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Emerging innovation niches: An agent based model☆

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ABSTRACT

The creation of an innovation niche depends on the interaction of three mechanisms involving: *converging* expectations, *networking* among the innovation actors, and *learning* about the novelty through efficient knowledge creation and diffusion. Such mechanisms define the key characteristics of a network of firms (i.e. the innovation niche), and the interaction among them guides the development and diffusion of a new technology. In this paper, we propose an agent-based model to investigate the dynamics characterising such interactions and the role that policy intervention can have in governing the niche development process. Specifically, we consider and assess the impact of two policy actions: (1) increasing actors' expectations towards the new technology by means of information spreading and (2) providing subsidies aimed at stimulating technological switch. Our results confirm the importance of policy intervention and show the dominance of information spreading activities over subsidies. The former policy action, in fact, preserves a broad consensus around the new technology, a fact which turned out to be fundamental in order to promote efficient knowledge diffusion and the effective use of individual and network resources.

1. Introduction

The diffusion of radical innovation shows different degrees of success and (typically long) time of development (Kemp et al., 1998). Under these circumstances, a reasonable policy objective would be to define strategy to augment the probability of success and to reduce the development period of a desired new technology. To address this issue the so-called strategic niche management (SNM) approach has been developed (Schot et al., 1994; Kemp et al., 1998; Weber et al., 1999). It focuses on the creation of "technological niches" – i.e. protected spaces in which radical innovations are developed and tested. More precisely, SNM has been described as "the creation, development and controlled phase-out of protected spaces for the development and use of promising technologies by means of experimentation, with the aim of (1) learning about the desirability of the new technology and (2) enhancing the further development and the rate of application of the new technology" (Kemp et al., 1998: 186).

In the mainstream literature SNM has been used for two purposes: understanding the process of technological development and influencing it in a desired way. Raven (2005) refers to these two ways of using SNM as a research model, when it is used to analyse past experiences in order to discern factors contributing to the success or failure of innovation diffusion stories, and as a policy tool, when it is used to define guidelines relevant for designing innovation policies.

Regarding the former aspect, SNM has been employed to analyse case studies in various fields of sustainable technologies such as wind turbines (Kemp et al., 2001), battery powered vehicles (Kemp et al., 1998; Hoogma et al., 2002; Truffer et al., 2002),[1] fuel cell vehicles (Lane, 2002), photovoltaic cells (Van Mierlo, 2002), organic food (Smith, 2003, 2006), renewable energy technologies (Tsoutsos and Stamboulis, 2005; Van der Laak et al., 2007; Caniels and Romijn, 2008; Lopolito et al., 2011a), biogas plants (Raven, 2005; Geels and Raven, 2006) and biomass co-firing (Raven, 2005, 2006). Such studies focused on existing projects, aiming to address the question

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[1] More specifically, Hoogma et al. (2002) uses a series of eight recent experiments with electric vehicles, carsharing schemes, bicycle pools and fleet management to illustrate the means by which technological change must be closely linked to social change if successful implementation is to take place.

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why some innovation trajectories were a success while others a failure, under specific local circumstances. This allowed identifying the fundamental niche mechanisms affecting the successfulness of innovation, an issue recently taken up by Schot and Geels (2008) who provide an up-to-date discussion on SNM and niche-internal dimensions and external processes.

Notably, none of these studies has attempted to operationalise such mechanisms in formal models. In this work we aim to address this very point, investigating how well-crafted policy actions can influence the internal dynamics of an innovation niche, fostering the diffusion of a new technology. We do so proposing a model designed to investigate the fundamental social processes involved in the rise of a stable innovation niche and assess the role that policy intervention can have in governing such processes.

As discussed in the following section, a technological niches can be conceived as a complex system – i.e. one characterised by a tight interrelation between parts and the collective behaviour of the system. In order to disentangle such complexity we adopt an agent-based methodology, which explicitly allows investigating specific features of the overall system emerging from the interaction of agents and their behaviours.

The model, described in Section 3, represents a simplification of the complex reality of transition dynamics. In order to allow an easier comprehension of its features, two specific bounds should be considered: (1) the model focuses only on the process of emergence of a technological niche, thus it does not allow investigating if the emerging niche would eventually be able to challenge the dominant technological regime – i.e. succession; (2) it is framed in terms of generic technological transition leaving aside the content of transition in terms of sustainability.[2]

The simulation presented in Section 4 allows for a comparison of two policy actions: (1) increasing actors' expectations towards the new technology by means of information spreading campaign and (2) providing subsidies aimed at stimulating technological switch. Implications and suggestions for further research are presented in the last section.

2. Technological transitions and innovation niches as complex systems

The occurrence of technological transitions seems to require various conditions to be fulfilled. First, opportunities for a technological change have to emerge. This is largely linked to the external dynamics taking place within the socio-economic environment. At the same time, the creation of a new technological design is needed. Typically, novel designs are introduced by engineers and scientists operating in R&D laboratories or research institutes, by means of *trial and error* procedures. In order to avoid the tendency for a new design to be outpaced by harsh competition before its value becomes clear, some kind of protection is needed. Protection is important in the early stages of product development, in particular when adverse conditions (no clear market, high production costs and social inertia for its adoption) can lead to the rejection of the novelty by market mechanisms. In order to boost innovation processes, market selection mechanisms can be mitigated by means of subsidies provided to those producers willing to innovate. Moreover, innovative behaviours can be triggered by management of perceptions: enhancing producers expectations of the value of novelties and future revenues associated with their adoption.

Along with proactive policy actions, contextual factors are crucial in creating the opportunities for the establishment of an innovative protected space. Specifically, changes in the socio-economic environment create continuous stimuli to which the incumbent technologies have to react and adapt to. These continuous stimuli, called "selection pressures" in the mainstream literature (Smith et al., 2005), are various in nature, and can be classified as: (1) *economic pressures* that operate at the firms' level changing their profitability (for instance pricing, competition, contracts, taxes and charges, regulations, standards, skills and knowledge); (2) *social pressures* originating from institutional structures and conventions, including changes in broad political economic 'landscapes', or wider socio-cultural attitudes and trends (e.g. demographic shifts, rise of consumer culture, neo-liberal model of globalisation, etc.); (3) *technological pressures*, deriving from variations in technological designs elaborated by engineers and researchers that can compete with the incumbent technology.

In order to give a systematic explanation of such dynamics, a multi-level perspective (MLP) has been developed in the literature (see, among others, Berkhout et al., 2003). This model can be seen as a nested framework formed by three interconnected levels. In such a framework the incumbent socio-technological regime is sandwiched between two external levels occupied by the socio-technical landscape and technological niches.

Occurring at the bottom level, technological niches can be conceived as protected *socio-economic* spaces where radical innovations are developed and tested. In this context business incubation can occur, i.e. rooms where the process of novelty (and its development) becomes a greatly valued criterion and where there are quite different selection mechanisms with respect to the normal environment. This level is relatively dynamic and there may be several simultaneously active technological niches at any given time. The socio-technological regime level consists of a relatively stable configuration of institutions, techniques and artefacts, as well as rules, practices and networks that influence technological development by generating incremental innovations (Rip and Kemp, 1998). It is identified by the social function it fulfils (e.g. electricity and water supply, education, health care, food supply) (Geels, 2002a,b) and can be defined as "the rule set or grammar embedded in a complex of engineering practices, production process technologies, product characteristics, skills and procedures, ways of handling relevant artefacts and persons, ways of defining problems; all of them embedded in institutions and infrastructures" (Rip and Kemp, 1998: 340). Finally, the *landscape* level represents the wider context in which socio-technological regimes and technological trajectories are embedded. This consists of deep structural trends, hard material and immaterial context of societies, natural resources, infrastructures (electricity, roads, city planning), political cultures and coalitions, lifestyles, macro-economic aspects (oil prices, recessions), demography, and so on (Geels and Kemp, 2000: 18).

Interactions among the three levels deeply influence the technological trajectory, shaping and constraining it. In particular, changes at landscape level can make a socio-technological regime less stable by creating windows of opportunity for niche innovations (Geels and Schot, 2007: 405). The insight is that conditions external to the niche create opportunities for technological change. Building on such opportunities, innovation's actors coordinate efforts in order to establish a technological niche.

A technological niche is successful when the firm that introduced the innovation grows stronger and/or when other firms imitate the novel design. Following Raven (2006), this results in an attack on the stability of the dominant socio-technical regime. As we shall discuss in what follows, three interrelated mechanisms affecting niche's internal dynamic are at the basis for

[2] Indeed, an important aspect of the strategic management of niches, at least in the context of sustainability transitions, is that innovation is goal-oriented in the sense that the transition process should be directed to create innovations potentially leading to more sustainable regimes. However, we decided to leave aside this aspect to overcome problems posed by the ambiguity of the concept of sustainability and the different visions that actors can hold about sustainable innovations.

niches' success. Namely such mechanisms are: (1) convergence to high expectations, (2) networking and (3) learning (Morone and Lopolito, 2010).

