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Abstract

In this paper we study the process of coalition formation conditioning the common decision to adopt a shared good, which is too expensive for one average consumer, who would also not be able to exhaust its use. We develop an agent based model to study the interplay between coalition formation and the diffusion of shared goods. We model coalition formation in an evolutionary game theoretic setting, and adoption using elements from the Bass and the threshold models. Coalitions formation sets the conditions for adoption, while diffusion influences the consequent formation of coalitions. Results show that both coalitions and diffusion are subject to network effects, which also have an impact on the information flow though the population of consumers. Consumers prefer to form large coalitions in order to buy expensive goods and share ownership and use, rather than establishing smaller coalitions. In larger groups the individual cost is lower, although it increases if higher quantities are purchased collectively. The paper concludes by connecting the model conceptualisation to the on-going discussion of diffusion of sustainable goods, discussing related policy implications.

Keywords: Coalition formation, diffusion, shared goods, agent-based model

JEL Classification: C73, D16, D71, E27, O33

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1 Introduction

Diffusion is usually studied as an individual decision to adopt a good for own consumption, overlooking cases when the decision is taken collectively (Rogers, 1962), such as when sharing a property. While collective action (e.g. Olson, 1971; Hardin, 1982; Oliver, 1993), such as group consumption (Borcherding and Filson, 2002), is usually studied independently from the formation of the group (e.g. Komorita and Chertkoff, 1973; Komorita, 1974).

This paper aims at combining the process of coalition formation leading to the diffusion of a shared good, where consumers agree to act cooperatively in order to share costs and use of a common property. Coalition formation and diffusion are studied as two co-evolving processes. Coalitions are necessary for the diffusion of shared goods, being adoption a collective decision; and diffusion influences the consequent formation of coalitions since it changes the structure of the social network.

We develop an agent-based model (ABM) to study the diffusion of goods that are characterised by high investment cost – above the budget constraint of an average consumer – but affordable by a coalition of people acting cooperatively. This is, for example, the case of common pool resources (CPR) (Bowles, 2004), such as large irrigation systems adopted by groups of farmers (Bardhan, 1993b,a, 2000). Sustainable goods, such as large-sized decentralised energy systems (DES), can be also considered as CPR (Wolsink, 2012). These are too costly for individual households, but can be purchased by a group of neighbouring households to access energy off the grid.

We model coalition formation in an evolutionary game theoretic setting, and diffusion using elements from both the Bass and the threshold models in which the role of innovators is central. In the model, agents sequentially interact in order to form a coalition: they form links, communicate, evaluate options, establish stable groups, and eventually adopt a shared good that produces a services which is alternatively available from a centralised provider but at a higher cost. Adoption is feasible only when a coalition is stable.

Agents are nodes of a network whose structure is not fixed, but evolves throughout time allowing for the formation of new spatially bounded links. The model differs in two main aspects with respect to the literature on diffusion over networks. First, instead of studying which network structure facilitates or prevents diffusion, it studies diffusion that co-evolves with the process of group formation, as the network of linked individuals grows. Second, the diffusion process is not considered to be dependent on an individual adoption decision, but, conversely, it is studied as a collective decision, conditioned by prior steps of coalition formation (Schlager, 1995).

The model fits in the category of sequential games of coalition formation as those formulated by Bloch (1995, 1996) and Mutuswami and Winter (2002), but is closer to the evolutionary model on firms formation by Axtell (1999, 2002). Nevertheless, we differ from the these models in a number of ways.

In the bargaining process to form the coalition, social interactions (Oliver and Myers, 2003) and individual characteristics play an important role. Negotiations aimed at the common investment depend on how much each individual is willing to contribute to the fixed costs of capital, and how much they expect to consume of the service produced with the good (demand). Agents communicate their demand for the service and the monetary contribution that they are willing to commit into the common investment. This contribution is a portion of agent's income and it is the amount that maximises individual utility. Agent's decision is not only based on individual income and demand, but it also considers their consumption preferences. Agent's utility in coalition is also related to the monetary contribution that other members have committed, and to the cumulative coalition demand for the service. Therefore, since agents adapt their behaviour and choices in relation to the evolving interactions with others, their attitude towards the common investment in coalition also changes over time. Once adopted, we assume that the shared good guarantees a more efficient service at a lower price, compared to the existing supply.

