Innovation niche stability with a short-term policy intervention

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Abstract: This article presents an agent-based (AB) model designed to investigate the emergence of innovation niches. The novel contribution of this paper is to assess whether the introduction of institutional agents of change (referred to as spreaders), whose sole activity is to persuade firms to switch from the dominant technology (i.e. the regime technology) to a new technology, can prompt the emergence of a stable and self-sustained innovation niche.

The following two results were obtained: (1) as the number of spreaders in the system increases, the latency time required for the niche to take off reduces steadily; (2) policy withdrawal can take place and this does not compromise the pathway towards full niche development, although it considerably slows it down. However, policy withdrawal can only be carried out with conditions that a critical mass of users is reached. Interestingly, as the number of spreaders increases, the critical mass threshold increases as well, but the time required for reaching the threshold decreases. This result stresses the importance of social resources in the niche development process as well as the importance of a dense network of supporters.

Keywords: Socio-technical transition, strategic niche management, critical mass.

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1. Introduction

In this paper we present an agent-based model developed to mimic the emergence of a stable and self-sustainable cluster of innovating firms. Such a cluster shall be referred to as an innovation niche – i.e. a small network of firms interacting among each other as well as with institutional bodies (e.g. local government officers, universities, private or independent research centres, etc.) for the development and use of a promising technology by means of experimentation.

The proposed agent-based (AB) model is an extension of Lopolito et *al.* (2012), which was developed as part of the SUSTOIL project[1] and addressed the issue of bio-energy production.

The question at stake is a rather relevant one. In fact, we intend to investigate whether the emergence of a stable innovation niche of firms can be stimulated through policy intervention. Earlier results (Lopolito et *al.*, 2012) confirmed the importance of policy intervention, showing the dominance of information spreading activities over the introduction of subsidies. Along this line, the contribution of this paper is to assess whether the introduction of institutional agents of change (referred to as *spreaders*), whose sole activity is to persuade firms to switch from the dominant technology (i.e. the regime technology) to a new technology, can prompt the emergence of a stable and self-sustained innovation niche. Putting it differently, we aim to assess if the emergence of an innovation niche is a stable feature of the system, resilient to policy withdrawal.

The remainder of the paper proceeds as follows: section 2 provides a theoretical background on innovation niches; subsequently, section 3 presents the agent-based model and clarifies how we model the temporary introduction of agents of change to stimulate/facilitate the emergence of the innovation niche. Section 4 presents the model set-up and provides account of our preliminary findings and section 5 concludes.

2. Sketching the theoretical background

As we discussed elsewhere to a greater extent (see Lopolito et *al.* 2011a), the niche formation process can be modelled as the emergence of a stable network of agents who directly form a sufficient "critical mass" able to support the development of the niche technology.[2] Following earlier works (Kemp, 1994; Kemp et al., 1998), we define a theoretical setting where the emergence of an innovation niche depends upon the simultaneous occurrence of three instances: (1) the convergence of actors' expectations around the niche technology and advantages associated with its adoption (what we referred to as *expectation mechanism*); (2) the involvement of powerful actors in the innovation niche. Their support is crucial to gather and mobilize the resources required to guide the technical change in a desirable way (what we referred to as *power mechanism*); (3) the emergence of effective patterns of learning interactions among agents in the niche, which lead to the creation of a significant knowledge base (what we referred to as *knowledge mechanism*).

These three mechanisms are interrelated and mutually reinforcing and represent the pre-conditions which need to coexist to allow the formation of an innovation niche (Raven, 2005). In the following section we shall present an agent-based model that captures the interrelations of these mechanisms and provides a useful framework of analysis that we will use to assess the impact of policy intervention.

3. The model specification

The model presented hereafter is based on Lopolito et *al.* (2012). In what follows we shall briefly summarise the key features of the model, referring the interested reader to the original model. The programmable modelling environment used for building the model is NetLogo 4.1 (Wilensky, 1999).

The AB model is structured around the three mechanisms described above, and it aims at capturing the major network dynamics that characterise the emergence of a stable innovation niche. It also aims at

[1] 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 ended in May 2010.