The *convergence to high expectations* towards a common view is crucial for the emergence of an innovation niche. Indeed, actors take part in risky projects and technological experiments on the basis of their expectations (Van der Laak et al., 2007); at the same time, diverging expectations can negatively affect the way goals are defined and prioritised (Smith et al., 2005). This initial obstacle can be overcome only through the development of a robust and shared vision among actors potentially involved. Hoogma (2000) highlights that this process of convergence mainly depends on external factors, in the sense that external circumstances, originated in landscape and regime level (e.g. change in regulation or in resources stocks) or in other protected spaces (e.g. breakthrough in R&D research), may create opportunities for developing new technology. These opportunities give rise to promises (of success) when stakeholders are informed about them. At this stage, indeed, the novelty is mostly a promise of success: it lacks clear market and functionality but presents interesting future development. Well-articulated promises[3] can influence firms' expectations; firms feel legitimated to invest time and effort in the new technology (Raven, 2005). Then, expectations can change dynamically over time, being influenced not only by external circumstances but also by the results of experimentations taking place within the niche. When this confirms the original vision, expectations increase in robustness and stability, and a larger number of actors share the same vision.

As it was pointed out in a recent study (Smith and Raven, 2012), positive expectations about the niche are argued and mobilised in a socio-political sense, rather than only in a socio-technical sense, in order to expand, adapt or withdraw protective/institutional concessions from key actors. We shall come back to the socio-political implications of expectations in Section 3.3, where we discuss a (sub)set of policy tools for the formation of a protected space.

A further essential feature of a technological niche is *networking* among the innovation actors (producers, users, regulators, societal groups). The formation of a stable social network is needed for gathering and mobilising the resources required to guide the technical change in a desirable way (e.g. costs reduction implemented via substantial investments in process innovations). This process takes time. In the initial stages of experimentations the network is small and fragile since only few firms are involved in the innovation process and their commitment is limited. When the network expands, powerful actors join it, bringing in strategic resources for the experimental activity. Gradually, actors assume a more defined role within the system and their contribution to the experimentations becomes clear. Thus, the networking mechanism is told to be successful when the network expands and the relationships among actors become more stable (Raven, 2005; Caniels and Romijn, 2008).

Finally, the *learning* mechanism is crucial to improve the technology or make adjustments to societal embedding (Raven, 2005). Within a niche, the learning process takes place in two ways. Once a group of actors has established an innovation niche, they start producing using the new technology; this activates a process of learning-by-doing, which augments the available stock of knowledge. Moreover, firms belonging to the emerging innovation niche have typically more chances of (and should be more keen on) sharing at least some of their knowledge for the further

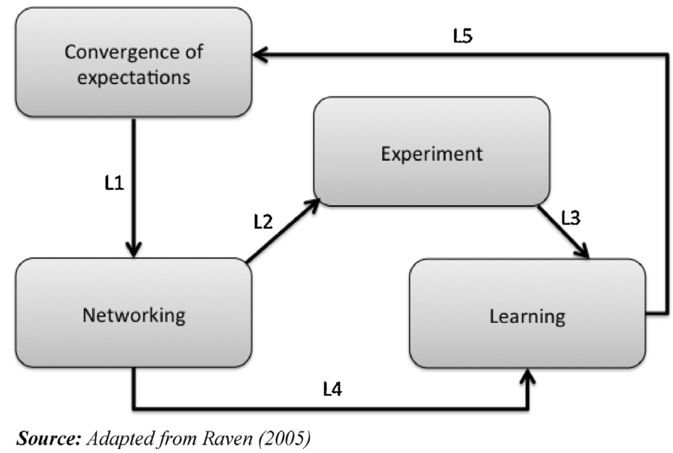

Fig. 1. Mechanisms interaction within the niche.
Source: Adapted from Raven (2005).

development of the new technology. This assumption rests on the idea that economic actors operating in close proximity might give away information for free for various reasons which include "altruism; incentive to support one's community; reputation-enhancements received by information providers; and expectations of benefits from reciprocal helping behaviours by others" (Lakhani and von Hippel, 2003: 924). A large part of this process is deeply informal as tacit and uncodified knowledge can only be acquired and shared by means of intensive and direct interactions – this corresponding to learning-by-interacting activities.

Within the niche, these three mechanisms closely interact, giving rise to a complex and self-reinforcing system. Raven (2005) offers a systematic description of such interaction as represented in Fig. 1, where niche's mechanisms and the links (L) among them are reported. First of all, it is highlighted that the expectations convergence mechanism affects the networking mechanism (L1). In fact, on the basis of their expectations, stakeholders engage in networking activities searching partners to set up experiments, and this results in a network with specific composition and potentiality. In turn, the network features are crucial in defining the particular set-up of experiments (e.g. research on technological performance, or economic feasibility) (L2). Feedback loops are present since technological experimentation produces results that contribute to the learning process (i.e. learning-by-doing) (L3); learning is also influenced by the characteristics of the network itself (i.e. learning-by-interacting) (L4), that is a part of the knowledge basis of each actor flows through its social links towards other actors of the net. Some authors distinguish between first and second-order learning (Grin and van de Graaf, 1996; Hoogma, 2000; Raven, 2005). First-order learning is mostly technical. It relates to learning about the effectiveness of a certain technology to achieve a specific goal, and mainly refers to the accumulation of facts and data. Instead, second-order learning concerns changes in cognitive frames and norms questioning the assumptions underlying the system. Since we are interested in the formation of a technological niche, here we focus mainly on a first-order kind of learning mechanism. Indeed, the introduction of a second-order mechanism would imply a more complicated structure (model) including different types of agents (users, outsiders, etc.). Finally, based on learning outcomes, expectations are confirmed (becoming more robust and widely shared) or falsified (weakened) (L5). This is reflected in an accordingly adjusted set of new technological experiments.

The final effect of such complex interaction patterns is largely unpredictable: how do expectations influence the network structure? How does this reflect on the experiment set and on learning processes? How do expectations change accordingly? How all these

[3] By well-articulated we mean that promises of the new technology are *credible* (supported by facts and tests), *specific* (referred to clearly identified problems), and *coupled with shared problems* not yet addressed by existing technology (Kemp et al., 2001).

factors affect the successful development of the niche as a whole? As it seems, a rather composite environment arises, where complex dynamics govern agents' behaviours and interactions. We shall attempt to address the whole complexity of the underlined conceptual framework building an agent-based model able to capture all the features and links summarised in Fig. 1.

3. Model description

The complex dynamics outlined in Section 2 can hardly be formally described through traditional mathematical methods (e.g. linear programming, data envelopment analysis, etc.). A more suitable analytical framework is represented by the agent-based computational economic (ACE) approach (Tesfation, 2006). Specifically, a technological niche can be viewed as a complex adaptive system endowed with three basic features: (1) it is composed of interacting units – i.e. entities capable of varying degrees of self-governance and self-directed social interactions; (2) such units are goal-directed – i.e. they are reactive and direct at least some of their reactions towards the achievement of built-in (or evolving) goals; (3) the system exhibits emergent properties – i.e. properties arising from the interactions of the units and that are not properties of the individual units themselves.

3.1. Agent-based models review

In recent years, formal modelling has gained growing importance within the community of transition researchers as a useful approach to draw insights into the complex mechanisms underlying transition dynamics (Holtz, 2011; Safarzyńska et al., 2012).

Holtz (2011) and Safarzyńska et al. (2012) engaged with a literature review on models of transition classifying them on the basis of their background and methodology. It has emerged that the theoretical frameworks mainly adopted by agent-based modellers are diffusion of innovations (Cantono and Silverberg, 2009; Schwarz and Ernst, 2009; Faber et al., 2010; Huétink et al., 2010), path-dependency and coevolution dynamics (Alkemade et al., 2009; Zeppini and Van den Bergh Jeroen, 2011; Safarzyńska and van den Bergh, 2010; Frenken et al., 2012; Van der Vooren et al., 2012), consumer behaviour and microeconomics assumption (Weisbuch et al., 2008; Windrum et al., 2009), and the MLP (Bergman et al., 2007; Schilperoord et al., 2008; Köhler et al., 2009; Papachristos, 2011).

In order to highlight the modelling advancement made in the present work, in this section we limit our attention only to those agent-based models grounded on the MLP theory, as a comprehensive review of models of transition goes beyond our aims.

The touchstone for this kind of model is represented by the one developed within the MATISSE project. This model aims to assess sustainable transitions using agents to represent niches and regimes (constellations) and consumers' behaviour. Agents are located in a two-dimensional practice space. The strength of constellations derives from the support given by the consumers. Consumers' support depends on their position in the space that is in turn influenced by signals from the landscape. In this model, transition derives from diverting support for the dominant regime to other constellations. The model was subsequently adapted to analyse specific problems as transitions towards sustainable mobility (Köhler et al., 2009), more general societal transition (Schilperoord et al., 2008), and change in housing (Bergman et al., 2007). MATISSE model was evaluated by Bergman et al. (2008), comparing its output with four historical case studies from Geels and Schot (2007). They conclude that the model is useful for theoretical development, since it is a formal method to bring together the several characteristics of transitions theory, representing at the same time a methodological tool to develop specific models for different empirical examples.

