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AGENT-BASED MODELS OF INDUSTRIAL CLUSTERS AND DISTRICTS

Guido Fioretti [1, 2]
University of Bologna

ABSTRACT

Agent-based models, an instance of the wider class of connectionist models, allow bottom-up simulations of organizations constituted by a large number of interacting parts. Thus, geographical clusters of competing or complementary firms constitute an obvious field of application. This contribution explains what agent-based models are, reviews applications in the field of industrial clusters and focuses on a simulator of infra- and inter-firm communications.

Keywords: Agent-Based Models, Industrial Clusters, Industrial Districts

INTRODUCTION

In the nineteenth century, Alfred Marshall used the expression “industrial districts” while remarking that industries tend to concentrate in specific geographical areas [28]. Marshall mentioned straw plaiting in Bedfordshire or cutlery in Sheffield, pointing out that geographical proximity provides specialized labor, nurtures subsidiary industries, stimulates innovative activity and enables technological spillovers.

Although contemporary industries are often oligopolistic and technologically sophisticated, geographical proximity is no less important today than a century ago. Indeed, a popular writer such as Michael Porter ascribed the dynamics of national competitive advantage to the ability to create, sustain and develop clusters of firms that attain world excellence in specific industries [32]. Writing from the perspective of a business economist,

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[1] E-mail: fioretti@cs.unibo.it

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Porter stressed that competition between neighboring rivals and availability of sophisticated customers stimulates innovation and engenders positive feed-backs for all firms in a cluster.

Are “districts” the same thing as “clusters”? Definitely yes, if we look at the original writings of both Alfred Marshall and Michael Porter. However, some authors have presented industrial districts as a peculiar path of economic development based on small family businesses that would preserve community values [7]. By reaction, the word “clusters” is eventually preferred by those who focus on the more general phenomenon of firms agglomeration. Since this review is not focused on the aspects that distinguish “clusters” from “districts”, these two terms will be used as synonyms. In other contexts, they are not.

A feature that attracted the attention of Marshall, Porter and many other authors who wrote on this subject, is that industrial districts are an instance of the dictum that “the whole is more than the sum of its parts”. Apparently, a cluster of competing and complementary firms, local institutions and shared values has more to offer on the international arena than the very same firms taken in isolation fron one another.

Economic theory accounts for this sort of phenomena by means of positive externalities. Since economics wants to describe competitive equilibria, but since competitive equilibria do not exist unless returns decrease with the scale of activity, the following trick has been devised: returns decrease for single firms but increase with the scale of activity of the whole cluster of firms. In this way, an empirical fact such as the existence of industrial districts can be accomodated with economic theory [25] [21].

However, one may be interested in out-of-equilibrium dynamics of industrial clusters. Economic equilibrium may not exist, for instance because competitive industries may be constituted by firms that experience increasing returns but whose growth is limited by the innovations introduced by their competitors. Or, it may exist because of reasons other than decreasing returns, such as a desire to keep a family firm at family size or a search for excellence in a minuscule market niche.

Most importantly, one may be interested in grasping the structures and contents of interactions that make a district “more” than the sum of its parts. What do these “positive externalities” between firms consist of? Qualitative accounts of industrial districts mention specific “atmospheres” conducive of innovation, entrepreneurship, collaborative efforts, shared values and institutions. How do we model these aspects?

The issue is one where structures of microscopic interactions generate a coherent whole. Typically, this is the sort of problems addressed by the sciences of complexity. Thus, one would expect that agent-based and other connectionist models have enormous potentialities for industrial clusters [27]. This review wants to summarize to what extent this possibility has been exploited hitherto.

It may be wise to be clear regarding which topics this review does *not* cover:

- Cellular automata models of surface occupation, e.g. models of the growth of urban areas;
- Prisoner’s dilemma and other pure models of competition, cooperation and collaboration;
- System dynamics models of inter-firm or inter-industry relations;
- Economic models of perfect vs. oligopolistic competition;
- Models of the distribution of the size of firms.

These exclusions are merely due to the need to keep the scope of this review within manageable bounds. It is obvious that the aforementioned research areas do have some connection with industrial districts.

The rest of this review is organized as follows. The ensuing section explains the functioning of connectionist models, particularly of agent-based models. It is followed by a section that illustrates a series of connectionist models of clustered firms. This section articulates in three subsections, depending on the questions addressed by particular models. The models of the first subsection are concerned with the relative advantage of clustered firms with respect to isolated firms. The models of the second subsection deal with issues of competition, collaboration and cooperation in industrial districts. The models of the third subsection investigate the evolutionary paths of clusters and districts. Those of the fourth subsection focus on their innovative activity. Finally, the models of the fifth subsection evaluate the impact of institutional policies on clusters of firms. Thereafter comes a section with a more practical flavor. In fact, it illustrates an agent-based platform that may support inter-firm relationships. Finally, the last section concludes with an evaluation of what is still to be done and which may be the most promising research fields.

CONNECTIONIST AND AGENT-BASED MODELS

Agent-based models constitute the bulk of connectionist models of clusters of firms. In their turn, agent-based models rest on object-oriented programming.