[2] As put by Rogers, "The *critical mass* occurs at the point at which enough individuals in a system have adopted an innovation so that the innovation's further rate of adoption becomes self-sustaining" (2003: 344).

simulating the effects of a policy action concerned with the expectations of potential producers on the new niche technology. As mentioned above, this policy target is achieved by introducing into the local system institutional agents of change called spreaders.

The local system is defined as a socio-technical space (represented as a 2-dimentional, finite, regular grid of cells) in which a finite set of agents $\left(I = \{1, 2, 3, \ldots, N\},\quad N << \infty\right)$ produce traditional commodities using an incumbent technology. Production of traditional commodities occurs under the conditions of perfect competition,[3] in which every firm has extra profits equal to zero:

$$\Pi_{i,t} = R_{i,t} - C_{i,t} = 0 \qquad [1]$$

where $R_{i,t}$ and $C_{i,t}$ are respectively firm i revenues and costs associated with production at time t.[4] Time is discrete and the generic time-step is denoted by t = 0, 1, 2, ….

Periodically, agents evaluate the possibility to switch production from traditional to niche production. Switching production involves a technological shift from the incumbent technology to the niche technology and might generate, with an endogenous probability p, positive extra profits in the following way:

$$\Pi^{n}_{i,t} = \begin{cases} R^{n} - C^{n}_{i,t} \ \ with \ \ probability \ \ p \\ 0.5R^{n} - C^{n}_{i,t} + \ with \ \ probability \ 1-p \end{cases} \qquad [2]$$

where R^n is the niche technology revenue (and is 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 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; it is set, at the initialisation phase, equal to 0.5 and reduces endogenously overtime as firms acquire new knowledge.

Firms switching to the new production become members of the innovation niche. However, a firm will switch technology only if it finds it convenient; this occurs any time its 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:

$$E\left(\Pi^{n}_{i,t}\right) = E\left(R^{n}\right) - E\left(C^{n}_{i,t}\right) \qquad [3]$$

where $E\left(R^n\right)$ is the expected niche revenue and $E\left(C^n_{i,t}\right)$ is the expected niche cost of firm i at time t.

3.1 The expectation mechanism

Each firm is characterised by a level of expectation $ex_{i,t}$ that is the preference of firm i at time t towards the niche technology and captures the expectation mechanism described above. The expectation level varies from 0 (if the firm does not have preferences for the niche technology) to 1 (if the agent has a complete preference for the niche technology). 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.

We can define the expected revenue as follows:

$$E\left(R^{n}_{i,t}\right) = R^{n} ex_{i,t} \qquad [4]$$

where R^n is the actual revenue associated with the niche technology[5] and $ex_{i,t}$ is the expectation of firm i at time t of the niche technology.

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[3] The assumption of perfect competition is based on the Product Life Cycle theory (Klepper, 1997), according to which as products mature and become commoditized, price competition intensifies. Hence, we assume that the incumbent technology is a mature and standardised technology characterised by perfect competition, as opposed to the niche technology which, being in the earlier 'introduction' stage of the cycle, is characterised by a lower level of competition.

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

[5] Note that this value does not vary across firms or over time.

We can therefore define the expected cost as follows:

$$E\left(C_{i,t}^{n}\right)=\frac{1}{ex_{i,t}}C_{i,t}^{n} \qquad [5]$$

where $C_{i,t}^{n}$ is the actual cost of firm *i* at time *t*, associated with the niche technology and, as before, $ex_{i,t}$ is the expectation of firm *i* at time *t* of the niche technology.[6]

Once a firm reaches a high level of expectation (set at 0.75), it becomes a supporter of the niche technology. Whenever two supporting firms meet they establish a tie. Note that two firms meet whenever they are socially proximate. This occurs any time they are on the same grid-cell. The social proximity of any pair of firms changes over time as firms are initially assigned a random position in the social space and they move randomly within the social space (moving among adjacent cells).

The established tie is, however, instable in the sense that every time that one of the two vertexes is no longer a supporter (i.e. its expectation drops below 0.75) it disappears. Thus, a dynamic *supporters network* emerges from firms' interactions.

