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Detection of communities of agents interacting through regional innovation policies

1. Introduction

As long as innovation is considered as an exogenous determinant of economic growth, it is difficult to correctly understand the processes that facilitate it. Although mainstream economic theory has depicted innovation as a unforeseen shock, new approaches to the comprehension of innovation processes have identified specific conditions that typically lead to its occurrence. Thus, with the goal of deepening the comprehension of a phenomenon whose architecture was being seen more and more as articulated and complex (although complexity is not a synonym of impossibility nor of randomness), at the beginning of the 90's new contributions (Freeman 1988; Lundvall 1988, 1992; Nelson 1988, 1993) started to investigate the role of the circulation of information and of interactions among agents (people, enterprises and institutions) in the context of the flourishing of innovative processes. While the main aim of these authors was to study the ability of national economic systems to innovate, the introduction of such an approach in the literature fostered the investigation of the interactive dynamics that characterize the rise and the development of innovation processes at a meso-level of analysis (Saxenian 1994; Breschi and Malerba 1997; Malerba and Orsenigo 1997, 2002) and at a micro-level of analysis (Lundvall 1985; Freeman 1991; Mowery and Teece 1996; Russo 2000).

2. Innovation and interactions among agents: structures, processes and functions

An inspirational contribution for the conceptualization and the investigation of innovation was given by David Lane (Lane and Maxfield 1997, 2005; Lane 2011) who outlined a theory capable of describing the most important entities and the most important phases that characterize the formation of innovation. Far from looking for predictability, Lane's theory focuses on how the processes that led to innovations are intertwined, making some acute elements emerge. Among those that have a crucial impact on the likelihood to generate innovations in geographically defined systems, the presence of a high level of interactions among agents has been emphasized (Lane 2011). More specifically, in order to analyze the innovation prospect of agents interacting in a local economic context, three aspects deserve to be investigated: (i) *relational structures*, (ii) *shared processes* and (iii) *common functions*.

These three aspects regarding the conceptualization of 'innovative organizations' (i.e. interacting groups of agents with the capacity to give rise to innovative activities) require the application of specific methodologies. Thus, in order to coherently investigate each of them, the use of three methodologies is proposed in this paper: (i) the Clique Percolation Method (CPM) by Palla *et al.* (2005); (ii) Infomap algorithm by Rosvall *et al.* (2008, 2011, 2014); (iii) the Dynamic Cluster Index analysis (DCI) by Villani, Filisetti, Benedettini, Roli, Lane and Serra (2013, 2015). I will apply these methodologies to a regional innovation policy programme. Policy implications will be discussed with regard to the design and measurement of network policies.

3. The case study: Region Tuscany (Italy) policies in sustain of innovation

Analyses have been realized thanks to an original and unique dataset of network projects funded by the regional government of Tuscany from 2000 to 2006 (Caloffi, Rossi and Russo 2014, 2015, 2016), in the context of an entire set of public policies (nine waves were realized over the considered period of time) exclusively aimed at the financing of innovative projects. More than 1,600 economic agents participated (enterprises, universities, trade associations, service centers, KIBS, business services enterprises, etc.) and more than 160 network projects were funded (out of nearly 300 proposals). In order to participate and to receive funds agents had to develop projects in collaboration with other agents (the policies allowed exclusively the granting of funding to partnerships of agents) and so the configuration of a high number of partnerships produced an intertwined and dynamic network of interactions. Thus, the objective of this work is to investigate if agents gave rise to entities which go beyond the boundaries of the single projects and in which new architectures arose with potentiality to foster the flourishing of innovative activities. To do this, partitions of the network were elaborated applying the three mentioned methodologies.

4. Application of three methodologies: motivations, informational basis and key-features of models

4.1. Three models of CPM analysis

The first methodology, CPM, is one of the most consolidated Social Network Analysis (SNA) methods and an unavoidable starting-point for an analysis that pursues the identification of overlapping communities of intensively connected nodes. The application of CPM followed the objective to investigate the presence of communities characterized by intense relational structures. The informational basis used for the application of this methodology regards the presence of connections (unweighted edges) among agents (nodes).

