even when rounded values are zero.

Because of the aforementioned empirical hints, Hypothesis (1) is chosen. The calculations above indicate that by this choice the traffic shares outside the town of Prato might be underestimated, whereas the traffic shares within Prato might be overestimated; however, § (6) will make clear that the most interesting empirical finding of this model is precisely the increase of traffic shares between communes other than Prato, so the possibility that the main result be underestimated adds to its significance.

5 Robustness and Validation

Validation is quite a problematic concept among ABM. In general, it is quite easy to check that the aggregate patterns produced by an ABM accord with reality; however, this merely ensures that the hypothesised micro-behaviors are *sufficient* to generate the observed aggregate patterns. In order to ascertain whether precisely the hypothesised micro-behaviors are those that generated the observed aggregate pattern it is necessary to observe the micro-behaviors of real social actors as well, with the relations that these behaviors generate and the aggregate patterns that ensue. Obviously, this is so an expensive kind of empirical research, that it is very seldom carried out. On the other hand, precisely the possibility of experimenting with different assumptions in order to generate a required aggregate pattern allows the modeler to ascertain what micro-behaviors are *necessary* in order to generate the observed aggregate patterns.

These state of affairs suggests to view ABM as powerful tools to carry out conceptual experiments, even when they rest on empirical data [24] [32] [19]. Their value lies in the possibility to explore the consequences of hypotheses; for instance, in the present context an ABM is used to explore possible trajectories in physical space, given reasonable and empirical assumptions on firms' behavior.

Within this exploration exercise, it is of utmost importance to distinguish micro-behaviors that generate macroscopic regularities from micro-behaviors that generate unpredictable macroscopic chaos [14]. Both outcomes are interesting, albeit for opposite reasons: macroscopic regularities point to the possibility of making predictions, whereas chaos may point to possible unpredictable consequences of quite normal mi-

	Mean Square Difference
Variance -10%	0.000017
Variance +10%	0.000013
Watching Area -10%	0.000022
Watching Area +10%	0.000023
Size of Space -10%	0.000035
Size of Space +10%	0.000022
Base Values	0.000022

Table 2: Sensitivity to variations of parameters. The value in the last row is due exclusively to random variations.

croscopic behaviors.

The model presented in this article has three parameters: the variance of the normal distribution by which the traders of finished products move at each step, the size of the area where they look for a middleman, and the size of the space of acquaintances where firms are placed. Let us measure how sensitive the model is to these parameters and, most importantly, whether their variations cause unpredictable, chaotic outcomes.

With 2,000 to 3,000 simulated firms each year, a parameters choice that yields sensible results is a variance of 10.0, a watching area of 100 pixels and a space of acquaintances of $500 \times 600 = 300,000$ pixels. Henceforth, these will be the base values of these parameters.

In order to evaluate the sensitivity of the model with respect to these parameters, six series of five simulations have been run. In each series, a parameter was decreased or increased by 10%. So the model was run five times with variance 9.0, five times with variance 11.0; five times with watching area 90, five times with watching area 110; five times in a space of 270,000 pixels and five times in a space of 330,000 pixels.

The effects of these parameters variations were measured on the relative proportions of the eleven different production chains that the model is able to reconstruct. For instance, one of these proportions is the number of production chains of the kind Trader Raw Materials $\rightarrow$ Dyeing Plant $\rightarrow$ Carded Spinning $\rightarrow$ Warper $\rightarrow$ Weaver $\rightarrow$ Finisher $\rightarrow$ Trader Finished Products, over all eleven possible production chains. This proportion can be computed for each simulation year, so it is a curve defined over the interval 1975 to 1997.

The curve obtained by changing a parameter can be compared with the curve obtained when parameters are at base values. The sensitivity to the variations of parameters is measured by the mean square differences between these two curves.

Table (2) reports this measure for all considered variations of the parameters. In order to minimize the effects of random variations, each curve is averaged over five simulation runs. The last row reports the values obtained by comparing two curves obtained from two sets of five simulation runs at base parameter values. Thus, the value in the last row originates exclusively from random variations.