Expectations of firms producing with the niche technology can increase or decrease overtime. Specifically, *ex* will increase any time the actual profit obtained producing with the niche technology exceeds the expected profit and *vice versa*. Hence, firms' expectation will increase if $\Pi_{i,t}^{n} \geq E\left(\Pi_{i,t}^{n}\right)$; 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. We also assume that agent's *i* expectation is mildly influenced by peers' expectations. Hence, it increases/decreases according to the following rule: $ex_{i,t+1}=ex_{i,t}+\Pi_{i,t}^{n}+\beta\frac{\sum_{j=1}^{S}ex_{j,t}}{S}$, where *S* is the size of the niche.[7]

3.2 The power mechanism

Each firm possesses some strategic resources – i.e. any resource which can be used in order to develop and promote the new technology. We refer to these resources as individual power. Any time a firm obtains an extra profit, it increases its individual power (I^{power}) as this extra profit is added to its pool of resources; likewise, individual power will decrease if the profit turns to be negative $\left(I_{i,t+1}^{power}=I_{i,t}^{power}+\Pi_{i,t}\right)$.[8] It is assumed that each time two supporting firms (*i*, *j*) establish a tie, the total amount of their respective resources flows through this tie. Thus, each tie has a power $T_{i,j}^{power}$ which is the sum of the resources of the agents on either end of the tie.

The total sum of tie powers represents, in turn, the overall network power $\left(N^{power}\right)$. Hence, we can write:

$$N_{t}^{power}=\sum_{i,j}T_{i,j}^{power}\ with \quad i\neq j \qquad [6]$$

Increasing individual power allows active firms to engage in costs reduction activities (e.g. by investing extra profits in R&D, firms could introduce process innovations). Moreover, as the network power increases, firms producing under the niche technology have access to a growing amount of external resources.[9] Hence we have:

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[6] Initial values of niche's cost and revenue are set equal to 1 and 1.3 respectively. Note that 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.

[7] As it appears, we are assuming that firms producing under the niche technology do not possess perfect information (i.e. their expectations are bounded) and base their expectations on past experience.

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

[9] Hence, we are assuming that resources accumulated by other firms can be exploited by means of spillovers within the emerging innovation niche.

$$\begin{array}{l} if \quad \Pi_{i,t}^{n} > 0 \quad \rightarrow \quad C_{i,t+1}^{n} = C_{i,t}^{n} - cI_{i,t}^{power} - nN_{t}^{power} \\ with \quad c \in [0,1]; \quad n \in [0,1] \quad and \quad c >> n \end{array} \qquad [7]$$

where $cI_{i,t}^{power}$ and nN_{t}^{power} represent respectively the cost reduction derived from the accumulation of individual and network power.

3.3 The knowledge mechanism

Each firm has an initial knowledge on the new technology. Each time a firm produces using the new technology, its knowledge increases. This captures the learning-by-doing activity. Knowledge will increase/decrease in a linear fashion according to the exogenous parameter θ.

Moreover, any supporting firm can learn from those firms with whom it has established a link. Every time-step a (randomly determined) proportion of knowledge flows among each pair of firms connected by an active link. Such a knowledge mechanism represents the idea of developing expertise as links provide the opportunity to refine the technology by means of learning-by-interacting.

Recall now that as the overall level of firms' knowledge on the niche technology increases, the probability p of obtaining the high profit $\Pi_{i,t}^{n} = R_{i,t}^{\;n} - C_{i,t}^{n}$ 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. Specifically, we assume that the probability p increases in a linear fashion: $p_{t+1} = p_t + \varepsilon \sum_{i=1}^{S} K_{i,t}$; where S is the size of the niche, $K_{i,t}$ is the relevant knowledge accumulated by firm i at time t, and ε is an exogenous parameter.

3.4 Agents of change: modelling policy action

This model is used to investigate complex niche mechanisms in order to draw insight on the spontaneous emergence of technological transition patterns. However, policy makers are also interested in how they can change the emerging patterns in a desirable way. In earlier studies (Lopolito et *al*., 2011b and Lopolito et *al*. 2012) we compared the relative effectiveness of two alternative policies – namely, the introduction of a subsidy given to those firms switching technology and the introduction of institutional *change agents* whose only purpose was to promote the new technology, enhancing firms' expectations towards it. These studies confirmed the importance of policy intervention and showed the dominance of information spreading activities over subsidies. The former policy action, in fact, preserved 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.