Since practical concepts may be easier to grasp than abstract concepts, this section proceeds from the particular to the general. First, it explains the idea of object-oriented programming. Subsequently, it arrives at the concept of agent-based models. Finally, it generalizes to the class of connectionist models.

Traditional programming, now sometimes called procedural programming, consists of:

- Instructions, such as value assignents and arithmetical operations of any kind;
- Conditions that command branching or looping over a set of instructions.

Figure 1 illustrates a possible structure of a piece of code. Programs may involve functions, i.e. pieces of code that are written separately and called at need, but this does alter their logical structure.

Flow charts may become very complicated as programs become very large. Since a programmer must overview all logical relations in a program, the cognitive burden may become unbearable.

Object-oriented programming consists of subdividing a computer program into relatively independent modules, called *objects*. Each object has the structure of a procedural program. Objects interact with one another by means of *methods*, which take the role of questions, answers or orders in the real life. Figure 2 illustrates a typical structure.

Objects may entail different algorithms, in which case they are qualitatively different from one another. Or they may all entail the same algorithm, in which case they are said to be instances of a class of objects. However, even objects entailing the same algorithms may behave differently from one another if their parameters have taken different values depending on the history that they experienced. Since it is very easy to replicate instances of a class, objects may be very many.

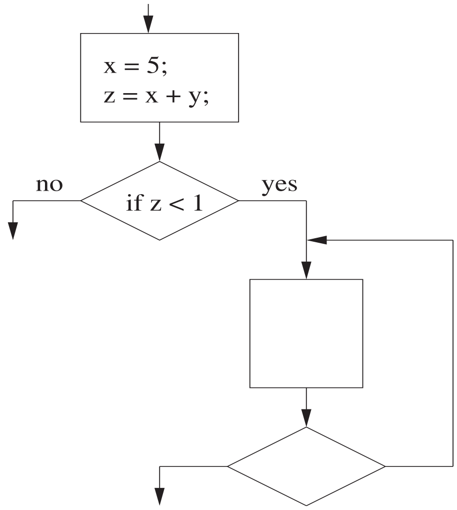

Figure 1. A typical flow chart of a procedural program. Instructions and conditions, where made explicit, should be meant as generic examples.

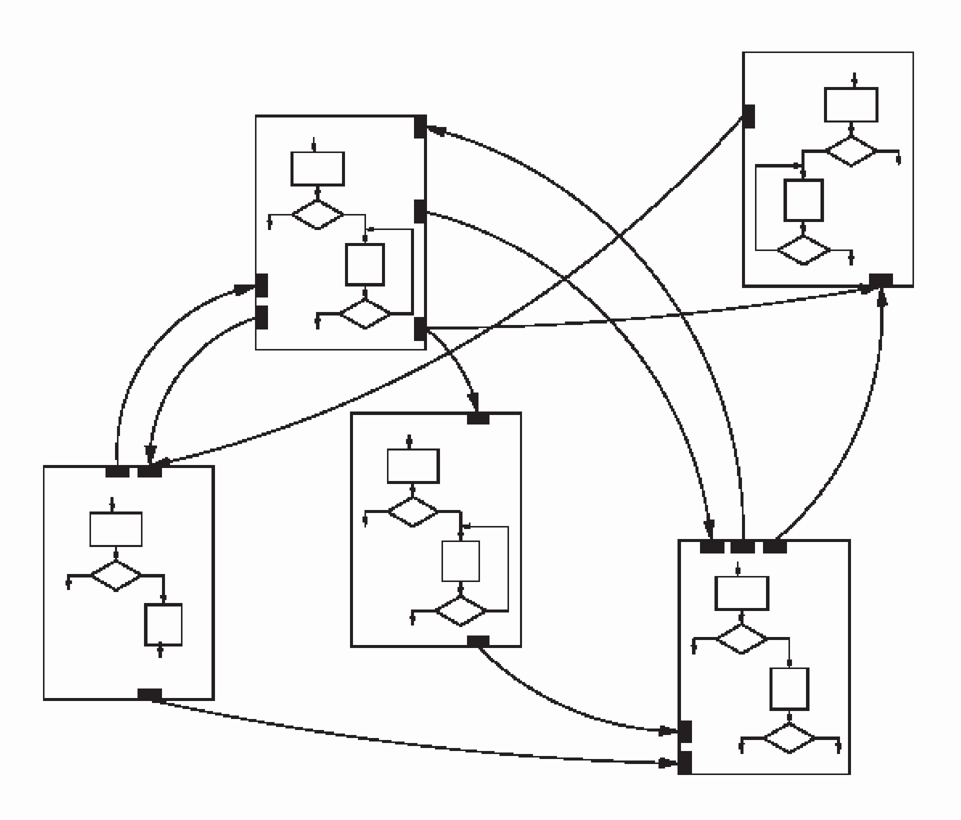

Figure 2. Computational objects (squares) and their relationships (arrows). Methods are denoted by black areas at the borders of objects. At any point in time, the objects are in a certain state of their flow diagram and only some of the depicted relations are taking place. Note that a method may issue/receive a communication to/from several other methods located in different objects.