According to table (2), variations of the parameters in a $\pm 10\%$ range generate variations that are of the same order of magnitude than the random variations exhibited by simulations with all parameters at base values, exhibited in the last row. Thus, this model is very robust and should be used to highlight regularities, rather than the possibility of chaotic behavior.

Among all possible regular behavior, the one that has been reproduced depends on assumptions that can be evinced from published data on production processes and registred firms. However, exploration of hypothesis might have been even more interesting if the actors would have been involved in the very formulation of the hypotheses made in the model, possibly integrating ABMling with role-playing games, semi-structured interviews or other techniques aiming at enlarging the set of possibilities conceived by the modeler [25].

Validation, among ABM, does not mean that the user of the model can be certain of the reliability of its results. Validation means that the model acknowledges the sources of the hypotheses that it makes, implements them with accuracy, and discovers the implications of these hypotheses rather than those of random disturbances, programming mistakes or hidden assumptions.

The model presented in §(3) is a valid implementation of the available theoretical and empirical descriptions of the production process in Prato at least in its "classical" years, i.e., the second half of the XX century. The validity of these theoretical and empirical descriptions is confirmed by the fact that an ABM yields results that accord with empirical findings (s. § (6); in this sense, the ABM validates the theoretical and empirical descriptions that it makes use of, rather than being validated by correspondence with reality.

6 The Results

By simulating encounters in acquaintance space, the model reconstructs communications between firms. These communications give rise to chains of production and, ultimately, to flows of goods between firms (s. Appendix (B)).

Thus, once communications have been reconstructed it is possible to derive the structure of the traffic of wares in physical space. In fact, if a middleman arranges a production chain that involves a warper at a place A who must ship his product to a weaver at a place B, then this production chain generates traffic from A to B. However, since the empirical relation between the existence of a production chain and the amounts of wares that it moves is unknown, only the shares of traffic between different communes can be obtained, not their absolute values.

The province of Prato is composed by seven administrative units, or communes: *Cantagallo*, *Carmignano*, *Montemurlo*, *Poggio a Caiano*, *Prato*, *Vaiano* and *Vernio*. The model reconstructs the shares of traffic within and between each commune. Henceforth, communes will be denoted in italics; hopefully, this notation will contribute to mark the difference between the commune of *Prato* and the province of Prato.

Figure (4) reproduces a map of the Prato province with its seven communes. Note that *Prato* and part of *Montemurlo* are lowlands, strongly urbanized communes; *Carmignano*, *Poggio a Caiano* and *Vaiano* are on the surrounding area, characterized by less urbanized plains and hills; *Cantagallo* and *Vernio* are up on the mountains. Note also that the commune of *Poggio a Caiano* is very small; therefore, it often plays a

Canta	0.017%						
gallo	**0.054%**						
Carmi	0.010%	0.000%					
gnano	**0.054%**	**0.036%**					
Monte	0.505%	0.077%	3.186%				
murlo	**1.108%**	**0.822%**	**5.283%**				
Poggio	0.017%	0.006%	0.258%	0.002%			
a C.	**0.040%**	**0.036%**	**0.514%**	**0.009%**			
Prato	1.926%	0.272%	26.800%	1.164%	58.633%		
(com.)	**2.722%**	**2.771%**	**29.529%**	**1.700%**	**43.827%**		
Vaiano	0.067%	0.006%	0.884%	0.031%	3.616%	0.054%	
	0.238%	**0.190%**	**2.432%**	**0.100%**	**6.468%**	**0.256%**	
Vernio	0.025%	0.004%	0.537%	0.024%	1.787%	0.076%	0.012%
	0.051%	**0.035%**	**0.453%**	**0.021%**	**1.153%**	**0.092%**	**0.005%**
	Cantag.	*Carmig.*	*Montem.*	*Poggio*	*Prato*	*Vaiano*	*Vernio*

Table 3: Reconstructed shares of traffic flows (three digits approximation) within and between the seven communes of the Prato province. Upper rows: 1975. Lower rows (bold): 1997.

negligible role.