Building on this finding, we shall concentrate our attention solely on information spreading activities and, specifically, we will investigate the impact of policy withdrawal once the innovation niche has emerged. As mentioned, spreaders are institutional agents whose only purpose in the model is to promote 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 action. These agents interact only with firms who are not already supporters (as spreaders have no interest in interacting with firms which are already supporting the new technology), warping on the nearest one to influence its expectations. Specifically, every time a firm interacts with a spreader, its expectation increases in a linear fashion according to the exogenous parameter η.

4. Preliminary findings

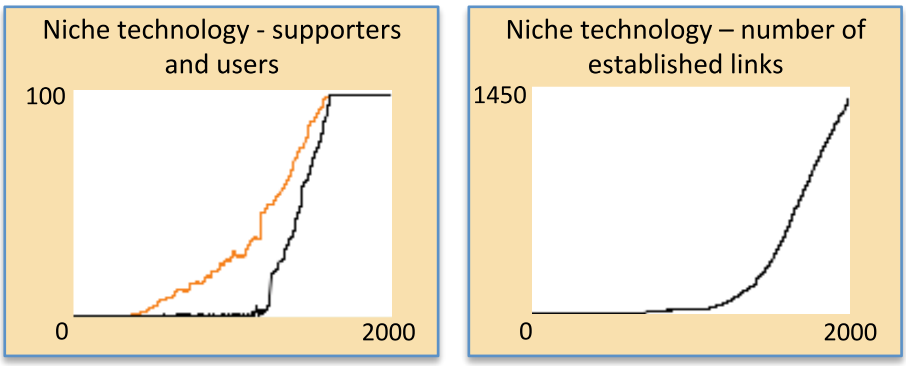
The preliminary results presented in this section are based on the parameterisation summarised in Tab. 1. We investigate the impact of temporary introduction of spreaders as described in section 3.4. As we did in previous studies, we consider a timeframe of 500 time-steps as the short-run and 5000 time-steps as the long-run. What we are interested in assessing is the *strength* of the policy action (i.e. the number of spreaders required for a niche to emerge) and its *duration* (i.e. the timeframe of the policy intervention for the niche to become stable).

Table 1: Experimental parameters' summary table

Parameter	Value	Description
Expectation	0.5	Initial level of expectations assigned to each firm
ß	0.0001	Rate at which expectation increases as an effect of peers' expectations
η	0.005	Rate at which expectation increases as firms interact with spreaders
Power	Rand. [0-0.3]	Initial power endowment assigned to each firm
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
Knowledge	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
R^n	1.3	Actual revenue under the niche technology option
$C^n_{i,t=0}$	1	Initial actual cost under the niche technology option

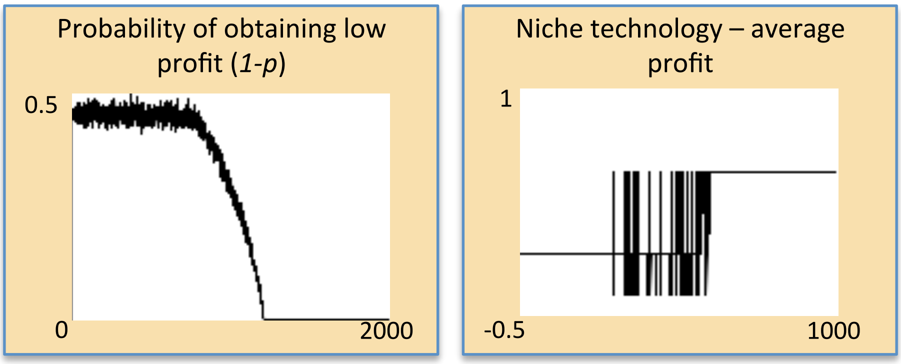
First, we present the results obtained with only one spreader which is the minimum amount of policy intervention, since with zero spreaders there would be no activity at all in the model. We will subsequently increase the policy effort raising the number of spreaders and investigate the impact of strengthening the policy action over the niche emergence. At this point we are not looking at policy withdrawal, as this will be the subsequent step of our investigation.