Even if there are no theoretical references that can help in selecting specific values of k, it is unfeasible to consider all possible values of k. However, looking at the characteristics of the possible partitions in terms of (i) the dimension of the communities detected, (ii) the number of the communities detected and (iii) the degree of overlaps among the communities detected, it was passible to define three ranges of the values of k, within which the partitions have similar features. The identification of different ranges of k has the purpose to support the process of selection of some specific values of k and, since three of these groups were identified, three models where elaborated: the first with k=5 (CPM_k05), the second with k=12 (CPM_k12) and the third with k=18 (CPM_k18).

4.2. Three models of Infomap analysis

The second methodology, Infomap, is a recent and largely acclaimed method that, performing random walks over the network, allows the detection of those groups of nodes within which the simulated flow tends to circulate for long before exiting. Through the observation of the intensity with which agents communicated among each others, Infomap was applied to detect groups characterized by the capacity to activate shared working streams. Since common working activities necessarily involve the spreading of communications, the flow simulated by Infomap was intended as a representation of the dynamics of circulation of information over the network. The informational basis regards the participations in common projects (weighted edges). Moreover, in order to give a better representation of the observed time dynamics, the chronological sequence of projects was used to constrain the circulation of the simulated flow (assuming second order Markov conditions).
After having described those Infomap features that have the most importance in the context of this analysis, I will be introduce the different models and explain their setting. The majority of settings are the same for all developed models. First of all, each Infomap model will be asked to detect overlapping communities and, concerning the teleportation probability, there are no reasons to fix it at values different from 0.15. About the weight structure, weights are attributed to edges, emphasizing the number of common participations that couples of agents had. Finally, what has still remained excluded, is the Markovian order that is going to be used. Since this is the most interesting aspect and since different considerations can be made about it, three different settings are used. The differentiation among the three different models that have been used relies exclusively on the Markovian order.

4.2.1. Infomap model MKV1: a memoryless flow of information

The first model I proposed (named *MKV1*) is a model in which the Markovian order is set equal to 1. This means that no information about the provenience of the flow is taken into account. When the flow moves through the network, at every step it faces a set of probabilities of moving in different directions that depends on (in order):

- the teleportation probability;
- the position of the flow;
- the weight structure of edges.

Simulating the propagation of a flow over the whole network without any kind of constraint (memoryless flow) is like observing the propagation of an information stream in a context where all edges are open. This is the case of a situation in which all agents maintained active their relations with all other agents they collaborated with. It is like observing the network at the end of the policy cycle, assuming that all edges have continued to be active.

4.2.2. Infomap models MKV2_AS and MKV2_DS: second Markov order models

The second and the third models that I developed (named *MKV2_AS* and *MKV2_DS*) are second order Markov models. This means that the direction that the simulated flow takes at every step depends also on where it was at the immediately preceding step. The process of creation of the fake flow was implemented through the creation of trigrams. The existence of a flow among ordered groups of three agents with one of these two characteristics was hypothesized:

- all three agents are involved in the same project (within project flows);
- the first agent and the last agent participated in two different projects, while the second agent participated in both of these (among projects flows).

The idea behind the construction of the fake flow is that agents, through participations in projects, first accumulate knowledge and information, and then they spread it over the network. The crucial aspect that emerged during the process of reconstruction of these fake flows, regarded the consideration of the temporal order of projects[1]. Since a flow is interpreted as a stream coming from the accumulation of information in the context of a single project, the hypothesis was immediately accepted that the flow could move between two projects, the first of which terminated before the end of the second. The point is that when a project ends, participants will not have any other information from it and so every thing that was learnt in that context could be transferred into another context. Thus, since it has been decided to simulate the presence of all possible flows

[1] The sense of these hypothesis is that after having finished a project, participants accumulated knowledge and so they can give rise to a flow of information.