Table (3) reports the values of the reconstructed traffic flows for the years 1975 (upper rows) and 1997 (lower rows, bold). These values will be commented with the aid of figures that illustrate their most salient features.

Figure (5) illustrates (top to bottom) the percentages of traffic within each commune for all years 1975 to 1997. The extremes of these curves are the top diagonal values of table (3).

Note that, since the percentages of traffic within *Prato* and *Montemurlo* are much larger than the percentage of traffic within the other communes, curves have been depicted on a logarithmic scale. The logarithmic transformation compresses variations among large values, so the strong decrase of traffic share within *Prato* exposed in table (3) — from 58.633% in 1975 to 43.827% in 1997 — appears as a just slightly descending curve.

Figure (5) highlights quite different patterns of development of traffic within each commune. Albeit compressed by the logarithmic transformation, the curve of traffic within the commune of *Prato* shows a continuous decrease of traffic. This implies a process of gradual diffusion of the textile industry from the town of *Prato* to its surroundings. However, this process slowed down with the 1980s.

The communes that are closest to *Prato* took the greatest advantage. Most of the traffic share lost by *Prato* accrued to *Montemurlo*, just 6 Km. from *Prato* and in the process of forming a single urban agglomerate with it, though also *Carmignano* and *Vaiano* increased their shares. On the contrary, the more isolated *Cantagallo* and *Vernio* on the mountains got very little of this share, or even decreased theirs. Note that the commune of *Poggio a Caiano*, though on the plain, is so small that its infra-communal

Figure 4: A map of the Prato province with its seven communes, morphology and communication infrastructures.

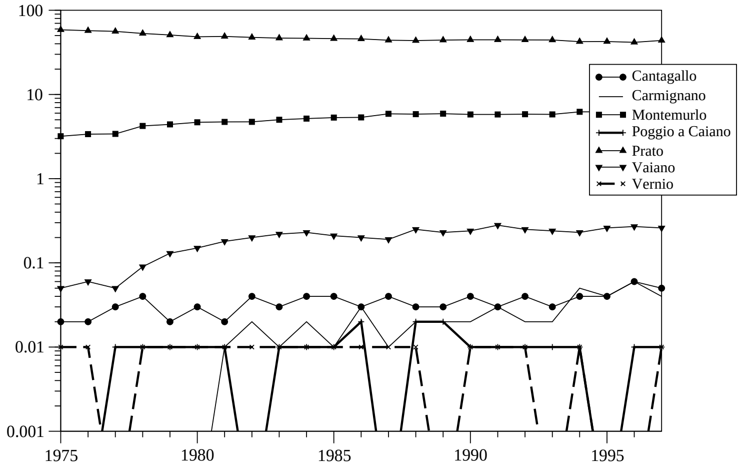

Figure 5: Reconstructed percentages of wares traffic within each commune originated by the textile industry, 1975 to 1997. Averages over ten simulation runs at base parameter values. Values smaller than 0.001 have not been reproduced in the picture.

traffic is negligible.

Infra-communal traffic indicates the extent to which a commune is a self-contained economic unit, with the proper number of each kind of specialized firms in it. Development of the textile industry could be also achieved with, say, Prato specializing in trading and Cantagallo specializing in weaving, which would cause a large amount of traffic between these two communes but little traffic within them. Indeed, the development of inter-communal traffic shares is much more interesting.

Figure (6) illustrates the shares of inter-communal traffic in 1975 and 1997, i.e., the out-of-diagonal values of table (3). The thickness of lines reflects the share of traffic in logarithmic scale.