Figure 1: Innovation niche emerging dynamic (*one spreader*)



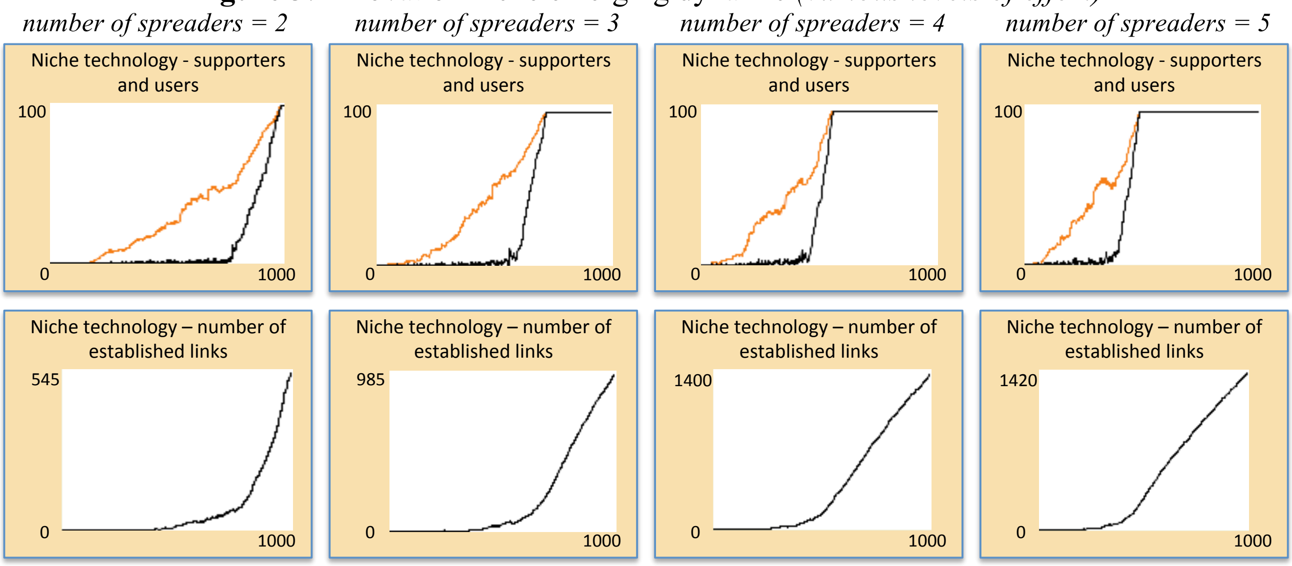
As it clearly emerges from Fig. 1 (left panel), after a period of latency (approximately 400 time-steps) the system shows a clear upward trend as for the number of supporters (see orange line) but the users niche does not emerge for the following 800 time-steps. Over this period a small bunch of agents start experimenting the niche technology but a stable niche takes over only in the long run and takes 1640 time-steps for the full niche to emerge as a feature of the system (see black line). Moreover, the network configuration (Fig. 1 – right panel) displays a similar upward trend showing that the innovation niche becomes denser as a growing number of users establish links with each other. As it appears it takes more than 1200 time-steps for the system to start gaining momentum. This is matched by a reduction in the uncertainty surrounding the niche option – ascribable to the knowledge mechanism which is driven by learning-by-doing. There is a significant drop in the probability of obtaining a low profit (Fig. 2 – left panel) which starts after approximately 560 time steps and completes after 1240 time-steps (i.e. when the niche starts its upward swing). Over the same timeframe (time-step 560 to time-step 1240) there is also an increase (although very unstable) of the average profit (ascribable to both the reduced uncertainty and the power mechanism which allows firms to reduce production costs; Fig. 2 – right panel), which stabilises right after. As it appears, with a minimum policy effort (i.e. only one spreader) the niche emerges as a configuration of the system only in the medium/long run.

