Emerging innovation niches model*

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1 The Model

1.1 Objective and assumptions

Objective of our model is to simulate the emergence and operation of a technological niches (*TN*) in terms of actors' interaction. A TN can be conceived as protected *socio-economic* space 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.

A TN is successful when the firm that introduced the innovation grows stronger and/or when other firms imitate the novel design. Three interrelated mechanisms are assumed to affect niche's internal dynamic. Namely such mechanisms are: (1) convergence to high expectations, (2) networking and (3) learning.

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, (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 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

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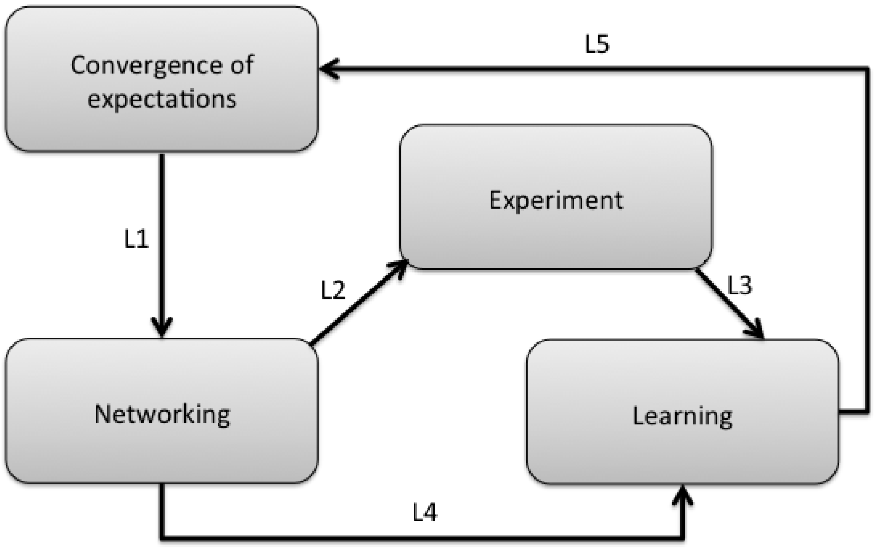
vision, expectations increase in robustness and stability, and a larger number of actors share the same vision.

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 mobilizing 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 become 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 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, p. 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 processes closely interact, giving rise to a complex and self-reinforcing system. Raven (2005) offers a systematic description of such interaction as represented in figure 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. 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.

Figure 1: Mechanisms interaction within the niche



Source: *Adapted from Raven (2005)*

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 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 attempted 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 Figure 1.