According to figure (6), the structure of traffic changed dramatically from 1975 to 1997. In 1975, *Prato* and *Montemurlo* monopolized any commercial relationship the other communes had. In fact, on the left side of figure (6) we can observe a very thick line between *Prato* and *Montemurlo* and, from both of them, lines of various thickness towards other communes. On the contrary, in 1997 firms in the other communes were much more likely to interact directly with one another, which reflects into much more intertwined structures on the right side of figure (6). The one exception is *Vernio*, the commune high up in the mountains (s. figure (4)) which, as can be observed reading the bottom row of table (3), increased its isolation in the period examined.

This development was caused by the specialization of some communes in one or a few phases of production. Thus, more inter-communal traffic was needed in order to arrange the production chains; furthermore, a substantial share of this inter-communal traffic did not pass through the commune of *Prato*. Figure (6) tells us that road traffic increased non-uniformly across space, a circumstance that could have never been highlighted by gravitation models.

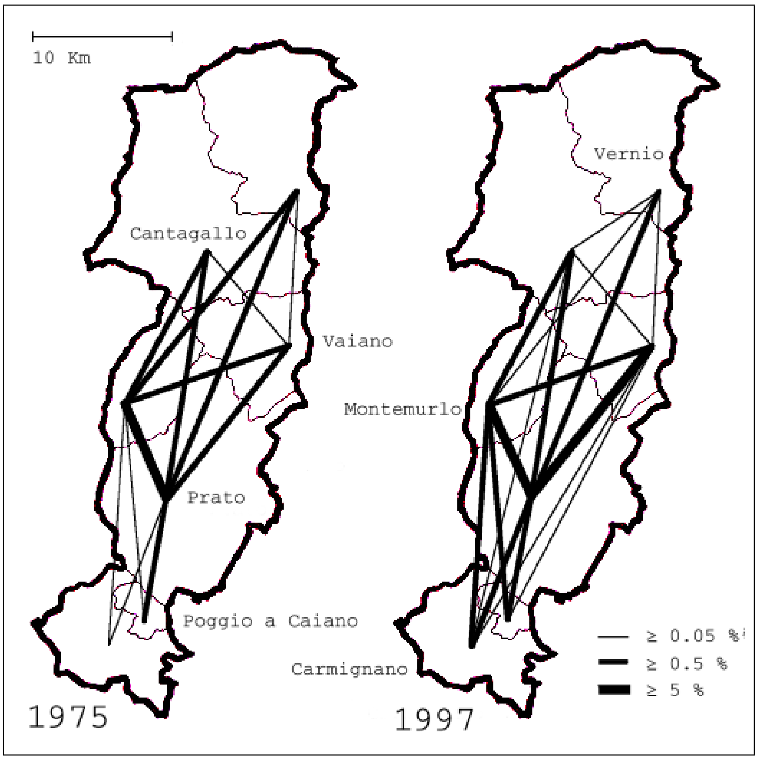

Figure 6: The traffic between the communes of the Prato province as percentages of total traffic in 1975 (left) and 1997 (right). Ends of segments do not reflect the physical location of main towns. Simulation outcomes have been averaged over ten runs at base parameter values. Values smaller than 0.05% have not been reproduced.

It could have been spotted by local sensors of traffic along the roads. Indeed, even without so detailed a monitoring, in 2003 an investigation funded by the province of Prato highlighted that in the years 1970–95 road traffic between small centers increased more than proportionately to economic growth [20]. This is a concern for public administrations because, having been unable to foresee this sort of development, they had built a road network that was still centered on the town of *Prato* [45].

Obviously, a solution could have been that of monitoring traffic with greater precision and planning road construction upon these data. However, the present exercise demonstrates that an ABM could have reached similar results by means of inexpensive information. All information used by the model presented herein is publicly available, and free. All that was needed in order to reconstruct shares of traffic was the number of firms by production phase, and some general information on the production process.

Of course, an ABM is no magic. Just like any other scientific method, it does nothing beyond extracting relevant information out of raw data. Thus, it is perfectly sensible to object that one could have arrived at this very same result by observing the spatial distribution of firms by production phase with time. The issue is that, since firms are very many, and the production process is characterized by many possible bifurcations, a computer simulation is a more reliable method than paper and pencil.