A parallel may be traced with the behavior of natural beings. The DNA is the analogous of the algorithm that is inside an object. The DNA specifies a substantial part of the behavior of an animal, but not all of it. Even animals with the same DNA such as omozygote twins — natural clones — may behave differently because they make different experiences so their basic algorithm specializes into different responses. In humans, this effect is paramount: Everyone knows that omozygote twins, though identical in appearance, may have very different characters and personalities. Coming back to the context of object-oriented programming, objects with the same algorithm may behave very differently depending on the parameters with which they are initialized and the communications they entertain with other objects.

Object-oriented programming lends itself very naturally to social simulation. In fact, it is straightforward to think of social actors as computational objects. Since computational objects that represent social actors are generally endowed with a substantial degree of autonomy and with sophisticated cognitive abilities, they are generally called *agents*. Hence the expression “agent-based models”.

Agent-based models are good at generating emergent macroscopic behavior. Of course, a necessary condition is that microscopic agent behavior is known reasonably well.

Agent-based models are appropriate when aggregate behavior depends on structures of relations, so it cannot be ascribed to a fictitious “representative agent” [26]. Indeed, simple agent-based models have been able to account for the emergence of social phenomena ranging from wealth distribution to the development of national cultures [19]. More flexible than differential equations and yet more precise than verbal descriptions, agent-based models offer to the social sciences a descriptive language that attains sharpness retaining the richness of verbal accounts [24].

Note that, in principle, any agent-based model could be written as a set of differential equations. However, when a system is composed by very many interacting parts, as social systems are, it is extremely difficult for a modeler to oversee all combinations of their dynamics. Agent-based models constitute a bottom-up approach that allows to reconstruct structures of interactions that would not be envisioned otherwise. Thus, the real difference in not in the tool *per se*, but in the psychology of the modeler when using it.

Ultimately, agent-based modelling consists of the idea of a bottom-up description of systems composed by many active and autonomous interacting parts, which is opposite to more traditional top-down descriptions. It is not necessarily linked to the technique of agent-based programming. And as a matter of fact, any model that is written with the idea of describing intelligent agents and letting them interact, rather than describing the macroscopic outcome of their interactions from the outset, may be called an agent-based model. Even if the modeller prefers to describe agent behavior by means of equations rather than by writing computer code.

Agent-based is a modelling philosophy. Object-oriented programming is a technique. It is the technique that best suits the agent-based modelling philosophy, but it is not the only one.

Agent-based models are an instance of the wider class of *connectionist* models. This class includes such diverse models as classifier systems, cellular automata, hypercycle models and neural networks.

All connectionist models share the idea that the interactions between a large number of micro-elements gives rise to complex macro-phenomena. In particular, the elements of agent-based models may be quite complex and “intelligent” on their own. On the contrary, other connectionist models tend to make use of simpler elements and to constrain their interactions to a greater extent.

The vast majority of connectionist models of industrial districts are agent-based models. However, there are also a few models based on cellular automata (2 models), hypercycles (1 model) and neural networks (1 model). Thus, a brief introduction to these branches of the connectionist family may be in order.

Nevertheless, agent-based models are expected to monopolize the scene of connectionist models of industrial districts. Thus, the following scheme illustrates cellular automata, hypercycles and neural networks by means of their differences with respect toagent-based models. Classifier systems have not been included because they have never been used in models of clustered firms.

- Cellular automata are composed by a set of elements in a ordered space, usually a plane, that change their state according to the state attained by the elements in their neighborhood. In general, the neighborhood is either defined as the four or the eight closest neighbors. Roughly speaking, cellular automata may be seen as agent-based models whose agents are constrained to communicate with a fixed subset of other agents and, most importantly, the state of whose agents does not depend on their own past state. Typically, cellular automata are good at describing diffusion phenomena such as growth of cities, herding behavior and sandpiles cascades.
- Hypercycle models are used to model the origin of life. The idea is that a set of chemicals may start a series of reactions that may eventually close in a loop and repeat themselves. If this happens, the process may continue for ever and constitute what we call “life”. Hypercycle models may be seen as agent-based models whose agents – the chemicals – have rules of behavior that are extremely simple and sufficiently compatible with one another to form stable loops. Indeed, nothing prevents agent-based models to form hypercycles.
- Neural networks are composed of elements — called neurons — which sum a certain number of inputs by means of proper weights. Eventually, the outputs of some neurons may feed the inputs of other neurons. Some neurons receive exogenous inputs, and some other neurons provide the outputs of the network. Since summation is a many-to-one function (e.g. $5 + 2 = 7$ but also $3 + 4 = 7$), neural networks provide the same outputs for whole classes of inputs. In other words, they classify exogenous inputs in a certain number of classes. Thus, they can be used to model the classification of stimuli into categories operated by our brains. Since the shape of these artificial mental categories depends on the weights of the neurons, various methods have been developed in order to make them evolve with time. For our purposes, neural networks may be considered as agent-based models where the agents’ algorithms consist of summing inputs by means of weights that are either fixed once and for all, or updated depending on communications with other agents and past states.