Another very recent attempt to model transition by means of agent-based approach grounded on MLP is found in Papachristos (2011) who presents a model that captures the dynamics of an existing technological regime and the emergence of niches as they compete and respond to landscape pressures. The model accounts both for landscape pressure and for endogenous regime feedback. Specifically the incumbent regime becomes unstable when a number of its members become aware of the regime's undesired effects. Transition occurs when a specific percentage of aware regime members shifts to the niche technology. The models' findings are consistent with MLP theory predictions and, as the author points out, it illustrates how formal models can provide a useful test for theory also in those cases in which the theories are stated in entirely qualitative abstract terms.

From this brief review, it emerges that the state of the art in agent-based models based on MLP is characterised by very broad models primarily focusing on the interaction among the various levels of the MLP. Indeed, these works provide rather useful modellisation of several theoretical concepts paving the way to theory enhancements. However, there remains the need for a better specification of transition dynamics that should be broken down into its specific components in order to allow a more in-depth comprehension of its mechanisms (Holtz, 2011). This is the gap the present work attempts to begin to fill, by introducing three internal niche mechanisms: niche network resources predication on existence of social relations among niche supporters (see Section 3.2.2), the role of actors' expectations (see Section 3.2.1) and 'social construction' (Van Lente, 1993) where learning advancements lead to the reduction of uncertainty in the performance of the niche option (see Section 3.2.3) and an improvement in producing firms' ability to profit from it.

In our model the interacting units forming the niche are representations of firms involved in technological change. This represents a simplification assumed in the model. Indeed, in the mainstream literature on SNM the process of niche formation is supported by a social network, including producers, users, policy makers, intermediaries, societal groups, researchers, etc. (Raven, 2005). In the present model we only claim to represent in an abstract and homogeneous way this one type of actor (i.e. producing firms). This is an operative choice aimed at maintaining the model as simple as possible, as the introduction of different kinds of actors would lead to a great complexity with related problems of model handling and results interpretation. For a similar operative approach see for instance Yücel (2009).

Firms (i.e. agents) are capable of socially interacting, sharing information, knowledge and resources; they are also goal-directed in the sense that they can change their attributes as a reaction to environmental changes, directing their actions to the achievement of profit. The niche as a whole exhibits properties (such as the convergence of firms' expectations towards a robust and stable view; the structure, dimension and stability of network; the accumulated technological knowledge; the diffusion of the niche option and its improvement) that are not present in the nature of individual agents, but arise from their interactions.

The model presented in this section is set up to represent and analyse: (a) the three fundamental niche mechanisms identified above; (b) how the formation of a protected space can activate these mechanisms and influence them; (c) how these mechanisms interact dynamically to reach a niche equilibrium.

The model is dynamically complete in the sense that, starting from the definition of units' attributes and environmental initial conditions, the formation of the technological niche can emerge through the interaction of agents over time without further intervention of the modeller.

3.2. The niche's mechanisms

The model depicts a system formed by a finite number of agents $I = \{1, 2, 3, \ldots, N\}$, $N \ll \infty$,representing firms widely using a specific incumbent technology (i.e. the regime option) in their economic activity (goods production). In order to approximate the mechanisms governing technical transition, the model assumes that all agents are profit-seeking, bounded in their rationality and operating in a complex and risky environment – i.e. firms behaviour is *intendedly* rational but only *limitedly* so (Simon, 1957). The risky nature of the environment within which agents operate stems from the uncertainty associated with the innovation process. Economists typically deal with uncertainty by postulating a probability distribution for a certain range of events. Using these probability distributions, the economic consequences of decisions can be weighted by their probability. Rational actors can make calculations that are more complex than those in an environment of certainty, but the results do not differ appreciably. This kind of uncertainty has been labelled 'weak uncertainty'. Conversely, we consider in our model a situation in which outcomes of the uncertain process are not known in advance, since agents do not have full information on the probability distribution of the events.[4] This condition of 'strong uncertainty' is, arguably, a better description of innovation processes and lies at the core of the distinction between the neoclassical and the evolutionary approaches (Verspagen, 2005).

In this model niche development is investigated by assuming that just one innovation is available as an alternative to the incumbent technology, and that this is 'seeded' in the initial period. Periodically, agents compare the incumbent technology with the alternative technology (i.e. the niche option) and decide whether to keep using the regime option or switch to the niche option.

The initial imposed condition is that all firms produce a generic good, using the regime option under the conditions of perfect competition, in which every firm has extra profits equal to zero:

$$\prod\nolimits_{i,t} = R_{i,t} - C_{i,t} = 0 \tag{1}$$

where $R_{i,t}$ and $C_{i,t}$ are respectively firm i revenues and costs associated with production at time t.[5] Time is discrete and the generic time-step is denoted by $t = 0, 1, 2, \ldots$ Profits might rise as firms switch to the niche option (we shall discuss how profits change for switching firms later in this section). Let us define the profits of firms producing with the niche technology as follows:

$$\Pi^n_{i,t} = \begin{cases} R^n - C^n_{i,t} & \text{with probability } p \\ 0.5R^n - C^n_{i,t} & \text{with probability } 1 - p \end{cases} \tag{2}$$

where $R^n_{i,t}$ is the niche technology revenue (note that we keep it invariant across firms and over time), $C^n_{i,t}$ is the niche technology cost for firm i at time t, and p is the probability (set, at the initialisation phase, equal to 0.5) that firm i will obtain at time t the highest profit. This probability captures the risk associated with production under the niche option, which stems from the lack of knowledge on the new technology.

Firms are located in a social space (i.e. not a geographic space) represented as a 3-dimentional, finite, regular wrapped grid of cells forming a torus. Not all the cells of the grid are occupied by agents and those occupied may contain more than one agent. The spatially explicit feature of the model serves to structure the spatial proximity on which the agents' interaction is based (i.e. each agent can interact with other agents within a certain radius). Specifically, we shall assume that two firms can interact any time their social proximity is at a maximum (i.e. their social distance is equal to zero when they are on the same cell). The social proximity of any pair of agents changes over time as firms are initially assigned a random position in the social space and move randomly within the social space (moving only among adjacent cells).[6] Any time two firms interact, they will establish a tie (i.e. a durable link) if they share similar high expectations towards the niche technology. The stability of ties and their intensity depends on some characteristics of the vertices (i.e. firms), which will be described in detail in Section 3.2.1.

The reiteration of interactions and the stabilisation of such ties will connect a growing number of actors over time. Hence, a network of relations among supporters will emerge. Such a network, which is the emerging innovation niche, can be seen as the space within which firms can start experimentation directed to improve and develop the new technology 'by doing' as well as 'by sharing' their knowledge.

3.2.1. Expectations mechanism

Those firms who switch to the niche option are labelled 'switchers'. For this to happen firms must find it convenient to produce with the niche technology; this occurs any time their expected profit is greater than zero (and therefore higher than the profit obtained producing with the incumbent technology). The expected profit is calculated as follows:

$$E(\Pi^n_{i,t}) = E(R^n) - E(C^n_{i,t}) \tag{3}$$

where $E(R^n_{i,t})$ and $E(C^n_{i,t})$ are respectively the expected niche revenue and cost of firm i at time t, which depends upon firms' expectations. More precisely each firm is characterised by a level of expectation $ex_{i,t}$ that is the preference of firm i at time t towards the new technology. The value of expectation will vary from 0 (if the agent does not have preferences for the new technology) to 1 (if the agent has a complete preference for the new technology). At initialisation phase we distinguish between two kinds of firms: niche supporters and regime actors. Niche supporters are those firms who have initially higher expectations; these are producers who are 'naturally enthusiastic' about the new technology, and support the niche formation process. Regime actors are, on the contrary, those firms who have lower expectations of the new technology as they are more firmly committed to the regime option (see Table 1 below).

Landscape developments can affect regime agents' expectations. This occurs in two different ways: *gradually* (*say by a constant factor* π), suggesting the existence of a common trend leading expectations away from the regime option and channelling them towards the new technology; and *randomly* (*say by a constant factor* ν), in the occurrence of unpredicted events able to significantly affect expectations (on this point see Section 3.4) according to the following rule:

$$ex_{i,t+1} = \begin{cases} ex_{i,t} + \pi \text{ if unpredicted events do not occur} \\ (ex_{i,t} + \pi)\nu \text{ if unpredicted events occur} \end{cases} \tag{4}$$

Once a regime actor reaches a high level of expectation (i.e. equal to the expectation initially assigned to niche supporters and set

[4] Note that this distinction between strong and weak uncertainty relates to the famous distinction made by Frank Knight (1921) between economic risk and uncertainty.

[5] Note that under the assumption of perfect competition, we set $R_{i,t}$ and $C_{i,t}$ constant over time and identical for each producer.