Results show that the formation of coalitions and the diffusion of shared goods co-evolve. Both are subject to network effects: agents' behaviour is affected by others' decision and by societal trends, and the social network evolves because of the changing links between consumers. Although the formation of coalitions is essential to the adoption of shared goods, they also reduce future adoption, by isolating consumers that do not find a suitable coalition on time. Network clustering and geography (the size of agents' neighbourhoods) and the speed at which information flows among consumers determine higher adoption in consumers' coalitions. We also find that consumers prefer to form larger coalitions which allow them to buy expensive goods with higher capacity, rather than smaller coalitions that can adopt smaller goods. This is because, although larger coalitions require longer negotiations, the individual consumer monetary contribution to the common investment is lower than in smaller coalitions, and the unit price of the service is lower. However, smaller coalitions are more cohesive, and agents' connectivity and centrality is higher. Larger coalitions also tend to induce free riding, up to a size ($N = 8$) after which free riding falls because the large cost of the investment would not be sustainable. Results crucially depend on the speed at which networks form and information circulates, and on the composition of individual geography.

We connect these results to implication for the diffusion of sustainable energy technologies that can be adopted by groups of consumers, and provide a local service, such as decentralised energy systems (Ackermann et al., 2001).

The paper has the following structure: the next section 2 reviews the literature regarding diffusion and coalition formation. Based on these two, the model conceptualisation is also explained. Section 3 presents the mathematical formulation of the model and its sequential process of coalition formation. Then, section 4 presents and discusses the results. Section 5 explains the potential of this model in the context of diffusion of sustainable goods and its policy implications. Section 6 concludes.

2 The Literature: Diffusion and Coalition Formation

Our modelling strategy builds on two rich literatures: diffusion of innovation (especially in networks), and coalition formation. We briefly discuss each in turn.

The literature has discussed extensively how diffusion is related to the influence of the social network on potential adopters (Burt, 1987). Innovation diffusion theory often deals with an individual decision-making process to adopt a new good or process, where the choice may change through time, as the awareness of adopting changes. The role of *initiators* or *early knower* is pivotal (Rogers, 1962) in starting the diffusion process, since they create the initial *critical mass* of adopters (Gersho and Mitra, 1975). Over time, social interactions is important for diffusion, facilitating *imitation effects* (Bass, 1969) and *fashion effects* (Smallwood and Conlisk, 1979; Arthur, 1989). *Late adopters* may imitate the innovation behaviour of *early adopters* in order to reach the same *social status* (Tarde, 1962). Therefore, interactions among individuals determine the *bandwagon effect* which influences the behaviour of *later adopters* (Abrahamson and Rosenkopf, 1993, 1997).

To examine the role of social networks, diffusion has been studied as part of network theory, where adopters are modelled as nodes of a social network and links represent the interactions necessary to spread information among nodes (Rogers, 1976; Cowan and Jonard, 2004). In this context, diffusion has been shown to depend on the network structure (Delre et al., 2010; Peres, 2014). The regular network is locally very dense and has a long average path since every node has the same number of nearest neighbours. With this structure, diffusion is slow since information must travel around the whole network before reaching nodes located at the opposite side. The small world structure (Watts and Strogatz, 1998) is a regular network in which few randomly chosen links are reconnected to distant nodes. This structure maintains the same level of clustering of the regular network, but reduces dramatically the average path, resulting in a faster process. In random networks (Erdos and Renyi, 1960) nodes are connected randomly to each other. This structure has low average path and low clustering, resulting in fast diffusion, although nodes are not locally connected. Beyond the structure, the position of potential adopters in the network also matters for diffusion (Granovetter, 1973).