Axelrod and Tesfatsion [6] is a key reference for readers interested in the wider topic of agent-based modeling in social science. The rest of this review is focused on applications to industrial clusters and districts.

MODELS OF CLUSTERS AND DISTRICTS

This section reviews the connectionist models of industrial clusters that have been made hitherto. They are few, but they cover most of the issues that are generally associated with clusters and districts. The rest of this section groups them in a few subsections.

The Advantages of Agglomeration

What is the competitive advantage of industrial districts with respect to isolated, vertically integrated firms? How can clusters be economically feasible and even more successful than large firms that exploit economies of scale? This is, obviously, a very basic question.

Brusco, Minerva, Poli and Solinas built a model based on cellular automata loosely inspired by the Carpi (Modena, Italy) apparel cluster [13]. This industrial district is characterized by a large number of very small family firms which can survive periods of low demand incurring a very small loss because most of their workers are the owners themselves. However, the district as a whole is able to mobilize a large productive capacity when demand is high for a particular item. Thus, its competitive advantage lies in its high flexibility with respect to oscillations and shifts of demand with respect to both quantity and features of the goods requested. Cellular automata are good at reproducing the avalanches triggered by a firm that discovered a profitable market niche. Essentially, this model rests on the fact that small flexible firms may be more profitable than large integrated firms if demand is variable enough, particularly in industries where returns to scale do not increase very rapidly with the scale of activity.

Fioretti built an agent-based model of the Prato (Italy) textile district [20]. This district is characterized by fragmentation of the production process, with each firm typically carrying out only one production phase. By making use of data on the number of firms for each production phase, the model reconstructs the structure of interactions that took place in the period 1947-1993. This highlights that while in the 1950s and 1960s the district based its competitive advantage on price competition between a large number of firms, through the 1970s, the 1980s and the 1990s a new structure emerged. A steep increase of the number of firms doing a variety of finishing operations caused the number of qualitatively different cloths to explode. As a consequence of this structural transformation, the Prato district re-directed its competitive advantage on the ability to offer an immense variety of products in a short time and small lots.

Chang and Harrington built an agent-based model of multiunit firms which may either centralize decision-making, as traditional hierarchical firms, or decentralize to single units [14] [15]. Though this model has not been designed in order to represent clusters of independent firms, it does deal with the alternative between a large integrated firm and a many small and proximate firms that imitate one another. Chang and Harrington find that centralized decision-making is superior in the short run, particularly if the units operate in similar markets, because best practices are immediately adopted. However, if the units operate in qualitatively different markets a decentralised structure may be superior because it fosters a higher degree of exploration.

Competition, Collaboration and Cooperation

Issues of competition, collaboration and cooperation are key in the debates surrounding industrial districts. Whilst the meaning of “competition” is obvious, the distinction between “collaboration” and “cooperation” is not always clear. Essentially, the expression “collaboration” should be used for all situations where agents do something together and have a material and immediate incentive to do it. For instance, competitors may collaborate within an industrialists union in order to improve the infrastructure of a region. On the contrary, “cooperation” should be used in situations where the prisoner’s dilemma applies, i.e. where agents do things together even if they lack an immediate material incentive. For instance, small competing firms may alternatively subcontract one another rather exploiting the whole order. As in the classical prisoner’s dilemma, the key to cooperation is repetition of interactions: because both firms repeatedly subcontract one another, if one of them exits the agreement, the other one can retaliate as well. As in the classical prisoner’s dilemma, the cooperative equilibrium is superior to the competitive one, because both firms can save the costs of underutilized productive capacity.

Agent-based models have a lot to say on these issues. However, this review does not report on the huge literature of agent-based models of the prisoner’s dilemma, but only its applications to the specific context of clustered firms.

Albino, Carbonara and Giannoccaro pointed out that inter-firm cooperation is an essential component of the competitive advantage of industrial districts [2]. Their agent-based model makes this point by means of a comparison with fictitious “super-agents” at various aggregate levels. Though interesting, this is possibly not the most profitable usage of agent-based technology.

Boero, Castellani and Squazzoni [10] [8] [9] constructed an agent-based model where three kinds of producers must combine their operations in order to yield a product that is commercialized by agents of a fourth kind. The cluster of firms undergoes two transitions through three technological regimes. Each regime is characterized by an optimal combination of production factors to be discovered by the producers. The crucial finding is that the final good can be produced at lower costs if the three component producers are in the same technological regime and at a similar stage in the process of discovery of the optimal combination of production factors. Consequently, random market-like search for the best partner may yield inferior results to long-term partnerships.

Allen and McGlade built an early agent-based model of the fishing fleets of Nova Scotia (Canada) that does not employ object-oriented programming [4] [5]. The model reproduces the interplay of fishing strategies, fishing innovations and environmental response. The highest performance is not reached if all ships imitate one the other’s behavior, but rather if they pursue complementary cooperative strategies. The study concludes that in order to exploit a complex system, creative exploration and consensual diversity of strategies may be more effective than selfish short-term adaptive reactions [3].