among projects, it follows that it is automatic to assume the existence of a flow between a terminated project and any other successive one (obviously through the presence repeated presence of at least one agent).
About the consideration of the chronological order of the sequence of the projects, the hypothesis to simulate the rise of a flow exclusively from terminated projects has more to do with an idea of accumulation concerning the knowledge of all the working processes, of all the experiences and of all the phases that constituted the project. On the other hand, admitting the possibility of a spreading of information before the project has terminated, seems to have more to do with a concept of acquaintanceship, rather than accumulation of knowledge. Both must be regarded with interest and both can be crucial in a process of flourishing of innovation. They represent two different situations and as a result the choice was to developed two different models reflecting these two different hypotheses. In the first of the two models with a second order Markov condition, the propagation of flow moving from projects that still have not terminated is considered. The name of this model is *MKV2_AS,* that stands for: Markov order 2 with Admitted Simultaneity[2]. In the second of the two models with a second order Markov condition, the propagation of flow moving exclusively from projects that have finished is considered. The name this model is *MKV2_DS*, that stands for: Markov order 2 with Denied Simultaneity.

4.3. Three DCI models of analysis

DCI methodology is a new method developed by Villani *et al.* (Villani, Filisetti, Benedettini, Roli, Lane and Serra 2013, 2015). Through the consideration of how agents' behaviors show levels of coordination during a considered period, DCI allows the identification of functional subsystems thanks to the calculation of some information-theory measures (entropy, integration and mutual information). The comprehension of the presence of integrated behaviors is done thought the computation of the statistical distance of the Cluster Index (CI) of the observed groups, from the CI of groups where behaviors are random. If the combinations of states of activation over time of agents belonging to a considered group are far from being random, then the significance of the CI (t_{ci}) of that group testifies to the presence of an emergent behavioral pattern.
Starting from the inspiring contribute of Tononi *et al.* (1994, 1996) in the comprehension of the functioning of neurons in the brain region, DCI aims to detect groups of agents that, even if not closely connected in the network, show behavioral patterns that are far from being random. Since the presence of integration among specific neurons' activities confirmed the hypothesis that these neurons have similar functions (Tononi *et al.* 1998), the application of DCI methodology reflected the intention of investigating the presence of communities whose agents are characterized by having similar objectives and similar purposes. The informational basis used regards the states of activity of agents in different instants over time (in terms of their participation in funded projects).

4.3.1. DCI model 'BOOL_1'

The first process of analysis with DCI methodology was characterized by the use of boolean variables[3] to describe agents' activity over time. For this reason, this process was called 'BOOL_1**'**. As for all other DCI applications, in BOOL_1 are considered those 352 agents that had at least two participations in funded projects, and these agents are observed in 59 different instants over time. BOOL_1 was a process that represented a completely new exploration. It is important to highlight that the discovery that groups (especially in first rounds) with the highest levels of t_{ci} were groups of uninteresting actors (regarding a context of analysis of regional economic processes of innovation), led to the necessity to guide the analysis in the direction of those agents that for many reasons were considered as holders of key roles.
Thus, in the first process of analysis groups that step-by-step were identified were progressively excluded from the analysis. This way to proceed was due to the difficulty to evaluate the resulting detected groups, since every time the algorithm is run, it detects 75.000 groups of agents that can differ from each other just for the presence/absence of one agent. It is immediately clear that the detected groups are very similar among each other and so, to overcome this situation, this was the procedure that was applied:
- after the algorithm was launched, the best detected group was selected as a community;
- the detected community was skimmed from the analyzed set;
- the same analysis was iterate over the remaining agents.

This procedure continued until the set of analysis was empty. By doing so, two drawbacks emerged:
- overlapping among communities is not possible;
- t_{ci} of different communities is not comparable because of methodological aspects.

Thus, a new way to evaluate the results produced by the algorithm was needed.

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[2] The term 'simultaneity' refers to the agents' capability (or not) to generate flows from ended projects.

[3] A boolean variable takes value 0 if the agent is not active, and it takes value 1 if the agent is active. In this analysis 59 variables were elaborated, one for each identified instant in time. The activity of agents has been defined as the participation to at least one funded project.