[6] The random movement of the firms serves to include in the model the chances each agent has to meet others. The interaction among agents in the niche is supported by a social network that represents a close social space where members have high possibility to interact with each other. We think the best way to capture this aspect is to allow firms to move (and meet each other) randomly. Although firms do not physically move, we assume that their managers move around, meeting other managers.

Table 1
Experimental parameters' summary table.

Parameter	Value	Description	Source
Niche expectation	0.75	Initial level of expectations assigned to niche firms	*Case study based*: Within the SUSTOIL project 17 agro-food firms (that potentially can form a technological niche) have been interviewed concerning their level of expectation towards the new technology using a five degrees Likert scale (degrees: very low, low, medium, high, very high). Nearly 90% of these firms (15 out of 17) reported a "high" level of expectation. Standardising this scale in the range 0–1, we associated a value of 0.75 to niche actors i.e. supporters. The expectation of regime actors was fixed at a lower value of 0.25; this is the authors' assumption and not based on data.
Regime expectation	0.25	Initial level of expectations assigned to regime firms	
η	0.02	Rate at which expectation increases as firms interact with spreaders	*Authors' assumption*: This parameter has been arbitrary fixed at a low level in order to account for the repetitiveness of interaction between firms and spreaders. Specifically, 0.02 is a rate of increment appropriate to show a transition from low (0.25) to high (0.75) expectation assuming that firms interact with institutions on a regular basis.
π	0.001	Trend rate at which expectation increases	*Authors' assumption*: Arbitrary chosen at very low level
ν	2	Factor at which expectation increases when external events occur	*Authors' assumption*: This value represents a 100 fold η
$I^{power}_{i,t=0}$	Rand. [0–0.3]	Initial power endowment assigned to each firm	*Authors' assumption*: These parameters have been arbitrary fixed at low levels. The reason is that they represent the endowment of strategic resources or the effects produced by these resources on the niche take off. Given that these resources are mainly created by social mechanisms, we stress the fact that at the earlier stage they are likely to be extremely limited and increase dynamically as the niche stabilises over time. The value assigned to θ is slightly higher if compared to n, c and ε. This decision was taken based on the fact that in SUSTOIL case study the most part of the firms interviewed reported on the crucial role of tacit knowledge accumulated by skilled workers through learning by doing
n	0.01	Rate at which production cost is reduced as network power increases	
c	0.01	Rate at which production cost is reduced as individual power increases	
$K_{i,t=0}$	Rand. [0–0.01]	Initial knowledge endowment assigned to each firm	
θ	0.025	Rate at which knowledge increases as firms learn by doing	
ε	0.01	Rate at which the risk associated with niche production decreases as the knowledge in the system increases	
Subsidy	Various	Amount of subsidies provided to firms operating within the niche	Various in order to depict the effect of various policy options
Spreaders	Various	Number of spreaders present in the system	
R_n	1.5	Actual revenue under the niche technology option	*Authors' assumption*: Provided that the probability capturing the risk associated with production under the niche option is initially set at 0.5 and that the profit is equal to R^n–C^n (see Eq. (2)), we consider that the niche revenue has an initial lower bound equal to 1 and a initial upper bound equal to 2. In fact, if $R^n = 1$ then the niche technology performs at the best – i.e. in the best scenario – equally to the regime technology; on the other hand if $R^n > 2$, then the niche technology performs always–i.e. independently of the risk associated with the niche technology captured by p – better than the regime technology. Departing from these considerations, we decided to set R^n at the medium level of this range, that is 1.5.
$C^n_{i,t=0}$	1	Initial actual cost under the niche technology option	

at 0.5), it becomes a supporter of the niche option and can start networking with other niche supporters (to this we shall come back in Section 3.2.2).[7]

Expectations of active firms can also increase or decrease over time. Specifically, the level of expectation will increase any time the actual profit obtained producing with the new technology exceeds the expected profit and vice versa (on this point see Section 3.4). Moreover, the higher is the expectation, the more likely it is that the firm will switch to the new technology. In fact, the level of expectation influences positively the expected cost (reducing it) and the expected revenue (increasing it) of the new technology, as shown in Eqs. (5) and (6):

$$E(C^n_{i,t}) = \frac{1}{ex_{i,t}} C^n_{i,t} \tag{5}$$

$$E(R^n_{i,t}) = ex_{i,t} R^n \tag{6}$$

where $C^n_{i,t}$ and $R^n_{i,t}$ are the same as above.[8] As we shall see, for a supporter such expectation varies between 0.75 and 1 and, therefore, unless expectations are at the maximum, firms tend to underestimate the potential revenue attached to the niche technology.

[7] Although the model is designed to capture niche emergence dynamics, and not entire socio-technical transitions, we believe that introducing the distinction between niche and regime actors, as well as landscape developments through trends and events, adds to the model a 'multilevel flavour' that is quite welcomed in this theoretical setting. In fact, as it was broadly acknowledged in the literature, "niches are to be perceived as crucial for bringing about regime shifts, but they cannot do this on their own. Linkages with ongoing external processes are also important" (Schot and Geels, 2008: 537). For guiding us in this direction, we are grateful to an anonymous referee.

[8] The initial values of $C^n_{i,t}$ and $R^n_{i,t}$ are set equal to 1 and 1.5, respectively. Recall also that the actual niche cost varies across firms and over time. In fact, as we will see later on in this section, we allow costs to decrease whenever firms accumulate extra profits. This is not the case for costs associated with production under regime technology, which are invariant across firms and over time since no extra profits are allowed.

3.2.2. Networking

As mentioned above, whenever two supporters (i, j) interact (i.e. their social proximity is at a maximum) they establish a tie. This gives them the opportunity to share knowledge and resources. Each firm has an attribute called individual power ($I_{i,t}^{power}$). At initialisation phase it is set at a specific value (see Table 1) describing the firms' endowment of strategic resources.[9] Any time an active firm (i.e. one producing under the niche option) obtains an extra profit, it increases its individual power as this extra profit is added to its pool of resources; likewise, individual power will decrease if the profit turns to be negative ($I_{i,t+1}^{power} = I_{i,t}^{power} + \Pi_{i,t}$).[10]

Each time two supporters establish a tie, the total amount of their respective resources flows through this tie. Thus, each tie has a feature called energy (En), which is the sum of the resources of the agents on either end of the tie:

$$\forall \ i, j \in N, \quad \exists En_{i,j} \geq 0 : En_{i,j} = \begin{cases} I_{i,t}^{power} + I_{j,t}^{power} \text{ if } i \text{ and } j \text{ are linked} \\ 0 \text{ if } i \text{ and } j \text{ are not linked} \end{cases} \tag{7}$$

The total sum of links' energy represents, in turn, the overall network power (N_t^{power}). Hence, we can write:

$$N_t^{power} = \sum_{i,j} En_{i,j} \text{ with } i \neq j \tag{8}$$

3.2.3. Learning

Each firm is initially assigned a specific level of knowledge $K_{i,t}$ with respect to the new technology (see Table 1). Each time the firm produces using the new technology, and/or interacts with other firms, its knowledge increases (see Section 3.4).

Moreover, each time two supporters establish a tie, the total amount of their respective knowledge flows through this tie. In fact, each tie has a feature called knowledge flow (Kf), which is the sum of the knowledge of the agents on either end of the tie:

$$\forall \ i, j \in N, \exists Kf_{i,j} \geq 0 : \ Kf_{i,j} = \begin{cases} K_{i,t} + K_{j,t} \text{ if } i \text{ and } j \text{ are linked} \\ 0 \text{ if } i \text{ and } j \text{ are not linked} \end{cases} \tag{9}$$

The total sum of links' knowledge flow gives the overall network knowledge NKn_t according to the following:

$$NKn_t = \sum_{i,j} Kf_{i,j} \text{ with } i \neq j \tag{10}$$

3.3. Policy tools for the formation of a protected space

The model described above can be used to investigate complex niche mechanisms in order to draw insight on the speed and timing of emergence of technological transitions. However, as discussed in Section 2, harsh competition (coming mainly from the established regime technology) can prevent the emergence of a stable niche. Under these circumstances, and provided that socio-political conditions for interventions are met,[11] well-crafted policy actions are needed to create a protected space within which a new technology can develop. Along the line of our earlier discussion, we will consider two policy tools that can be used to promote niche emergence.

The first policy tool is represented by the introduction of a particular set of agents called 'spreaders' $S = \{1, 2, 3, \ldots, M\}$, with $M < N \ll \infty$. Spreaders are institutional change agents whose only purpose in the model is to promote the new technology, enhancing firms' expectations towards it. As put by Rogers "a change agent is an individual who influences clients' innovation-decisions in a direction deemed desirable by a change agency" (2003: 366). In other words, their role is to stimulate the adoption of the new technology enhancing firms' expectations towards it. Their number (M) is an exogenous parameter, which could be varied in order to fine-tune the policy effort. Spreaders are initially located randomly in the torus representing the social space. Spreaders interact only with firms who are not already supporters (as they have no interest in interacting with firms which are already supporting the new technology), moving directly to the nearest one to influence its expectations. The way spreaders choose firms is arbitrary and depends on the random movements of the firms. Specifically, every time a firm interacts with a spreader, its expectation increases by a constant small amount set equal to η (whose value is set exogenously at initialisation – see Table 1 below).