Development Dynamics

Why do industrial districts form, and why do they disintegrate? Birth and death dynamics are crucial to understanding clusters, and the range of problems is probably larger than the number of connectionist models that have addressed this issue hitherto. In particular, there does not exist any connectionist model dealing with the death of industrial districts in countries of early industrialization and the corresponding birth of other districts in newly industrializing countries.

Giaccaria built the only model where an industrial district is modelled by means of a neural network [22]. A set of small firms compete with a large integrated firm for the production of one single good in variable quantities and prices. The small firms, the large integrated firm, a computational agent and consumers are all represented by means of neural networks. Since some of the small firms learn to react in a similar ways, clusters of firms emerge. In particular, Giaccaria investigates the emergence of leader-follower relationships.

Otter, Van der Veen and De Vriend developed an agent-based model where firms and households decide where to locate according to availability of labor, services, natural resources and recreation areas [29]. The model distinguishes between firms operating in heavy industries, in light manufacturing and in services. Both firms and households do not have perfect information but can only observe the agents that are within a visibility range. The authors observed the emergence of clusters of firms and households of various size and composition depending on exogenous parameters as well as the initial configuration.

Padgett, Lee and Collier proposed an hypercycle model of productive systems where goods flow through firms as chemicals through reactors [30]. Eventually, clusters form around production loops, that are reminiscent of Marshallian industrial districts. Interestingly, economies with more than 4 goods require the existence of clusters in order to sustain production.

Page and Tassier developed an agent-based model where local economies are superseeded by chained stores [31]. Chains form because they exploit a niche that is profitable at several locations. Subsequently, wherever they arrive they homogenize the economic structure and beget other chains in other sectors. Thus, the process is cumulative. However, the final configuration is likely to be suboptimal though it is a local optimum in the environment created by the existing chains. Indeed, decay may be the fate of clusters that do not attain world-wide recognition in the globalized economy.

Brenner constructed a cellular automata model of the spread of industrial clusters depending on a number of factors [11]. The model is calibrated on German regions and suggests that industry concentration depends, among else, on the number of spin-offs, on human capital and its spill-overs, on technological synergies and the availability of shared facilities. Brenner and Weigelt calibrated this model on knowledge spill-overs and specific regional features [12].

Innovative Activity

Proximity to partners and competitors provides opportunities for imitation and innovation that constitute a major drive of the success of industrial clusters. Two interesting agent-based models have been developed on this issue.

Gilbert, Pyka and Ahrweiler built an agent-based model of innovation networks [23] [1]. This model wants to capture the observed empirical trend towards more collaborative research efforts in many industries. The authors apply it to biotechnology and other high-tech industries that exhibit clustered collaborative research efforts. Notably, this model applies also to clusters whose components may be geographically distant from one another, which happens e.g. in the software industry.

Zhang built an agent-based model of industrial clusters inspired by the Silicon Valley [36]. Zhang makes the point that firms do not move to industrial clusters, they are born in them. Thus, the main thrust of industrial clusters is that they nurture an entrepreneurial atmosphere. The model creates a dynamics of creation and imitation of firms and generates a distribution of firms size in accord with empirical data.

Policy Making

Finally, agent-based models have been used in order to evaluate the impact of economic policies on industrial districts. Policies may range from the provision of infrastructures to the creation of consortia to setting up a State-owned enterprise. In many instances, policies for industrial districts are joint efforts of Government agencies and private stakeholders.

Squazzoni and Boero, in the first version of the above mentioned model based on inter-firm cooperation, examined the impact of several policies [33] [34]. In particular, they investigated the impact of a consortium that monitors the evolution of markets and technologies or, alternatively, of a research center that develops technologies on its own. According to their model, the impacts of these two institutions are nearly indistinguishable from one another.

Coelho and Schilperoord developed an agent-based decision support system for the management of science and technology parks [16] [17]. This model has been inspired by and has been tested on the Tagus (Portugal) technology park. Firms build networks depending on technological compatibilities and occasions for social meetings, ranging from conferences to occasional encounters in restaurants and cafeterias. Eventually, technological variety and geographical or institutional drives lead to the formation of clusters of tightly networked firms. By experimenting with different occasions for establishing social ties that can be provided by different institutions, a policy-maker is able to run computer experiments that evaluate the outcome of alternative policies.

APPLICATIONS FOR FIRMS

The models reviewed in the previous section have been designed for scientists and policy makers. Agent-based models of inter-firm networks can be useful for firms as well.

In order to be utilized in the daily operations of firms, agent-based models must be very detailed. They must represent the operations that are carried out by the single units within firms and they must be able to coordinate them.

Furthermore, standardization of inter-firm communication protocols is required. The field is still in its infancy, but important steps have been undertaken in the field of textiles <http://www.moda-ml.org> and heavier industries <http://niip.org>.

Software houses are developing proprietary software for consultancy firms, the reliability and depth of which cannot be accessed. The rest of this section is devoted to introduce the only open-source platform for detailed agent-based modelling of real firms. It is the *java*

Enterprise Simulator developed by Pietro Terna at the University of Turin, <http://web.econ.unito.it/terna/jes>.