Social networks evolve over time, as new links are formed and existing links are severed, influencing information flows and individuals' decisions, which are, consequently, dynamic and spatial-dependent (Jackson and Wolinsky, 1996; Dutta and Mutuswami, 1997; Bala and Goyal, 1998; Johnson and Gilles, 2000; Jackson and Watts, 2002). In the evolving process of network formation, highly connected nodes are *hubs* in the social structure, and they accelerate the contagion between individuals, thereby facilitating diffusion over the network (Barabasi, 2002).

Coalition formation has been mainly studied in the context of game theory. Studies on coalitions in triads (Caplow, 1956; Gamson, 1961) and the n-person coalition formation games, with n>3 (Komorita and Chertkoff, 1973; Komorita, 1974), have analysed the bargaining process among agents in relation to individual resources share. Negotiations is influenced by the initial distribution of resources and coalition members aim at forming coalitions that guarantee stability. Smaller and homogeneous coalitions are most likely to be formed compared to larger and heterogeneous coalitions, since the probability to reach stability and reciprocity is higher.

The *hedonic coalitions* literature (Dreze and Greenberg, 1980) has studied the process of coalition formation in relation to individuals' effort, where the objective is to carry out joint activities, such as production. In these models the individual payoff depends on own and other members' characteristics and effort. As a result, members tend to form coalitions that maximise the common utility. They have been used, for example, to investigate strategic alliances among firms (Axelrod et al., 1995) and task allocations within an organisation (Shehory and Kraus, 1998). More recently, players' motivation and trust have been introduced (Griffiths and Luck, 2003; Griffiths, 2005), which were shown to lead to the formation of small *clans*.

Bloch (1995, 1996) models the process of pairwise coalition formation with infinite horizon and with finite number of players. In these models the aim is to find a stable equilibrium with all the players belong to a coalition. Mutuswami and Winter (2002) extend those models, allowing agents to remain out of coalitions and have a payoff equal to zero, and introducing in the offer to form a coalition a "conditional cost contribution" (Mutuswami and Winter, 2002, p. 244) which represents the cost an agent is willing to pay to form the coalition. Both Bloch (1995, 1996) and Mutuswami and Winter (2002) study the payoff division rule that guarantees stability, efficiency and equity among agents.

Built on this literature, the model in this paper fits in the category of sequential models of coalition formation with the "best reply" type of adjustment dynamic, that are common in the evolutionary game theory (Axtell, 1999, 2002). It makes it possible to overcome two common difficulties relative to the one-stage models of coalition formation, as explained by Bloch and Dutta (2011). First, agents in sequential models of coalition formation are not anymore "myopic", meaning that they are aware of what might be the subsequent outcomes. Second, sequential models are more likely to result in efficient coalitions since agents are "forward-looking" and there is an endogenous resolution of the problem of coordination among agents.

3 The Model

We model self-interested agents that have two options to satisfy their demand for a given service: purchase it from the market from a central provider, or invest in an expensive capital good, whose cost is larger than anyone's income, and which can provide the same service.[1] Agents' cost and the utility related to the first option are given and depend solely on the individuals' characteristics. The second option requires to form a coalition of consumers. Agents' cost and utility of this option depend on own characteristics but also on those of the other coalition members and on characteristics of the coalition, such as its size. Driven by their interest in improving their utility, each agent interacts, attempts to form coalitions, and compare the different options. At the offset, all agents satisfy their demand from the general provider, and no coalition exists (all agents are singletons).

In the sequential process of coalition formation, an agent announces the investment (s)he intends to make, and proposes to form a coalition to different agents. These agents, in turn, after negotiation, may accept or reject the proposal. Agents decide to become coalition members if their utility is higher, and cost of service is lower, compared to the case of acting as singleton. If contacted members do not reach an agreement to form a coalition, the coalition formation process evolves by including more agents, or allowing for the exit of some the members contacted earlier (some members may manage to free-ride). After each interaction, agents adjust decisions, which are also influenced by what happens in the whole population, such as changes in the potential members, their monetary contribution to the investment, and demand of the service.

[1] One may think, for example, at transportation or energy. Consumes may purchase transport from a local service, or purchase a car; or they can buy energy from the grid, or invest in a decentralised energy grid.