4.3.2. DCI model 'BOOL_2'

The second process of analysis with DCI methodology, was done using the same informational basis as BOOL_1: 352 agents and 59 boolean variables that describe the activity status (in a binary form) of agents over time, with respect to their participations in regional public policies. Considerations and reflections that emerged from the first process of analysis BOOL_1, led to the desire to elaborate another model that would be less arbitrary. The choice was to conduct a new analysis that, starting from the same initial basis as the previous one, could advance trying to overcome the perplexing aspects that emerged during the first process. Because of that, this new process is characterized by a more rigid structure that tries to furnish a more reliable support for the revealed difficulties. This new process of analysis identifies a completely new model, and it will be referred to it as 'BOOL_2'. Here the main steps (in order) that characterize the model are summarized:

- 30 runs of the algorithm in every round and single final ranking of all analyzed masks;
- selection of the mask with the highest t_{ci} value at the end of every round;
- progressive skimming, round after round, of the mask selected at the end of the previous round;
- iteration of the analysis over several rounds;
- stopping of the skimming procedure after the substantial loss of agents that the researcher retains must not be excluded;
- hierarchical agglomerative cluster analysis of 12.500 masks with the highest t_{ci} value: simple matching as similarity criterion and complete linkage as agglomerative method.
- dendrogram cut with respect to (i) the length of branches, to (ii) the identification of clusters with a good degree of diversity among them, and to (iii) the involvement of a good number of agents;
- in every cluster, selection of the mask with the most significant score of DCI, as the representative mask of that cluster.

4.3.3.DCI model '∂LoA'

After exploring the process of analysis BOOL_1 the decision was taken to experiment other models with an ameliorated structure in terms of methodology. This is what has been done with BOOL_2 and with another process of analysis which was called '∂LoA'. The acronym has to be read in this way: '∂' stands for 'variations' and 'LoA' stands for '<u>L</u>evels <u>o</u>f <u>A</u>ctivity'. Instead of considering boolean variables, here variables were used that express the relation between the number of projects in which the agent was active in a specific instant, and number of projects in which the agent was active in the previous instant[4]. What was done was a further step in the characterization of the activity status: the elaboration of this new series of variables allows the real introduction of the time dimension, while with boolean variables the time was considered only through the necessary identification of instants in which to observe agents, in this new model the activity of agents is described in terms of evolution. All features of model ∂LoA, except the nature of variables, are the same as BOOL_2.

5. Main results

First of all, in the context of CPM analysis, the problematic definition of the value of *k* was overcome thanks to the observation of the specific features of all possible partitions that the algorithm makes it possible to detect. Thus, after the identification of three ranges of *k*, three specific values of it were selected (*k*=5, *k*=12 and *k*=18) and three models were elaborated. Then, in the context of Infomap analysis I computed simulations through the development of (i) a model characterized by a memoryless flow, and (ii) two second order Markov models elaborated considering the chronological sequence in which projects were carried out. Finally, in the context of DCI methodology I developed its application to a socio-economic context of analysis. An explorative process was determinant to make emerge some limits, mostly related to the available informational basis, which required the evaluation of new strategies. Then, after having elaborated specific proposals, I developed two other processes of analysis over two different sets of variables describing the behavioral profiles of agents.

The tailoring of these nine models required in-depth understanding of the methodologies considered and also an intense degree of originality, since no specific literature references were found concerning previous applications to similar case studies. All these nine models were developed taking into account the peculiarities of the object under analysis: (i) a cycle of innovation network policies made up of nine waves with various

[4] Thus, 58 variables were elaborated in this way:

- if the agent has a number of active projects higher than the number of projects the agent was participating in, in the previous instant, the corresponding variable assumes value 3;
- if the agent has a number of active projects equal to the number of projects the agent was participating in, in the previous instant, and the number is greater than zero, the corresponding variable assumes value 2;
- if the agent has a number of active projects lower than the number of projects the agent was participating in, in the previous instant, and the number is greater than zero the corresponding variable assumes value 1;
- if the agent is participating in no funded projects, it has to be considered inactive and so the corresponding variable assumes value 0.

important features, (ii) in which agents' participations were not constant and (iii) in which partnerships' compositions changed over time. The complex nature of the processes supported (innovative projects) and the discontinuity of temporal dynamics have to be borne in mind in order to understand how the different methodologies and the different models were considered and developed in an intricate context of analysis .