The *java Enterprise Simulator* (henceforth *jES*) describes the interactions between organizational units that may be production islands or single workers or whole departments or divisions, depending on the level selected for investigation. Furthermore, there may be units that do not belong to any firm, such as contracted workers. Figure 3 illustrates the scene.

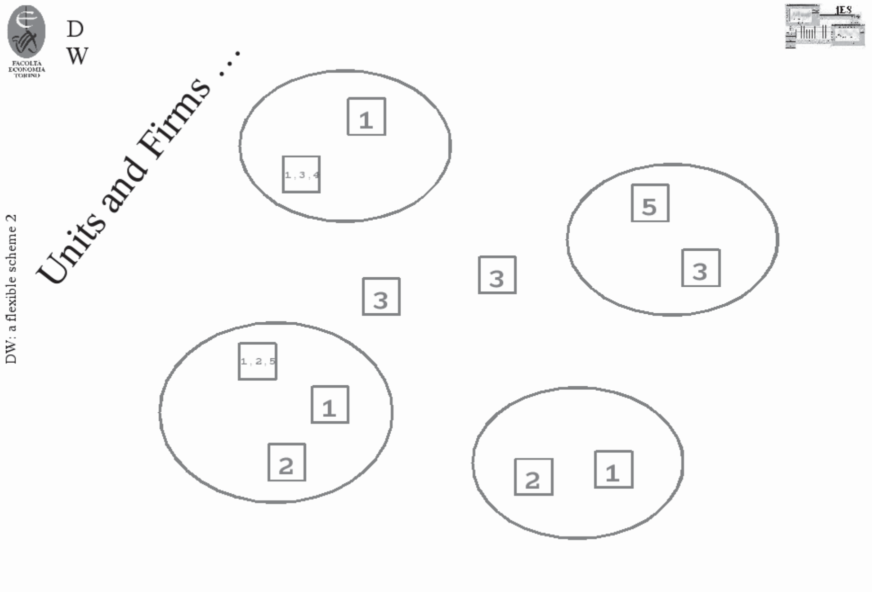

Figure 3. Organizational units and firms in the *java Enterprise Simulator*. By courtesy of Pietro Terna.

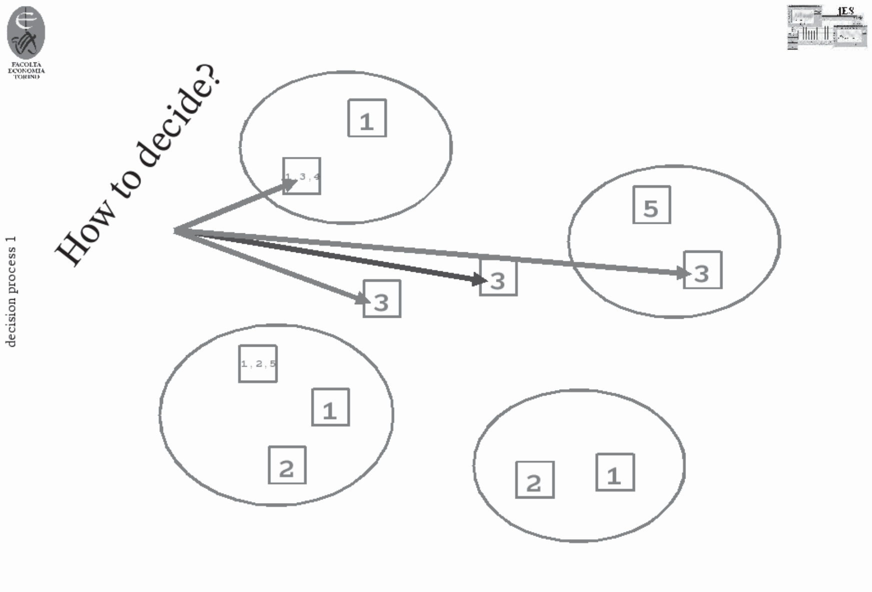

Figure 4. Routing an order that requires step "3" on one of the organizational units that are able to carry it out. By courtesy of Pietro Terna.

The problem is that of routing orders that require a series of steps on units that have different capabilities for each step. Figure 4 illustrates the simplest kind of problem, a situation where step “3” can be accomplished by independent specialized units, by a specialized unit of a firm or by a unit included in a firm which is also able to carry out steps “1” and “4”.

In general, problems are more complicated than that. Orders may require specific resources to be procured, or they may entail the possibility of executing one out of several series of steps. Choices may depend on sophisticated algorithms that may require memories of past performances. Outcomes may need to be stored and units themselves may be endowed with warehouses.

The *jES* is able to handle these situations. Orders are modeled as separate objects that are routed by organizational units according to their own behavioral algorithms. Furthermore, a communication matrix specifies which units talk to which other units. This communication structure may represent formal or informal ties as well as collaboration networks within or between firms.

The simulator reconstructs the flows of orders between units and tells decision-makers where the bottlenecks are. Decision-makers may experiment with alternative organizational arrangements and evaluate the costs incurred in each case. For instance, one may evaluate whether it is the case of adding a machine, exchanging internal production with an external partnership or re-arranging the formal hierarchy in order to enforce communication between isolated departments.