More formally, agents (i) have the following characteristics: demand for the service (d_i), income (e_i) and preferences for income, shared consumption and shared contribution (respectively θ_i, α_i and β_i). Agents have two options to consume the same service: purchase it form a central provider at a given price (singleton), or purchase a capital good in coalition and use its services shared with other members (investment in coalition). The latter implies an investment cost, I, which is shared among the agents belonging to the coalition. To decide among the two options, consumers compare their cost and utility.

Singletons ($i1$) pay a given unitary price p_1 to purchase the service. Agents in coalition ($i2$) pay the unitary price of the services produced by the shared capital good (p_2) and a share of the fixed cost of the investment (x_i). We express the two cost functions (c_i) as:

$$c_{i1} = d_i p_1 \tag{1}$$

$$c_{i2} = d_i p_2 + x_i \tag{2}$$

where x_i<I in the second option (Eq. 2) is the monetary contribution that an agent is willing to commit in the joint investment. x_i is computed as to maximises agent i utility in coalition, such that U_{i2}: dU_{i2}/dx=0.

The utility functions for the two options are computed using a Cobb-Douglas function combining the indirect utility of saving, the direct utility of consuming, and in the case of coalitions the (dis)utility derived from other members' contribution and their common consumption. Formally, the two utility functions are written as follows:

$$U_{i1}(e_i; c_{i1}; d_i; \theta_{i1}) = (e_i - c_{i1})^{\theta_{i1}}(d_i)^{1-\theta_{i1}} = [e_i - d_i p_1]^{\theta_{i1}}(d_i)^{1-\theta_{i1}} \tag{3}$$

$$\begin{aligned} &U_{i2}(e_i; c_{i2}; d_i; D_{-i}; x_i; X_{-i}; N; \theta_{i2}; \alpha_i; \beta_i) = \\ &= (e_i - c_{i2})^{\theta_{i2}}\{(d_i + D_{-i})[\frac{\alpha_i d_i}{d_i + D_{-i}} + (1-\alpha_i)(\frac{\beta_i x_i}{x_i + X_{-i}} + \frac{1-\beta_i}{N})]\}^{1-\theta_{i2}} = \\ &= [e_i - (d_i p_2 + x_i)]^{\theta_{i2}}\{(d_i + D_{-i})[\frac{\alpha_i d_i}{d_i + D_{-i}} + (1-\alpha_i)(\frac{\beta_i x_i}{x_i + X_{-i}} + \frac{1-\beta_i}{N})]\}^{1-\theta_{i2}} \end{aligned} \tag{4}$$

where Eq.3 refers to consumers purchasing from the central provider (singletons), and Eq.4 to consumers that enter a coalition. $\theta_i \in [0; 1]$ is the preference for income; 1-θ_i is the preference for consumption; $\alpha_i \in [0; 1]$ the importance given by agent to the proportional division rule based on consumption; $\beta_i \in [0; 1]$ measures the preference for the proportional rule to divide the shared investment based on the agent's contribution, with respect to the equal rule, when all agents receive the same amount of service, irrespective from the contribution (1-β_i); X_{-i}=(X-x_i) is the total monetary contribution of the $N - i$ coalition members belonging to the coalition; D_{-i}=(D-d_i) is the total demand of the other $N - i$ coalition members belonging to the coalition; and N is the coalition size.

The function of the members purchasing from the central provider (Eq.3) is straightforward. The utility reduces with the cost of purchasing, relative to income, and increases with consumption. The relative importance of each factor depends on θ_{i1}. This is the reference utility whenever an agent evaluates the opportunity of joining a coalition. In this second case (Eq.4) we use a function similar to Axtell (1999, 2002), and take into account the agents' characteristics and their willingness to commit part of their income into the common investment.[2] Higher θ_{i2} indicates a higher preference for saving rather than consuming, reducing the propensity to invest, and vice versa. More importantly, the utility in coalition is function of other members' contribution. α_i measures a member preferences for sharing consumption based on each relative demand, rather than sharing on the basis of the contribution. β_i measures the preference for a proportional division of consumption based on each member relative contribution, with respect to an equal division with all coalition members. The individual utility in coalition also depends on the sum of the contributions and on the demand of the other $N - i$ members. To compute the individual's utility in each time period we model an iterative process with feedbacks between negotiating members, which stops only when a stable coalition is either formed or or not. During this process X_{-i} and D_{-i} vary as a result of members' decisions, affecting the remaining members' utility.