7 Conclusions

This article expounded agent-based modeling with respect to the reconstruction of the dynamics of road traffic induced by economic activities scattered along neighboring communes. In this particular instance, production chains involve several firms before reaching a marketable product; this is quite a peculiar arrangement of production, but similar models could be made for other arrangements as well.

The main point of this article is that it is possible to reconstruct trajectories in physical space out of information on communications in acquaintance space. This is a methodology that, in principle, could be applied to any setting where communications and physical movements influence one another.

Furthermore, it has been shown that ABM can prove useful in reconstructing communications in acquaintance space and, consequently, trajectories in physical space. In fact, ABM reconstruct possible interactions out of knowledge of possible behavior, following a logic that is in many respects akin to that of Hägerstrand's Time-Geography.

With respect to this specific case, it could be ascertained that the ABM provides insights on traffic development that were not foreseen by policy-makers, albeit all the data required by the model were available. This makes a strong case for the parsimony of data and the richness of information provided by ABM, yet it does not exclude that ABM should be combined with GIS in order to obtain more reliable insights. For instance, some information on actual traffic flows could make this model yield absolute values of traffic, rather than traffic shares.

Broadly speaking, the perspectives of applying ABM depend on the availability of relational and behavioral data. Besides collecting information on the activities of single firms, as statistical institutes presently do, it would be extremely useful that information be collected on the relations firms entertain with one another as well as with other actors. Furthermore, it would be extremely useful that researchers investigate the typical behavior of crucial actors in typical situations — for instance, it would have been extremely useful if anybody cared about collecting stylized facts about the typical behavior of geographically clustered firms with respect to isolated firms. This sort of qualitative, yet empirically profound information, is essential in order to build reliable ABM.

Under certain respects, GIS are beginning to provide data that fit very well into ABM and Time-Geography. In fact, sensors of various kinds can easily provide information on movements of single actors, enabling a detailed comparison with the dynamics produced by ABM or space-time prisms foreseen by Time-Geography. Thus, this kind of data is very useful for all issues of models calibration and validation.

However, GIS data are not pertinent to the kind of qualitative information on typical behavior that is urgently needed in order to build better ABM. In order to collect this sort of information, researchers should not simply ask decision-makers what they did, but also *why* they did what they did. Rationales, causal maps and world visions that could be translated into behavioral algorithms are strongly needed. They cannot be provided by automatic sensors; rather, detailed field work is in order.

In particular, field work could elicit the role of geographical space and path-dependence in the decisions of the actors involved. If this would be done, the relationship between acquaintance space and physical space would run both ways: not only from acquaintance space to physical space, as it happens in this model, but from physical space to acquaintance space as well.

A Flux Diagrams

This appendix expounds the behavior of the agents in the model by means of flux diagrams. These diagrams represent the logic of their algorithms.

At each step, the story begins with the Traders of Finished Products. The Traders of Finished Products walk around in acquaintance space, look around in their watching range and, if they find a Middleman, they move close to it and place an order. The corresponding flux diagram is expounded in figure (7).

Middlemen, as soon as they receive an order, begin to look around in order to find firms to build production chains. The kind of chain that they build depends on which firms are closest to them in acquaintance space. Figure (8) illustrates the algorithm employed by a Middleman.

The other firms are all alike in their behavior. All of them jump around in acquaintance space – i.e., they try to become acquainted with as many firms as possible — until a middleman calls them to be part of a production chain. Figure (9) illustrates this algorithm.

The above sequences repeats itself for all Traders of Finished Products, all Middlemen and all other agents; this constitutes a simulation step. At the end of each step all chains are destroyed and a new step begins.