Figure 5 illustrates the functioning of the *jES*. Orders implement recipes, which entail instructions regarding what operations should be carried out but no specification concerning which unit will carry them out. This decision is made by the organizational units, assigning e.g. the current step of recipe A (encoded as “101”) to unit 2. Depending on the decisions made, the graph on the right of figure 5 illustrates the queues at each unit. Furthermore, detailed outputs regarding costs and proceeds are made available.

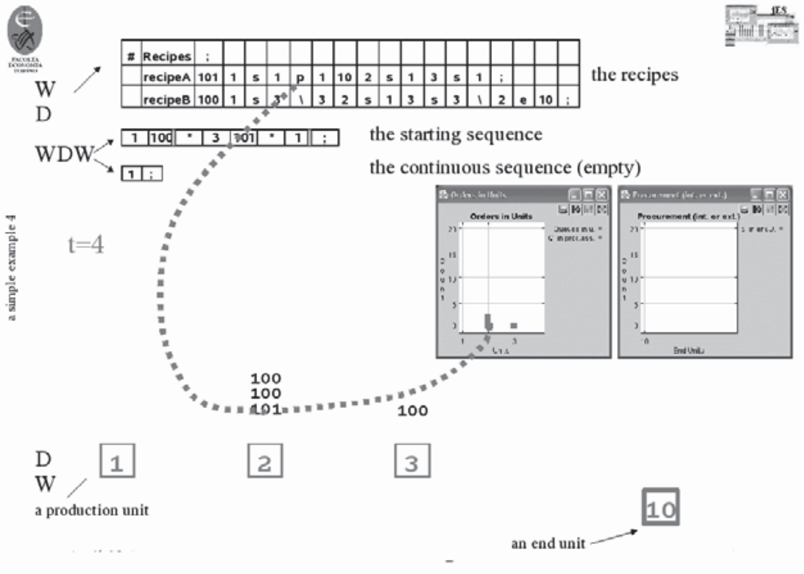

Figure 5. The orders entailing recipes A and B (top) are routed on units 1, 2, 3 (bottom). Eventually, their products arrive at the end unit 10 (bottom right), which may represent a warehouse. The graph on the right illustrates the queues at each unit. By courtesy of Pietro Terna.

It is also possible to explore the evolutionary path of a cluster of firms. Suppose that we are able to specify rules by which firms are started and closed down following an economic performance that depends on their interactions. The simulator *jESevol* allows to reconstruct possible histories of birth, life and death of industrial districts. Figure 6 illustrates a typical simulation step, where stripes denote queues at particular firms and light areas the geographical range where they look for partners.