The results that emerged from the different analyses seem to be in line with what was investigated. Even if further research is needed in order to better understand how agents' participations in innovative projects can have affected the creation of a solid and dynamic interactive pattern, the analyses developed revealed meaningful partitions. First of all, the application of the three different models of CPM allowed the detection of communities that the higher the values of *k*, the higher their characterization in terms of participations in specific waves. The observation of meaningful contingency tables allowed me to see how, especially in the model with *k* equal to 18, every detected group is characterized by a significant number of participations in projects developed in one of the nine waves. Thus, having applied CPM to study the presence of communities characterized by intense relational structures, it seems to me coherent that the detected groups are made up of agents that have significant participations of this kind. The waves and, before them, the policies' implementation, were crucial to determine the shape of the agents' connective framework. Through the definition of specific domains of interventions and through the imposition of different constraints to the agents' participations, the policies that were implemented over time necessarily affected the construction of the network relations.

Infomap models also show results in line with the purpose for which this methodology was applied. The three partitions detected are made up of communities characterized by agents' participations in projects related to specific technological domains. A similarity emerged between the communities identified, especially those detected by imposing restrictions on the circulation of the flows, and the partnerships that during the policies were realized. Infomap methodology, which was applied to investigate groups of agents characterized by the capacity to share working processes, allowed me to detect communities which seem to reflect the participations in the most important common activities observed in the context of the cycle of policies: the projects. A further investigation of how these groups proceeded (or did not) to develop shared activities would probably provide useful elements in the comprehension of how the policies really supported the creation of continuative innovative collaborations.

Finally, the application of DCI algorithm, also revealed results that deserve attention. The partitions that were detected were analyzed through the computation of meaningful contingency tables. While with the preceding methodologies characterizations regarding the agents' participations emerged, with this analysis the communities detected seem to be related to a different kind of feature, the typology of the agents involved. The third model in particular, the one in which the method was applied over the most refined informational basis and in which I introduced a procedure of cluster analysis of the large quantity of masks detected by the algorithm, allowed the identification of a partition in which, on one hand, KIBS and enterprises, and on the other, KIBS and enterprises and universities, determine two distinct groups of communities. Since this methodology originated to detect functional groups (Tononi *et al.* 1994), the emergence of the salience of the typology of agents seems to underline that similar agents have similar finalities. The presence of integrated activities (that are what DCI algorithm investigates) can be reasonably related to the presence of similar typologies of economic institutions, since it can be said that the specific nature of agents necessarily influences their functions and these, in turn, determine specific behavioral patterns.

This is what the application of the different methodologies produced and what their results suggested. This work has attempted to start out on possible paths to analyze a complex theme, that of innovative organizations, and clearly the results have to be further investigated. Nevertheless, some elements have emerged and they seem to suggest that these analyses were coherent with the intent to which they were applied. Since there are no specific examples in the literature that testify to the appropriacy of the application of these methodologies to the investigation of innovative dynamics in a socio-economic context, there was no guarantee that the described characterizations would be found.

6. The coexistence of relational structures, and of shared processes and of common functions

Moreover, to understand if there are agents that are simultaneously grouped together by CPM, and by Infomap and by DCI analysis, I calculated the intersections generated by all possible combinations of three communities as follows:

- the first community is one of the communities detected with CPM;
- the second one is one of the communities detected with Infomap;
- the third one is one of the communities detected with DCI.

After having computed for each combination the corresponding Jaccard index (i.e. the ratio between the number of agents that are present in the intersection and the number of agents that are present in the union set), to every agent was attributed the highest ratio among those referred to intersections in which is present. Considering the elaboration of three probit models (with robust standard errors) were the dependent variables describe different kinds of participations in the policy cycle 2007-2013 (the one following 2000-2006 policies), the coefficient of the independent variable describing the highest Jaccard ratio becomes significant and positive only when the dependent variable is a dummy that assumes value 1 if the agent signed at least one collaboration agreement (in the period 2007-2013). Since collaboration agreement has to be considered the type of relation the most oriented to the purpose to develop innovative initiatives, the presence of the agent in an 'intense' intersection (a combination of three communities in which, with respect of the union set, there are many agents that are grouped together under each of the three perspectives adopted) seems to have a significant role in the continuation of innovative activities over time. Thus, the identification of those groups of agents that are simultaneously detected by the three different methodologies (that reflects the simultaneous presence of relational structures, and of shared processes and of common functions*)* seems to be coherent with the purpose to detect those agents that have a key role in the regional economic system from the perspective of the capacity to produce innovation activities. Further analysis are needed to a better comprehension of who belongs to this groups resulting from intersections. Nevertheless first results are in line with the objective of the entire analysis.