The second policy tool consists of the allowance of a subsidy to those firms switching to the niche technology. Subsidies modify the equations of actual and expected profit (Eqs. (2) and (3)) as follows:

$$\Pi_{i,t}^n = \begin{cases} R^n - C_{i,t}^n + \text{sub with probability } p \\ 0.5R^n - C_{i,t}^n + \text{sub with probability } 1-p \end{cases} \tag{2 bis}$$

$$E(\Pi_{i,t}^n) = E(R^n) - E(C_{i,t}^n) + sub \tag{3 bis}$$

where *sub* is an exogenous parameter which refers to the presence of a subsidy (it will be greater than zero if the policy maker decides to encourage the adoption of the niche technology, and equal to zero otherwise).

It is worth noting that a third policy action could be implemented within the framework of the proposed agent-based model. In fact, it could be possible that instead of supporting novel niches, policy actors might choose to directly influence regimes by introducing legislation or environmental taxes. Such policy intervention might be modelled by taking away some of the resources from regime actors, hence weakening their relative position. In turn, this would have some significant effect both on the niche formation process as well as on the succession process (i.e. regime shift). Although very relevant, we shall leave aside this third policy option, referring to it as a future extension of the model.

3.4. The interaction of the three mechanisms

According to the theoretical framework, the model accounts also for the interactions between the three mechanisms (L1–L5 in Fig. 1). We can say that such interaction leads to an equilibrium when the niche reaches a stable configuration (i.e. its structure does not vary sizably over time) and a certain number of firms have switched permanently to the niche option. The interaction between the niche's mechanisms is reviewed in what follows.

L1: the convergence to high expectations influences the networking activity. In fact, as expectations towards the niche

[9] Intuitively, a strategic resource is a resource that can be used in order to develop and promote a new technology. For instance, an R&D laboratory is a resource that could serve the purpose of developing a new technology. A wide-ranging proxy of such resources could be firms' turnover as, in general, larger firms would also be the most powerful.

[10] Note that the individual power is subject to an upper bound set equal to100.

[11] Smith and Raven identified narratives as a key political strategy to argue for empowering institutional reforms. The authors "proposed that narratives for empowerment [of policies of protective spaces] will show a number of characteristics: (a) positive expectations about the future that justify the niche to wider audiences; (b) explicit claims for present-day niche friendly institutional reforms; and (c) statements that re-frame the past to criticise the prevailing regime in ways that emphasise future opportunities for the innovation" (2012: 1034).

technology rise, also the stability of ties among firms increases. In the model this is expressed by the fact that the tie established between two firms is unstable in the sense that every time one of the two vertexes (i.e. one firm) is no longer a supporter (i.e. its expectation drops below 0.75) it disappears. Thus, the emerging network is dynamic in nature and its very existence relies upon firms' expectations.

L2: network characteristics and composition are crucial in defining the particular set-up of experiments. This is due to the fact that no single actor has sufficient resources on its own to coordinate the experimentation activity and this makes them dependent upon each other for crucial resources (Smith et al., 2005). As the network grows, such resources become available for R&D activities. In the model this is represented by the fact that both individual and network power have an impact on the cost structure faced by switchers engaged in experimental activities. On the one hand, we assume that increasing individual power will allow switchers to make cost reductions (e.g. by investing extra profits in R&D, firms could introduce process innovations). On the other hand, as the network power increases, switchers will have access to a growing amount of external resources. In other words, we maintain that resources accumulated by other firms can be exploited by means of spillovers within the emerging social network. Hence we have:

$$C^n_{i,t+1} = C^n_{i,t} - cI^{power}_{i,t} - nN^{power}_t \quad \text{with } c \in [0,1];\ n \in [0,1] \text{ and } c \gg n \tag{11}$$

where $cI^{power}_{i,t}$ and nN^{power}_t represent respectively the cost reduction derived from the accumulation of individual and network power.

L3: the experimentations conducted by innovators affect the learning mechanism. This captures the learning-by-doing activity and is modelled letting the firm's attributed knowledge increase (decrease) in a linear fashion (according to an exogenous positive parameter θ whose value is set at initialisation – see Table 1) any time a firm produces using the niche technology (the regime technology) according to the following rule: $K_{i,t+1} = K_{i,t} + \theta K_{i,t}$.

L4: network characteristics and composition influence the learning mechanisms since, as explained in Section 3.2.3, the knowledge of firms involved in the network is shared and accumulated.

It is quite important to observe that as the overall level of firms' knowledge on the niche technology increases, the probability p of obtaining the high profit $\Pi^n_{i,t} = R^n - C^n_{i,t}$ increases. This is because, overall, as agents become more knowledgeable on the niche technology, the risk associated with the production involving such new technology decreases. This is a system feature that affects also firms currently not involved in the niche option; in fact, if they do switch to the niche option they will get $R^n_{i,t}$ with a higher probability. We assume that the probability p increases in a linear fashion[12]: $p_{t+1} = p_t + \varepsilon NK_t$; where ε is an exogenous parameter.

L5: the outcomes of learning activities re-shape expectations. As profit opportunities increase, firms' expectations rise. Specifically, firms' expectations will increase if $\Pi^n_{i,t} \geq E(\Pi^n_{i,t})$; if the contrary is true (i.e. the actual profit is smaller than the expected profit), then the expectation of the niche technology will decrease.[13] In order to take into account the effect of L5 on firms' expectation, equation 4 is changed accordingly:

$$ex_{i,t+1} = \begin{cases} ex_{i,t} + \pi + \Pi^n_{i,t} \text{ if unpredicted events do not occur} \\ (ex_{i,t} + \pi + \Pi^n_{i,t})\nu \text{ if unpredicted events occur} \end{cases} \tag{4 bis}$$

4. Simulation experiment: experimental set-up and results

4.1. Experimental set-up and methods

We used the NetLogo 4.1 platform (Wilensky, 1999) for implementing the model and R language and environment for statistical computing and graphics (http://www.r-project.org/). Because simulations are usually not deterministic – they contain several random elements – we carried out repeated simulation experiments (batch of 100 runs) in order to identify different trajectories of model behaviour. Within the batch we then took averages for all the relevant indices. The batch has the same set of initial conditions: what varied within the batch was the random seed, which had implications for the agent orderings for sequential actions (e.g. initial locations, movement within the social space), random choices such as uncertainty, etc. A high stability of results is guaranteed by repeated simulation experiments (e.g. batches of a hundred runs each), to dispose of artefacts introduced by the random aspect of model initialisation.[14]

The parameterisation used is summarised in Table 1. In order to assure robust simulation results, empirical data have been used to limit the parameters' space as well as to define the initial conditions. Specifically, we consider a population of $N = 100$ firms located on a grid sized 32×32. Parameters capturing firms characteristics have been calibrated based on data gathered by a survey carried out on 17 agro-food firms interviewed while conducting a case study, as part of the SUSTOIL project,[15] on the potential development of a biorefinery industry in the province of Foggia over the period May–July 2009.

The model includes spreader agents: their role is to inform those firms that have not yet adopted the niche technology. This inclusion was inspired by the activity conducted by the Agro-Food Technological District (DARe) promoted by the Apulia Region. DARe is a private company grouping together the most important stakeholders in the Agro-food field at regional level (it is composed by Universities, businesses, banks, trade associations, local authorities, public and private research centres). Its task is to bridge the gap between research centres and private companies acting, essentially, as a broker of innovation. Since 2008, DARe launched a programme called 'Innovation Angels' whose main objective is to get in contact with less innovative local entrepreneurs to stimulate technological changes. In this sense, the Innovation Angels are effectively spreading information, trying to enhance firms' knowledge and expectations towards a set of innovations deemed valuable by the Agro-Food Technological District. Such 'Innovation Angels' operate in the following way: they preliminary identify a list of firms potentially interested in the proposed technical innovation and, subsequently, contact them based on contingency. This *modus operandi* inspired us in modelling spreaders' movement within the social space as random as specified in Section 3.3 above.

[12] Note that we keep a minimum level of uncertainty in the system – i.e. the value of p has an upper bound at 0.9.

[13] Note that in this model we are, therefore, assuming that firms producing under the new technology do not possess perfect information (i.e. their expectations are bounded) and adapt their expectations on past experience.

[14] We computed also standard deviation for relevant indices within each batch, finding low values for all the nine simulations (i.e. the baseline model and the eight alternative policy measures) which confirm the model robustness against changes to random number sequences. A summary table is available from the authors upon request.

[15] SUSTOIL is a support action project funded by the European Commission through the Seventh Framework Programme (Energy Theme). The project started in June 2008 and finished in May 2010.