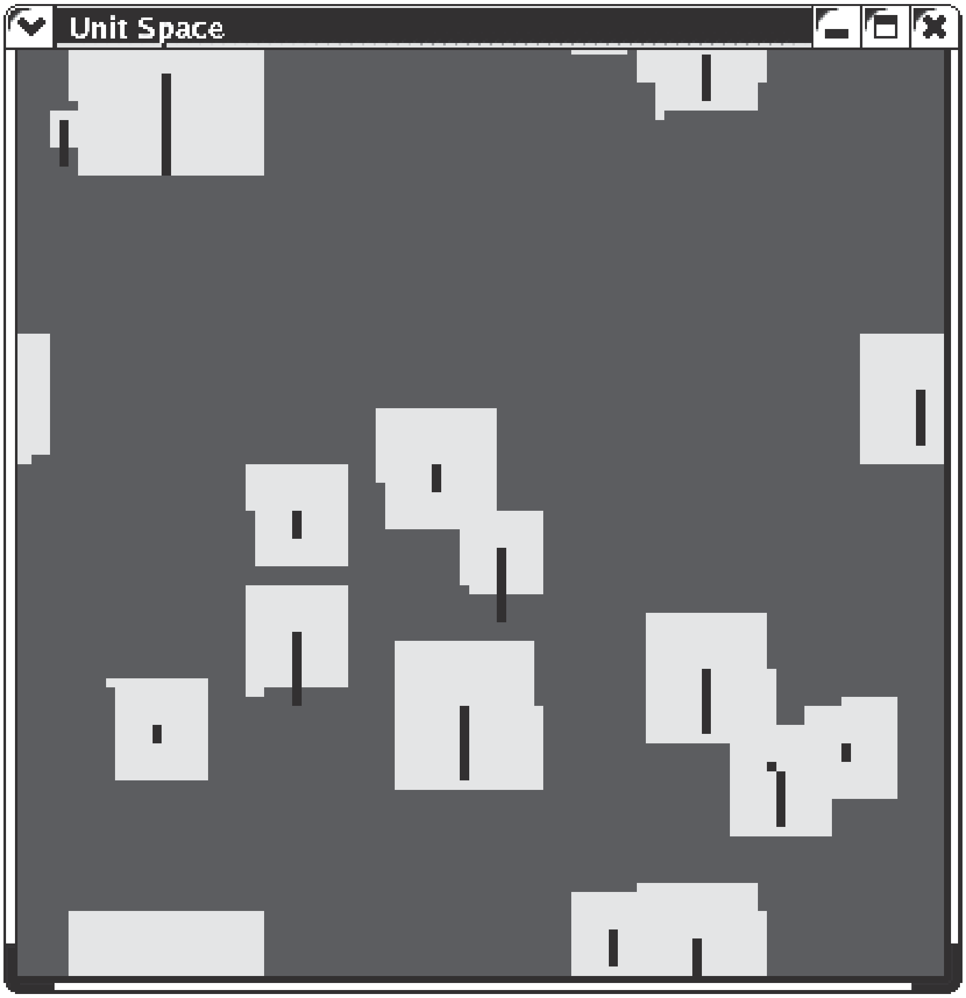

Figure 6. A simulation step of *jESevol*, the evolutionary version of *jES* designed for studying the lifecycle of industrial districts. By courtesy of Pietro Terna.

Detailed agent-based models developed on simulators such as the *jES* provide a bottom-up perspective that complements the top-down approach of models based on differential equations. In fact, bottom-up agent-based models allow to explore the state space that is actually spanned by an organization, possibly discovering configurations that had gone unnoticed from a top-down perspective. The strength of agent-based models of real organizations is that, typically, managers end up with saying “I would have never thought that *this* could happen!”. Indeed, the practical value of agent-based modelling is its ability to produce this sort of emergent properties.

THE CONCLUDING REMARK: TRY IT!

The field of connectionist models of social organisms is burgeoning, it is novel and it is still largely unexplored. In particular, connectionist models of industrial clusters offer an unparalleled tool to understand a fundamental organizational structure of many national productive systems.

Agent-based models are probably the most appropriate connectionist model in this particular field. It is not difficult to become acquainted with this technique, which can be mastered at several levels.

Agent-based models are most easily written in object-oriented languages such as *SmallTalk*, *Objective C* and *Java*. Eventually, a platform may aid the construction of an agent-based model. In general, the more a platform simplifies the construction of a model, the more it constrains it. Therefore, the most user-friendly platform are not appropriate for large empirical agent-based models.

The following list includes the most common non-commercial platforms for agent-based simulation. More comprehensive evaluations of simulation platforms can be found in specialized publications [18] [35]; in particular, a commented list of simulation platforms is available at <http://www.econ.iastate.edu/tesfatsi/acecode.htm>. As a general rule, it is wise to make oneself acquainted with several tools.

Swarm <http://wiki.swarm.org> is the least user-friendly, least constraining platform. It provides the modeller with template structures for building a model, graphical interfaces, random numbers generators and other facilities. Essentially, textitSwarm is a collection of libraries written in *objective C*. *Java* interfaces are available, so models can be either written in *Java* or *objective C*.

JAS (Java Agent-based Simulator) <http://jaslibrary.sourceforge.net> offers the same template structures as *Swarm* making use of *Java* libraries developed for other purposes. Ranks equal to *Swarm* in the trade-off between user-friendliness and programming-freedom, and requires *Java* programming. Potentially, it may capture the interest of the free-software community.

SDML (Strictly Declarative Modelling Language) <http://sdml.cfpm.org> checks the consistency but does not require completeness of logical statements. This might be useful in order to model real-world decision-makers. *SDML* differs in many respect from other platforms, which is its both a weakness and a strength. It requires writing code in its own language, derived from *SmallTalk*.

MADKit (Multi-Agent Development Kit) <http://www.madkit.org> is a platform designed for modelling organizational structures of agents. Agents may be programmed in *Java*, *Jess* or *BeanShell*.

RePAST (Recursive Porus Agent Simulation Toolkit) <http://repast.sourceforge.net> is a *Swarm*-like but more user-friendly platform, explicitly designed for social simulation. Obviously, it is a bit more constraining than *Swarm*. It requires writing in *Java*, *C++* or other languages.

Ascape <http://www.brook.edu/es/dynamics/models/ascape> has been used to make many early social agent-based models, such as *SugarScape*. It requires the basics of *Java* programming, but a number of libraries facilitate the programmer's work. Ovbiously, the usual trade-off between user-friendliness and programming-freedom applies.

NetLogo <http://ccl.northwestern.edu/netlogo>, an offspring of *StarLogo*, is the most user-friendly and most constraining platform. The model builder is required to write pieces of code in a simple procedural language, which this platform combines into an agent-based model. Of course, the drawback of user-friendliness is that the model builder has very little freedom. This platform should not be used for anything beyond very simple models of agents moving on a surface.

PS-I (Political Science – Identity) <http://ps-i.sourceforge.net > is a very user-friendly platform expecially designed to build models in Political Science. Within established Political Science theories, it offers wider possibilities than *NetLogo*.

The most constraining, most user-friendly platforms are generally inappropriate for large empirical models, but they are sufficient to build toy models that may provide interesting insights. However, the reader should be aware that toy agent-based models are being made since several decades. The space of abstract concepts has been largely explored, and those who criticize the connectionist paradigm rightly point to the paucity of empirical and applied models. The next frontier, the challenging task for inventive researchers, consists of getting down to reality.

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