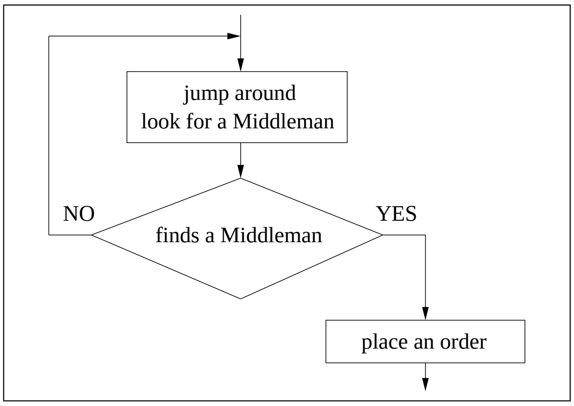

Figure 7: A Trader of Finished Products jumps around in acquaintance space, looks for a Middleman and, if it finds one, places an order.

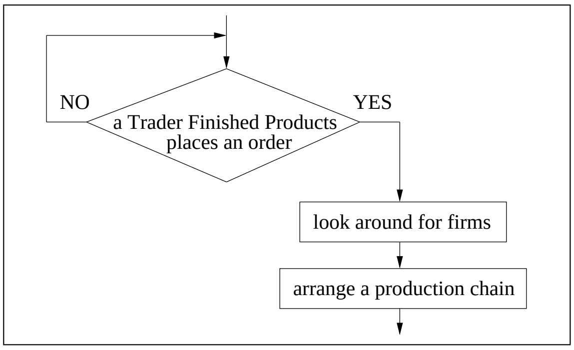

Figure 8: A Middleman receives an order, looks around for firms and arranges a production chain.

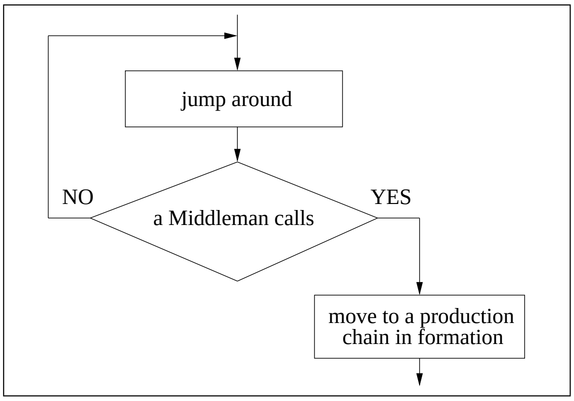

Figure 9: The other firms jump around in acquaintance space until a Middleman calls them to be part of a production chain.

B From Production Chains to Traffic Shares

The output of the model are the production chains that are constituted each year. Thus, for each year the model generates a matrix where a typical line looks as follows:

9865471 104 33 75 40 71 16 63 3 3 6

The first number indicates which one, among the 11 possible production chains, has been formed. In this example, the number 9865471, right to left means TRM $\rightarrow$ DP $\rightarrow$ CoS $\rightarrow$ Wa $\rightarrow$ We $\rightarrow$ F $\rightarrow$ TFP.

The other numbers denote the identity of the agents involved. For instance, the Trader of Finished Products n. 104 was involved in this chain.

Note that each kind of agent has its own numbering series. For instance, the above example entails Dyeing Plant n. 3 as well as Combed Spinning n. 3. This notation is crucial for subsequent calculations.

For each year, the geographical positions of firms are codified in 7×10 matrixes, where rows denote the seven communes in the prato province and columns refer to the ten kinds of firms (Traders of Raw Materials, Rags Collectors, etc.). As an example, here is the matrix for year 1997:

2	0	1	6	6	0	1	24	0	0
5	1	8	0	29	1	0	31	0	1
44	9	33	15	225	73	15	129	20	34
47	0	36	0	244	0	17	137	0	0
188	112	113	68	571	209	31	349	51	106
195	114	118	74	606	220	40	382	0	107
0	0	119	75	613	221	42	387	53	0

In such a matrix, element $(1,1) = 2$ means that in the *Carmignano* commune there are two Traders of Finished Products, named "1" and "2", respectively. Element $(2,1) = 5$ means that in the *Cantagallo* commune there are three Traders of Finished Products, named "3", "4" and "5", respectively. And so forth.