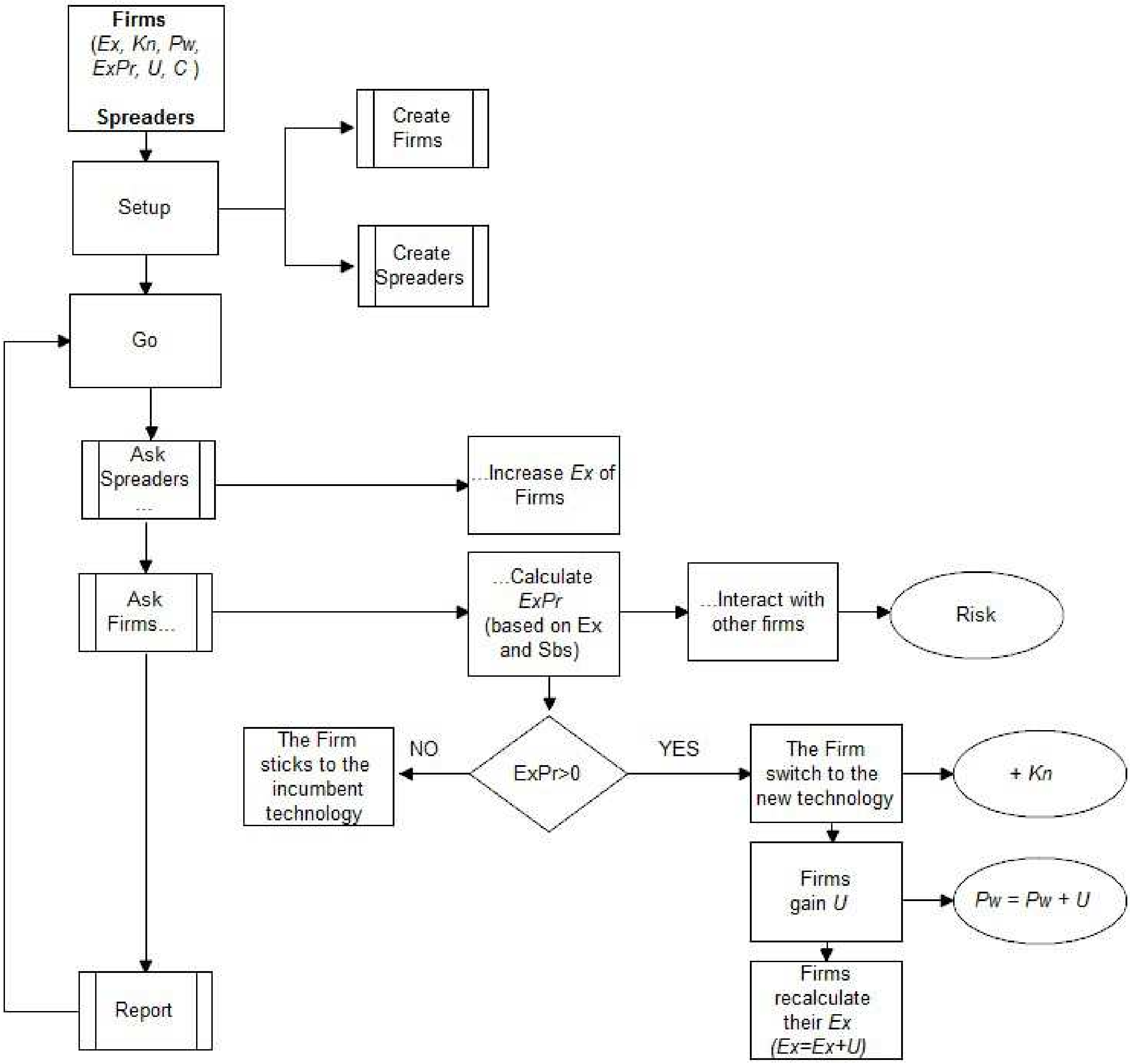
1.2 Structure and procedures

The model depicts a system formed by a finite number of agents $I = \{1,2,3,\ldots,N\}, N << \infty$, representing firms widely using a specific incumbent technology (i.e. the regime option) in their economic activity (goods production).

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 end-to-end process flowchart is plotted in **Errore. L'origine riferimento non è stata trovata.**

Fig. 1. Flowchart of model procedures



It is detailed in what follows. 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:

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

where $R_{i,t}$ and $C_{i,t}$ are respectively firm i revenues and costs associated with production at time t.[1] Time is discrete and the generic time-step is denoted by t = 0, 1, 2, …. 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 as 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).[2] 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 1.1.2.

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.

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[1] 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.

[2] 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.

1.1.1 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:

$$E\left(\Pi_{i,t}^{n}\right)=E\left(R^{n}\right)-E\left(C_{i,t}^{n}\right) \tag{3}$$

where $E\left(R_{i,t}^{n}\right)$ and $E\left(C_{i,t}^{n}\right)$ are respectively the expected niche revenue and cost of firm i at time t, which depend 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 from 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 1.2) according to the following rule:

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

Once a regime actor reaches a high level of expectation (i.e. equal to the expectation initially assigned to niche supporters and set 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 1.1.2).[3]

[3] 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

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 3.3). 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 equations (5) and (6):

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

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

where $C^n_{i,t}$ and $R^n_{i,t}$ are the same as above.[4] 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.

1.1.2 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 ($I^{power}_{i,t}$). At initialisation phase it is set at a specific value (see table 1 below) describing the firms' endowment of strategic resources.[5] 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 ($I^{power}_{i,t+1} = I^{power}_{i,t} + \Pi_{i,t}$).[6]

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:

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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.

[4] 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.

[5] 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.

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

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

The total sum of links' energy represents, in turn, the overall network power $\left(N^{power}_{t}\right)$. Hence, we can write:

$$N^{power}_{t} = \sum_{i,j} En_{i,j} \quad with \quad i \neq j \tag{8}$$

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 toward 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 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
v	2	Factor at which expectation increases when external events occurs	*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 stabilise over time. The value assigned to θ is slightly higher if compared to *n*, *c* and ε. This decision was taken
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	based on the fact 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
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 lucky event - 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 to 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	

1.1.3 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 3.3).

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:

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

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

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

1.2 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,[7] 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 $M < N << \infty$. 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 (equations 2 and 3) as follows:

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

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

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

[7] 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).

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.

1.3 The interaction of the three mechanisms

According to the theoretical framework, the model accounts also for the interactions between the three mechanisms (L1 to L5 in figure 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 influence the networking activity. In fact, as expectations towards the niche 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:

$$C_{i,t+1}^{n} = C_{i,t}^{n} - cI_{i,t}^{power} - nN_{t}^{power} \quad \text{with} \quad c \in [0,1]; \quad n \in [0,1] \quad \text{and} \quad c >> n \qquad (11)$$

where $cI_{i,t}^{power}$ and nN_{t}^{power} 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 initialization - see table 1 below) 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 1.1.3, 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:[8] $p_{t+1} = p_t + \varepsilon NK_t$; 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 $\Pi^n_{i,t} \geq E\left(\Pi^n_{i,t}\right)$; 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.[9] In order to take into account the effect of L5 on firms' expectation, equation 4 is changed accordingly:

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

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[8] 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.

[9] 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.

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