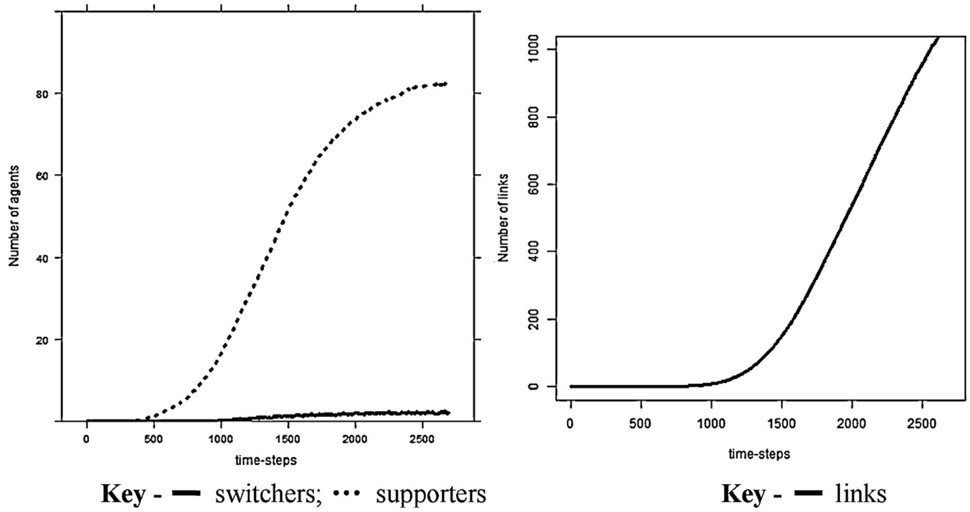

Fig. 2. Innovation niche emerging dynamic: agents and links (zero subsidies and one spreader).

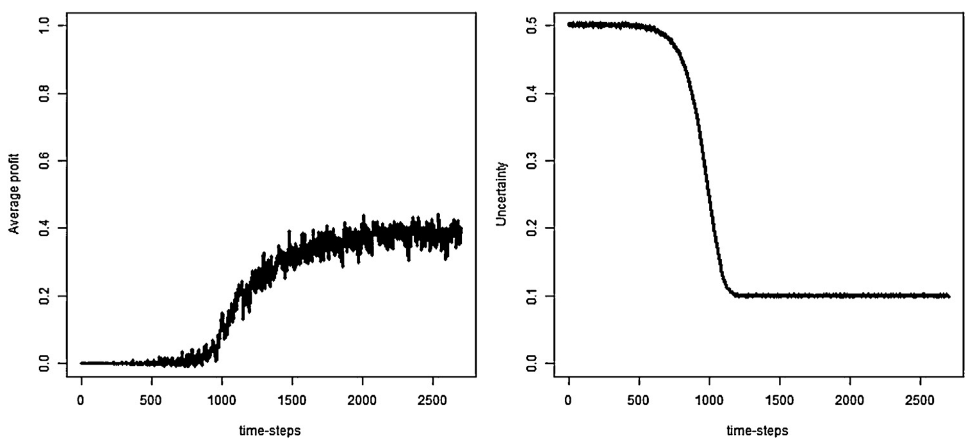

Fig. 3. Uncertainty and profit for niche technology: average profit and uncertainty (zero subsidies and one spreader).

The timeframe we investigate is 2600 time-steps, corresponding roughly to a 50-year time span. Each time-step corresponds to a week (on this see Lopolito et al., 2011b). As suggested by most of the agro-food producers interviewed as part of the SUSTOIL project, generally speaking a week seems a good time proxy for a step: in the real world, a week is, in fact, a reasonable time for an entrepreneur to evaluate whether it would be convenient to switch technology or not.

We will present the results in the following order: (1) first, we present results obtained by what we call the reference model, that is the model ran with zero subsidies and only one spreader (i.e. the minimum amount of policy intervention, since with zero spreaders there would be no activity at all in the model), both excluding and including external events; (2) second, we present results obtained introducing the two policy tools described in Section 3.3. For the sake of clarity of exposition, in this second case we shall not consider external events.

4.2. The reference model – results

As it clearly emerges, the system is characterised by a growing number of supporters which, in the end of the simulation, exceeds 80 percent of the population (see dotted line in left panel of Fig. 2). Moreover, it is worth noting that the supporters network configuration (Fig. 1 – right panel) is rather dense, with more than a thousand links established at the end of the simulation. The presence of a sizeable and dense network of supporters is matched by a substantial reduction in the uncertainty surrounding the niche option – ascribable to the knowledge mechanism which is driven by learning-by-interaction occurring among supporters (see the significant drop in the probability of obtaining a low profit in Fig. 3 – right panel, around the time the supporters' network takes momentum) and a sharp increase in the average profit ascribable to the reduced uncertainty (Fig. 3 – left panel).

Surprisingly these promising dynamics contrast with a very small number of firms actually switching technology: in fact, the niche is almost inexistent for the first 1000 time-steps and reaches a size of three at the most (see continued line in left panel of Fig. 2).[16]

Similar outcomes emerge in the case of external events stimulating agents' expectations. We found that immediately after the occurrence of the event the majority of agents switch to the niche option reverting, however, to the regime technology right after, producing a single period spike in the number of niche agents. This outcome suggests that, actually, external events could lead to the formation of a niche. However, the emerging niche does not seem

[16] Note that the presence of a niche is detected any time a minimum of two agents switch technology. Firms producing with the new technology are not necessarily connected; yet, they belong to the supporters network.

Table 2
Levels of support – expectation of supporters.

	Time step 500	Time step 1000	Time step 1500	Time step 2000	Time step 2500	Time step 2600
Average exp.	0.750	0.779	0.780	0.781	0.782	0.781
Minimum exp.	0.750	0.767	0.769	0.771	0.773	0.772
Maximum exp.	0.810	0.819	0.794	0.794	0.792	0.793

to be self-sustainable; this result points at the importance of implementing some kind of policy support right after the occurrence of the external event.

These preliminary outcomes call for a careful investigation of the modelled mechanisms governing the emergence (or non-emergence) of a technological niche. In fact, it seems difficult to explain why a large number of firms supporting the new technology emerged, but almost no agent actually switched technology. Intuitively, this might suggest that although there is a general positive feeling about the niche option, this is not sufficient to induce firms to abandon the regime option and switch technology. In other words, supporters seem to be not fully convinced of the benefits associated with the niche option and, consequently, their support to it is only mild.

As we specified in the model, a firm will switch technology if its expected profits (under niche technology) exceed normal profits (i.e. profits obtained producing under regime technology). This crucially depends on the level of expectations of firms from the niche technology (see Eqs. (5) and (6) above). As it seems, an agent with an expectation level just above the threshold of 0.75, in spite of being a supporter, is unlikely to switch technology. Now, the presence in the system of a very large number of such mild supporters might, in turn, generate what we shall label a *mild-support trap* – i.e. a situation in which there is a large number of supporters unable to actually experience the new technology, that is to switch to the niche option. The trap is represented by the fact that without switchers the relations L3 and L5 in Fig. 1 are enabled, avoiding the convergence of expectations towards higher levels.[17] Our hypothesis is that a level of expectation that allows a wide support for the new option exists, but that at the same time it avoids the formation of the niche; this level of expectation is just above the threshold of 0.75.

In order to verify this hypothesis we calculate the average expectation level of supporters reached during the simulation. Specifically, we calculate the lowest and the highest (within the batch) levels of expectation as well as the mean value at various time-steps. These values are summarised in Table 2.

As it clearly emerges, the level of expectation among supporters is pretty low in all considered cases (with two exceptions, it never exceeds 0.80 and average expectation values reach 0.781 at the maximum), confirming our hypothesis that the support provided to the new technology is only marginal. Hence, the occurrence of a *mild-support trap* seems to be confirmed.

On the other hand, a sufficiently large number of *early switchers* might revert this equilibrium giving momentum to the system and promoting the emergence of a sufficiently large niche. Most importantly, this group of switchers will lower the niche production costs employing their resources for experimentation (recall that in the model we assumed that switchers make cost reductions employing both individual and network power, which increase as profits increase). This, in turn, will induce more producers to switch technology and contribute to the emergence of a sufficiently developed technological niche. Such result could be triggered by a policy intervention as described in Section 3.3; we turn to the assessment of such policies in the following section.

4.3. Comparing policy tools

We will now investigate the impact of the two alternative policy tools on the emergence of a stable innovation niche. Namely we will consider: (1) the impact of subsidies and (2) the impact of an information campaign conducted increasing the number of spreaders (change agents). First, we look at the impact of introducing a subsidy. As we raise the subsidy to 3, 5, 7 and 9 percent of the initial revenue ($R^{i,t}$),[18] we can observe that the innovation niche becomes increasingly larger (Fig. 4 – solid line in the four top panels). However, for the niche to gain momentum it takes around 1000 time-steps, it reaches the inflection point (i.e. maximum speed of adoption) at around 1250 time-steps and flattens out after 1500 time-steps. Noteworthily, a sufficiently large niche emerges only if subsidies are equal to or larger than 5 percent – the size of the niche varying from 10 to 18 firms as subsidies rise from 5 to 9 percent.