With this notation, it is easy for a computer program to find out that, with respect to the above production chain, the Trader of Finished Products n. 104 is in *Prato*, as well as the Finisher n. 33. Thus, the last two steps of the above production chain generate traffic within the *Prato* commune.

C Firms Selection

This appendix explains the criteria by which firms have been selected by examining their name and the description of their activity. Not all textile firms have been selected, but only those that could be identified as carrying out one of the production phases described by the model. In order to include all words with the relevant root, only parts of keywords have been included in the search. In most cases, computer search had to be integrated by manual refining.

Carded Spinning Search for entries that entail FILATUR [spinning], or PROD [production] and FILAT [spun fabrics], excluding those that entail LANIF [woolen mill] or COMM [commerce], VENDIT [selling] or PETT [combed spinning]. Subsequent manual exclusion of spinners that also declare LOCAZIONE [tenancy], PERSONALE DIR [managing personnel] or COPERTIFICIO [blanket production] without FILATURA [spinning].

Combed Spinning Search for entries that entail FIL [spinning] and PETT [combed] but not TESSITURA [weaving]. Manual exclusion of a firm that declared to produce MOQUETTE [carpets].

Dyeing Plant Search for entries that entail TINTORIA [dyeing plant]. Manual exclusion of entries that also entail LAVANDERIA [laundry].

Finisher Search for entries that entail FINISS [finishing], RIFIN [refinishing], NOBIL [ennoble] but not PELLICC [fur], GUANTI [gloves], CONFEZION [clothes], ABBIGLIAMENTO [clothes] and METAL [metallic]. Manual exclusion of refinishing of synthetic furs.

Middleman Search for entries that entail IMPANN [middleman] and LANIF [woolen mill] but not C/T [for a third party], S.P.A. [large firm]. Search for TESS [textiles] but not C/T [for a third party], FINANZ [financial] and COMM [commerce]. Manual exclusion of entries that suggest activities for third parties: TESSITURA [weaving], ORDITURA [warping], RIFINIZIONE [refinishing], FINISSAGGIO [finishing], CONTROLLO [check], RAMMENDO [mending], TINTORIA [dyeing], PELLICCE [fur] and FIBRE SINTETICHE [synthetic fibers].

Rags Collector Search for entries that entail STRACCI [rags] or CASCAMI [fabric waste] but not LAVORAZ [processing], TRASFORMAZ [transformation], SFILACCIATURA [fraying out], STRACCIATURA [tearing], CARBONIZZ [carbonization], CARTA [paper]. Subsequent exclusion of LAV [washing].

Trader Finished Products Search for entries that entail COMM [commerce] or ESPORT [export] or RAPPRESENT [commercial agent] or INGROSSO [wholesale], and TESSILI [textile] and PROD [products], or TESSUTI [textiles] or STOFFE [material].

Trader Raw Materials Search for entries that entail COMM [commerce], IMPORT [import], RAPPRESENT [commercial agent], INGROSSO [wholesale] and LANA [wool] or FILATI [spinned materials] or MAT and PRIME and TESS [textile raw materials]. Manual exclusion of entries connected with the wool guild.

Warper Search for entries that entail ORDIT [warper].

Weaver Search for TESSITURA [weaving], TESSUTI [textiles], ARTICOLI TESSILI [textile articles], PRODOTTI TESSILI [textile products] and INDUSTRIA TESSILE [textile firm] but not S.P.A. [large firm], GRUPPO [group] or GROUP [group] unless they explicitly declare to work C/T [for a third party]. Exclusion of entries that entail also FILATURA [spinning], VENDITA [selling], COMM

[commerce], FINANZIARIA [financial], MODA [fashion], ABBIGLIAMENTO [clothes], CONFEZIONI [clothes], FIBRE SINTETICHE [synthetic fibers] and generic sentences such as LAVORAZIONE TESSUTI [textiles processing].

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