Figure 2: Risk and profit for niche technology *(one spreader)*



We will now investigate the impact of an intensification of the information campaign on the use of the niche technology (i.e. increasing the number of spreaders). This should lead to a significant increase in the speed of niche emergence.
We report in Fig. 3 findings of four simulations where the number of spreaders was set equal to 2, 3, 4 and 5. As it clearly emerges, this time the full niche convergence trend is achieved in the medium run any time two or more spreaders are involved in the diffusion process. As the number of spreaders increases the time required for emergence reduces and the speed of the converging process increases. Also, as the number of spreaders increases the density of the innovation niche rises from a maximum of around 500 ties with two spreaders to approximately 1500 ties with five spreaders.

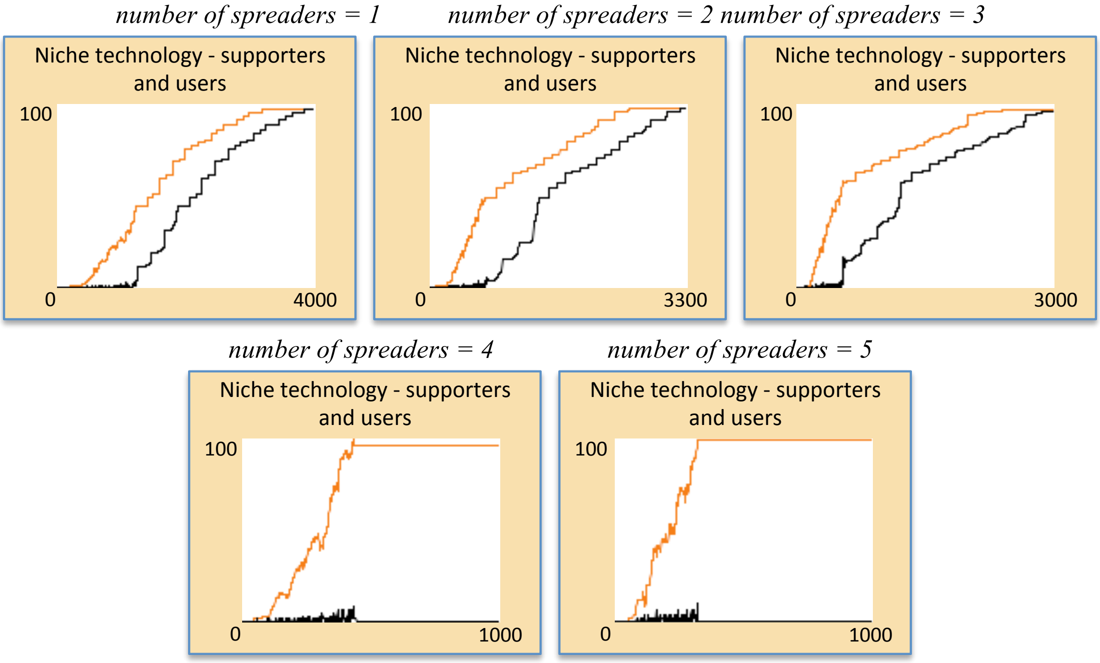
Figure 3: Innovation niche emerging dynamic *(various levels of effort)*



Although relevant, these findings are quite predictable: i.e. as the policy effort increases the time-frame required for the niche to emerge reduces. What we should look at now is whether the emerged niche is self-sustainable – i.e. we shall investigate whether withdrawing the policy action leads to a collapse of the niche or not. In the latter case, we shall also attempt to find out the minimum threshold (in terms of number of firms switching technology) above which the niche emerges even if the policy is withdrawn. Putting it differently, we shall attempt to measure the *niche critical mass*, which 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 (Rogers, 2003).
We initially consider a policy withdrawal whenever 5% of the firms have switched technology. We do so in order to verify first if such threshold is sufficient for the niche to be self-sustainable and also to assess the time required for this threshold to be reached.