The most striking result comes from the network of supporters. As we look at the dotted lines in the four top panels in Fig. 4, we can immediately observe how the number of supporters drops as subsidies rise from 3 to 5 percent. Similarly, also the number of links drops significantly as subsidies increase. Also in this case we are facing an apparently counterintuitive result: as the innovation niche takes-off, the supporters' network collapses (both in terms of size and density).

However, the explanation of this dynamic rests on the mechanisms activated by the emergence of an innovation niche. As subsidies increase, a growing number of firms are encouraged to experiment (switch to) the niche technology. Due to the initial high level of uncertainty, this results in some firms experiencing positive profits (and, consequently, increasing their expectations), and some other firms experiencing negative profits (and, therefore, reducing their expectations); a fact which is consistent with the high level of instability of average profits. In its turn, this turbulent situation results in a reduction of the number of supporters and, correspondingly, in an increase of the strength of the support. This is confirmed by average level of expectations, which rises sharply as subsidies increase from 3 to 5 percent (see Table 3).

Basically, increasing the level of subsidies to 5 percent and above allows the niche to take-off and simultaneously reduces the size and density of the supporters network. Although supporters are now, on average, more committed to the new technology, experimentation leads to weakening of links and, through this, to a contraction in the channels of communications and knowledge exchange. This fact explains also the slow pace at which firms switch technology (as mentioned, it takes 1000 time-steps for the process to initiate).

We shall now turn our attention to the second policy tool – i.e. the introduction of change agents (labelled spreaders in the model)

[17] In fact, as we stated at the end of Section 3.4, firms' expectations increase if actual profit is greater than (or equal to) than the expected profit and decrease otherwise. However, if firms do not switch technology, they will never get the opportunity to experience positive profits and therefore increase their expectations. Hence, they will permanently stick to their role of mild supporters, never being sufficiently committed to the new technology to adopt it themselves.

[18] By initial revenue we refer to the revenue obtained by those firms operating under the regime option.

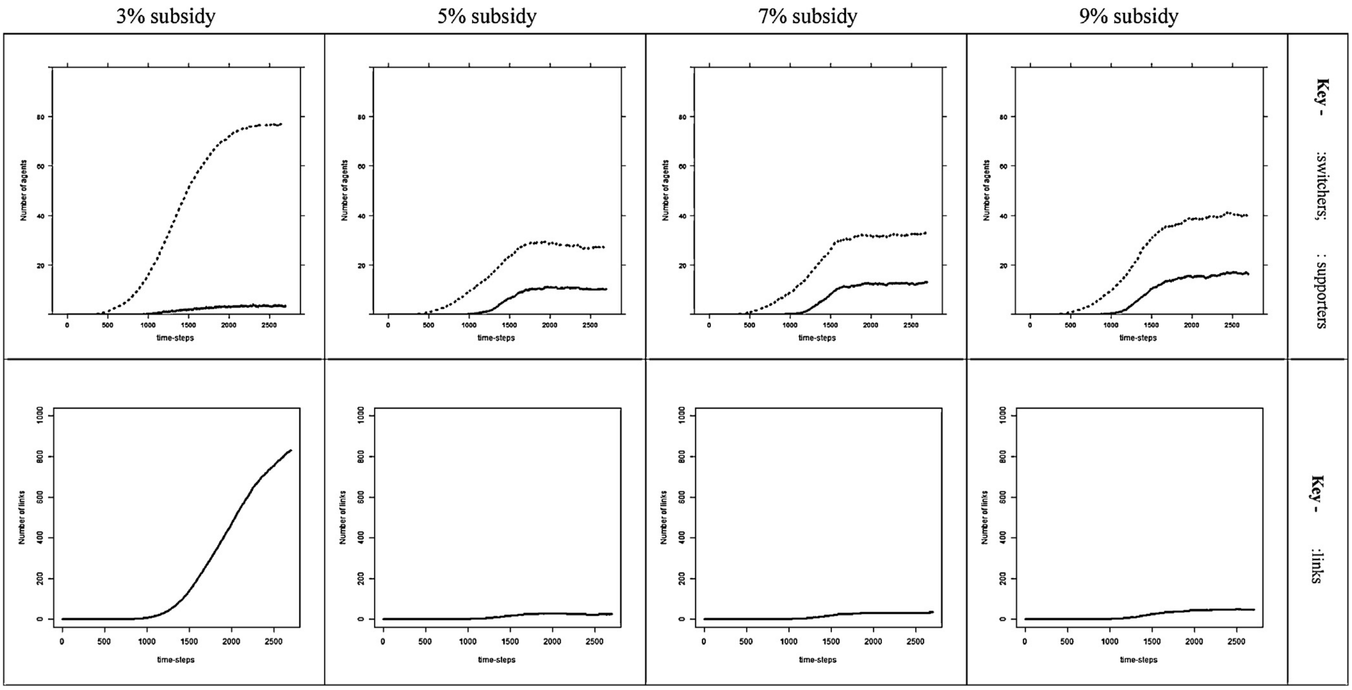

Fig. 4. Innovation niche emerging dynamic: agents and links (one spreaders and various levels of subsidies).

Table 3
Levels of support in the presence of subsidies – expectation of supporters.

	Time step 2600			
	3% subsidy	5% subsidy	7% subsidy	9% subsidy
Average level of exp.	0.797	0.835	0.856	0.860

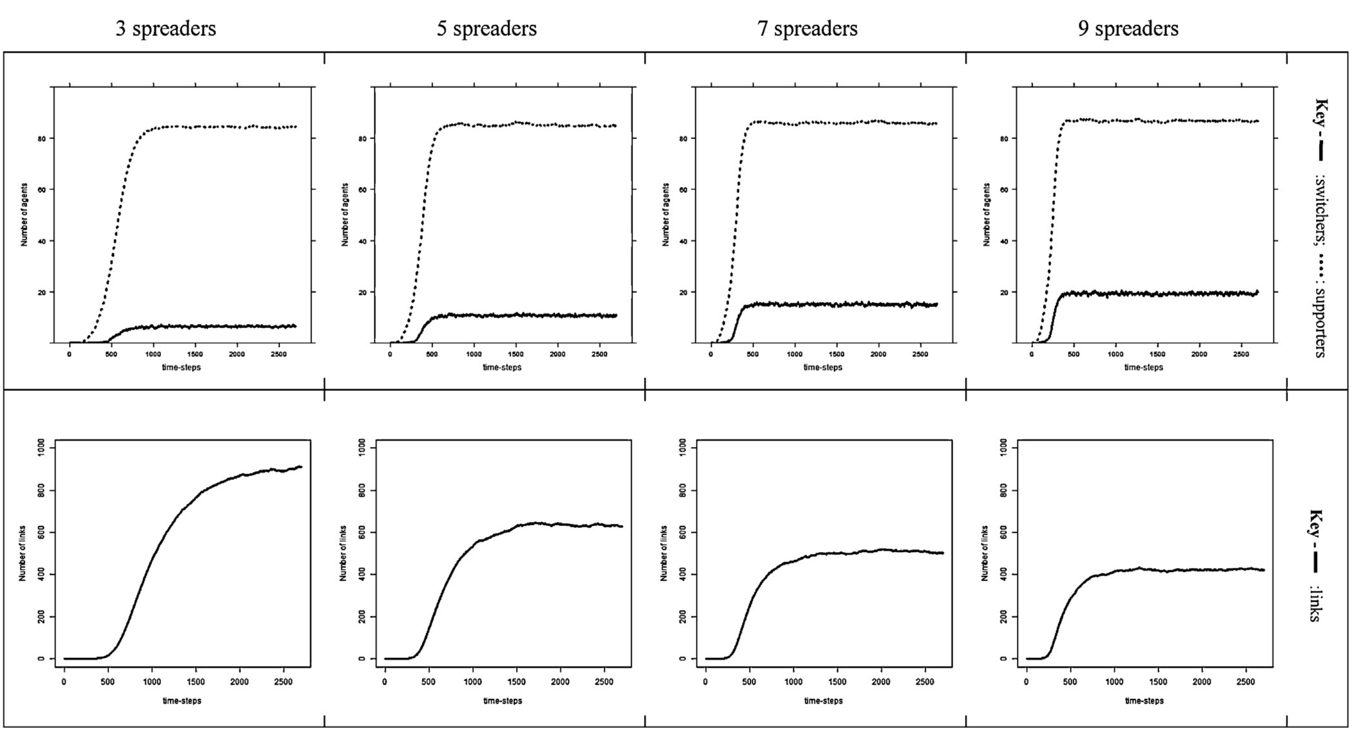

Fig. 5. Innovation niche emerging dynamic: agents and links (zero subsidies and various levels of spreaders).

Table 4
Levels of support in the presence of spreaders – expectation of supporters.

	Time step 2600			
	3 spreaders	5 spreaders	7 spreaders	9 spreaders
Average level of exp.	0.794	0.804	0.815	0.824

Table 5
Overall niche stability index.