(1)

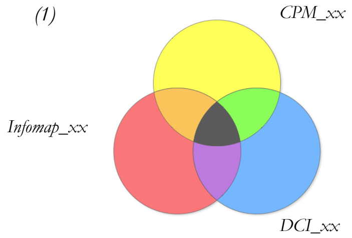

Figure 1. The Venn diagram represents the overlaps that were investigated. Every combination is made up of one community detected through CPM analysis, of one community detected through the application Infomap algorithm and of one community detected though DCI analysis. The overlap generates distinct 7 areas. The overlaps among them are colored in orange (CPM and Infomap), in purple (Infomap and DCI) and in green (DCI and CPM.), and the intersection of all three communities is colored in black.

(2)

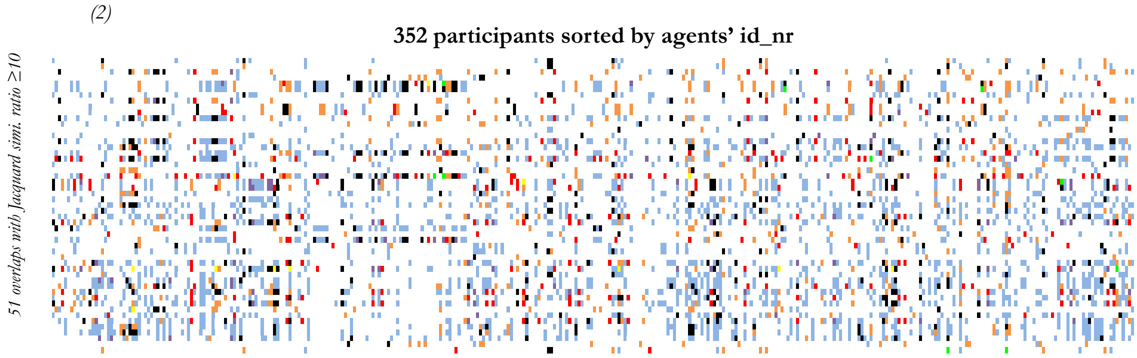

Figure 2. The matrix represents the 51 combinations with the a Jacccard similarity ratio higher than or equal to 10.00%. Each row represents a combination and each column represents an agent. Columns are ordered in descending order with respect of the corresponding Jaccard ratio (the one with the highest ration on top). Cells are colored in the same way as the Venn diagram, depending on the kind of the communities to which the agents belongs in that specific combination.

7. Policy implications

To conclude, some consideration regarding policy implications. The study of the intensity of the overlaps among communities detected with the three methodologies makes possible to conclude that the simultaneous presence of relational structures, of shared processes and of common functions has to be regarded as a relevant element in the identification of those agents that tends to develop innovative activities. With regard to policy implications, the most important aspect is that the identification of the key groups of agents can be done without relying on the agents' technological or economic classification, but considering agents' interactions. Policy interventions should be implemented taking care of the evaluation of the results reached by agents, as well as of the observed ongoing dynamics.

The proposed methodological approach needs to be further developed and the results need to be investigated with a more in-depth research. Nevertheless, some considerations regarding the case study presented in this paper can be made. From the analysis of intersections, DCI communities emerged to be much more different to communities detected with other methodologies than CPM and Infomap communities do (it is possible to see this from the dominance of color blue in Figure 2). A possible conclusion is that the policies should have supported more specifically the pursuing of common functions over time. This could have been done through the facilitation of conditions that allow agents to protract their activity in specific topics, like for example allowing longer time horizons of projects or facilitating the granting of funds to projects whose objectives constituted an upgrading of preceding projects' objectives. In general, thanks to the observation of the intersections, it is possible to have indications regarding those aspects that in each specific local system need to be more sustained by policies, in order to favor the capacity of interacting groups of agents to innovate.

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