Figure 4: Innovation niche emerging dynamic *(policy withdrawal at 5%)*



As we look at Fig. 4, we can observe some interesting features of the model. When we introduce one, two or three spreaders we observe a trend which is in line with what one would have expected: as the number of spreaders increases the emergence of the niche is faster and the withdrawal of the policy measure can be applied earlier. Specifically, with one spreader it takes – as we have seen before – around 1250 time-steps for the niche to gain momentum and therefore for the policy to be withdrawn. Adding an extra spreader leads the niche to emerge as a self-sustainable feature of the system after approximately 800 time-steps and with three spreaders the policy can be withdrawn after around 700 time-steps. Whenever the policy is withdrawn, the converging trend slows down and it takes between 3000 to 4000 time-steps for the niche to reach its full development (when all firms switch technology).
However, most interesting results emerge if we look at the two bottom boxes of Fig. 4 where we have four and five spreaders in the system. Here we can observe that although the 5% target is reached in a shorter timeframe, this does not produce a self-sustainable niche and, once the policy action is withdrawn, the niche collapses. Indeed, what is occurring here is that the 5% threshold is reached in a too early stage, when the niche is not sufficiently mature for the policy to be suspended and the niche to take-off autonomously. Hence, there seems to be an inverse relation between the strength of the policy action and the emergence of the *niche critical mass* able to self-sustain itself in the absence of a policy action. We inspected this feature of the system and found out that indeed this inverse relation exists. In Tab. 2 we report the size of the *niche critical mass* as well as the time-frame required for this to occur.
Data reported in Tab. 2 show clearly that, as the policy strength increases, the size of the niche critical mass rises; yet the time required for policy withdrawal reduces. Furthermore it has been shown that this reduces in a non-linear way. A possible explanation for the non-linear relationship between the number of spreaders and the niche critical mass (columns one and two in Tab. 2) is that spreader agents tend to act locally with firms (i.e. within a sub-region of the grid) which may result in group of users establishing permanent ties. When the threshold is reached this group may be able to kick-start a self-sustaining development. This is feasible in the case of few spreaders, whereas in the case of many

spreaders the initial users may not form a sufficiently connected group. So in this case a higher overall number of users will be needed before significant interaction occurs (i.e. the niche critical mass is higher).

Table 2: The emergence of a self-sustainable niche

Number of spreaders	Niche critical mass	Time-steps required for policy withdrawal
1	3%	c. 1200
2	4%	c. 800
3	5%	c. 700
4	6%	c. 600
5	8%	c. 500

This also relates to the fact that, to make the niche self-sustainable, a certain amount of links (through which strategic resources circulate) needs to be established among users and supporters. However, the formation of stable links requires that agents perform a relatively high number of interactions. The number of interactions increases either because agents have more time to interact or because there are more agents (supporters) involved in the interactions. What happens in this experiment is that as the policy effort increases (i.e. the number of spreaders rises from one to five), the number of supporters increases and this, in turn, reduces the required timeframe for the niche to become stable.

5. Conclusions

From these preliminary results, which from many simulations have formed very stable outcomes, we conclude that the policy measure investigated (increasing the number of spreaders) is an effective way to promote the emergence of a stable niche and that that policy measure can indeed be withdrawn within a finite period, provided that critical mass thresholds are taken into account. The relationship between the period and the threshold needed to establish the niche was then explored.

The first result was that as we increased the number of spreaders in the system the latency time required for the niche to take off reduced steadily, as could be expected. The next - and most interesting - result was that policy withdrawal could take place and this would not compromise the pathway towards full niche development (i.e. when all firms switch to the new technology) although it would considerably slow it down. We likened this to the concept of self-sustaining development, i.e. firms continue to switch independently of the policy support action. However, policy withdrawal could only be carried out upon the condition that critical mass is reached. As we increase the number of spreaders the critical mass threshold increases as well, but the time required for reaching the threshold decreases. This result stresses the importance of social resources in the niche development process. Indeed, a self-sustaining mechanism is activated only when a certain amount of links (through which strategic resources, such as knowledge, circulate) is established. Increasing the policy effort allows for the creation of such links in a shorter timeframe.

A further interesting aspect of these experiments is that overall policy effort can be evaluated quantitatively taking into account policy withdrawal (overall effort = level of effort * time steps required). In financial terms, policy options could be compared by multiplying column one by column three values in Tab. 2 (assuming that level of effort is a linear function of number of spreaders and that a fixed financial input over time is required for any level). Subsequently, a value judgement is needed as to whether it is desirable to the policy-maker (or to the society) to minimise the overall effort or whether it is desirable to maximise the speed of emergence of the niche, or more likely what kind of *trade-off* between speed of uptake and overall level of effort is possible.

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