	Subsidies			
	3% subsidy	5% subsidy	7% subsidy	9% subsidy
Overall niche stability index	81.59%	91.05%	91.38%	92.16%
	Spreaders			
	3 spreaders	5 spreaders	7 spreaders	9 spreaders
Overall niche stability index	85.36%	86.22%	86.96%	87.26%

whose activity is to persuade firms to switch technology (this could correspond, in the real world, to an information campaign aiming at creating a favourable environment to the niche technology). We perform several experiments increasing the number of spreaders from 3 to 9 and report findings in Fig. 5.

Results show that the system under this intervention performs well overall. An innovation niche (although rather small in the simulation with 3 spreaders) emerges in all four cases considered and the system reaches a stable equilibrium rather quickly. As the number of spreaders increases, it increases the size of the innovation niche, the speed at which the niche emerges, and the size of the supporters' network (see continuous and dotted line in four top panels in Fig. 5). However, the density of supporters' network decreases as the number of spreaders operating in the system increases (see four bottom panels in Fig. 5).

This can be explained by looking at the number of switchers, which grows (also as a proportion of supporters) steadily as we increase the number of spreaders. As the number of switchers increases, some may experience negative profits, an event that leads to the removal of links as we already discussed. Note that in this case we do not observe the sharp reduction in supporters and links observed in the case of subsidies because of the presence of a conspicuous number of spreaders whose activity is to persuade firms to become supporters. Hence, we should expect to observe, on average, a weaker level of support if we compare this policy tool with subsidy. This fact is confirmed by summary data reported in Table 4.

Another consequence of such dynamic would be a less stable innovation niche – i.e. a niche characterised by a smaller number of firms that have stably switched technology. In order to control for this occurrence, we calculated an overall niche stability indicator[19] (see Table 5) the values of which vary between 0 and 100 percent. The closer it gets to 100 percent the higher is the stability of the innovation niche; a value of 100 percent implies that all firms in the niche have permanently switched to the niche technology.

When comparing spreaders with subsidies, the latter performs better in terms of niche stability. This is a predictable result, since the stability of the niche depends on the level of expectations of supporters, and subsidies generate, on average, higher expectations (compare Tables 3 and 4 above). However, the most interesting result is that in all considered cases the emerging niche is rather stable with always more than 80 percent of switchers that are, on average, stable switchers. As we believe, this is an important feature of the system as niche stability is a key element for a new technology to take-off.

Finally, we observed a quick reduction in uncertainty matched by a sharp increase in the average profit. Note, however, that average profits are generally lower than those obtained by switchers in the case of subsidies, exactly because of the absence of these extra sources of revenue.

All in all we can conclude that spreaders are more efficient than subsidies: overall, the size of the niche is consistently larger and its emergence is significantly faster. Moreover, a policy action based on spreaders is able to keep high the number of supporters in the system, a fact which allows the development of a dense network through which knowledge is effectively exchanged, resources are rapidly shared and, eventually, costs of production are reduced.

5. Conclusions

In this study we developed an agent-based model aimed at investigating the fundamental social processes involved in the rise of a stable innovation niche and the role that policy intervention can have in governing such processes. Generally speaking, we found that agent-based modelling is a useful analytical tool for a long-term policy analysis, especially when investigating systems characterised by rather complex behaviours (e.g. novelty, indeterminacy, adaptive behaviour).

The model developed in this paper helped us to operationalise some fundamental concepts from SNM. We moved from the assumption that an innovation niche is successful when the number of firms switching to niche technology grows sufficiently large, allowing the local system to reach a critical mass that eventually can represent a threat to the stability of the dominant socio-technical regime.[20] As we discussed, three interrelated mechanisms affecting niche's development are the basis for its success; these are: (1) convergence to high expectations, (2) networking and (3) learning.

[19] The index was calculated in the following way: for each time-step of each simulation we calculate the number of switchers that have switched also in the previous time-step. This value was then divided by the total number of switchers and returned the share of stable switchers. Subsequently, we calculate the average value over each simulation and the average value over the batch – this was the overall niche stability index.

[20] Note that in the earliest phases of adoption, the critical mass notion works against adoption, since it takes a number of other switchers to be seen as advantageous to adopt. This is particularly true in the presence of network externalities – which in our model occur through the network power mechanism and through the interactive knowledge diffusion process. Valente (1995) notes that the critical mass is achieved when about 10–20 percent of the population has adopted the innovation. When this level has been reached, the innovation can be spread to the rest of the social system. These figures are in line with our findings.

Integrating these mechanisms into our model, we carried out repeated simulation experiments to investigate the importance of policy interventions aimed at governing the niche creation process in a desirable way. In the absence of any policy intervention, although a very large number of firms (almost 80 percent) showed interest in the niche technology, only a very limited number of them actually switched technology – hence, the innovation niche did not always emerge as an endogenous feature of the model. In our reference model simulations the system got locked into a *mild-support trap* – i.e. a situation in which in spite of a general support for the new technology, this was unable to promote adoption and the actual emergence of a technological niche.

Interestingly, both policy actions modelled (i.e. subsidy and information spreading) showed some valuable consequences leading, ultimately, to the emergence of a stable innovation niche. However, in the case of subsidies we observed a drastic decrease of support in the earliest stage of experimentation – a fact that delayed significantly the emergence of the innovation niche. Conversely, a policy action based on information spreading succeeded in maintaining a high number of supporters in the system and, in turn, facilitated the emergence of a dense network through which knowledge was effectively exchanged, resources were rapidly shared and, eventually, costs of production were reduced.

Occurrence observed through this model allowed us to conclude that a policy action might be required to give momentum to an innovation niche. Moreover, favourable elements for the rapid and stable emergence of such a niche are: (1) the constant promotion of a supportive environment, since experimentation can be a harsh process (at least in the earliest phases) that undermines expectations from the new technology and, consequently, reduces network resources; (2) the promotion of a strong support which should supplement a general endorsement of the new technology and that should be sufficiently strong to overcome adverse conditions that might occur in the earliest experimentation phases.

However, as discussed in Section 3.3, socio-political conditions for interventions have to be met if the policy-maker has to play a proactive role in promoting niche development. Indeed, these conditions can be present at some point in time (hence justifying the policy intervention) but not in subsequent periods. Moreover, policy-makers can be deliberately looking for a temporary (as opposed to permanent) policy interventions, to be removed once a self-sustaining niche has emerged.

In both cases non-linear developments of policy action should be expected. In this regard, the agent-based model presented in this paper could be possibly extended to take into account policy withdrawal, hence adding a further dimension to assess policy effectiveness.

6. Further developments

As it often happens, while designing and analysing a model several interesting ideas arise which nevertheless are scarified for the sake of clarity and simplicity. Some of these ideas, however, deserve further development as they might develop into fertile new lines of research. Moreover, further insight came from three anonymous referees who contributed to the refinement of this model as much as to the development of new ideas for research.

In this final section we shall try to give an account of these ideas, providing some 'food for thought'. We have identified three key lines for further research, which can be summarised as follows:

(1) As broadly discussed throughout the paper, the agent-based model focuses only on the process of emergence of a technological niche. However, a socio-technical transition is a deeper phenomenon the outcome of which depends on the co-evolution of three levels: (a) niche-innovations build up internal momentum, (b) changes at the landscape level create pressure on the regime and (c) destabilisation of the regime creates windows of opportunity for niche innovations (Geels and Schot, 2007). Indeed, transition is enabled from the alignment of these processes that facilitates the breakthrough of novelties in mainstream markets (Geels and Schot, 2007).

As an additional development of this agent-based model we would suggest to further investigate how the process of succession could take place. This should involve the full modelisation of the multi-level framework, looking at interactions between innovation niches and existing technological regimes, situated in a broader environment–i.e. the socio-technical landscape (see: Kemp et al., 1998; Rip and Kemp, 1998; Lopolito et al., 2011a).

(2) This first point leads us to a second issue. As discussed in Section 3, in this model we offer a 'flavour' of the abovementioned multi-level complexity, introducing landscape change patterns, which affected regime agents' expectations both gradually and randomly – in the occurrence of unpredicted external events. In this paper we investigated only a positive external event – i.e. an event that positively affected niche expectations. We found that immediately after the occurrence of the event, most agents switch to the niche option reverting, however, to the regime technology right after. As a further development of the model it could be interesting to assess the possible impact of several external events, inspecting a broad range of variation for such events. Specifically, it could be worth investigating both positive and negative external events, so that events could also strengthen existing regimes instead of only creating windows of opportunity. Additionally, it could be interesting to study the impact of a single (either positive or negative) event occurring at different times of the simulation. This should provide insights to the relevance of the timing of the event which, as we believe, might produce drastic differences in the final outcome.

(3) Finally, in this model we do not consider policy withdrawal – i.e. the introduction of policy measures last for the whole duration of the simulation and accompany the niche until its full development. We propose to investigate the impact of policy withdrawal and specifically we suggest investigating the existence of a critical mass that occurs at the point at which enough firms in the system have switched to the niche technology so that the niche's further rate of growth becomes self-sustaining. This would have a non-trivial policy implication since – depending on the size of the critical mass – a policy action can be economically feasible or not.

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