At the outset of the simulation, agents are nodes of a regular network with l neighbours with whom they can tie and form a link. We also assume that neighbours must be within one step from the originating node, because the shared good provides a localised service. We distinguish between regular, *active*, and *initiator* agents. The sequential game of coalition formation starts with m randomly chosen agents that are *initiators*, hence they are the innovators needed to start the diffusion process according to Rogers (1962). An *initiator* is always *active*, meaning that they are always aware of the technology, and willing to consider joining a coalition. Not all *active* agents are *initiators*. A regular agent becomes *active* as soon as an *initiator* proposes to form a link: in this way *active* agents become aware of the opportunity to make the common investment, and replace the centralised service provider. By means of this interaction information flows among agents. When *active* agents become

[2]Please see Annex I for a complete discussion regarding the properties of equation 4 and its parameters.

initiators, they can tie new links, thereby continuing the processes of knowledge diffusion following the percolation diffusion model in networks (Mort, 1991; David and Foray, 1994; Solomon et al., 2000). An *active* agent becomes *initiator* when the interest for the investment in coalition is higher compared to a minimum level, computed endogenously each time step. This threshold is defined *visibility*, as in Faber et al. (2010), and represents the minimum level of agent's awareness towards the new good. Every time step a random value, $RND \in [0; 1]$, is generated and associated to *active* agents. An *active* agent becomes *initiator* when this number is lower than the *visibility* (W_t):

$$W_t = MAX[V_{t-1}; min[1; Adv + (ShareInCoalition_{t-1})^{\xi}]] \tag{5}$$

where Adv is the level of advertising, exogenously defined, as in the Bass model; $ShareInCoalition_{t-1}$ is the share of agents that have entered a coalition; and ξ is an exogenous parameter reflecting the bandwagon effect (Smallwood and Conlisk, 1979). Once an *active* agent becomes *initiator*, this characteristic is maintained for the remaining time steps.

Only *initiators* can contact other agents, tie new links, and start the process of coalition formation. As more capital goods in coalition are diffused, *visibility* increases, and more agents become *initiators*, increasing the likelihood that agents are involved in coalition formation and adoption. However, agents who already belong to coalitions cannot participate in further coalition formation processes, reducing the number of *initiators* and the likelihood that new agents are contacted. For this reason, coalition formation and diffusion co-evolve.

In each time period the process of coalition formation begins with *initiators* (not yet in coalition) that randomly tie a new bidirectional link with one of their neighbours not yet linked (Action 1). *Initiators* then choose the product they want to purchase and propose the investment to their linked neighbours (Action 2). The choice is done considering the set of products available in the market, each of them with different investment cost (I), amount of service supplied (S) and price (p_2). A product q is chosen randomly with probability proportional to its diffusion share, $Diff_q$, over the total number of products already adopted, $\sum_{q=1}^{Q} Diff_q$. Therefore, the probability that a product is chosen by an *initiator* is:

$$\Omega_q = \frac{Diff_q + 1}{(\sum_{q=1}^{Q} Diff_q) + Q} \tag{6}$$

where the terms (+1) and (+Q) are needed in order to guarantee equal probabilities at the beginning of the simulation, when diffusion is zero. *Initiators*, therefore, are subject to the indirect network influence. This feature integrates in the model the concepts of *imitation* and *fashion effects* that are common in diffusion theory.

Next, *initiators* explore the investment in coalition options (Action 3), taking into account investment, demand, utility and cost constraints (Eqs.7, 8, 9 and 10 below). First, they evaluate coalitions of size two. Then, one of the two coalition members chooses randomly one of his or her linked neighbours and invites him or her to join the coalition and evaluate the investment proposed by the *initiator*. After evaluation, one more linked neighbour is invited. Actions 2 and 3 are repeated a number of time in each time step, allowing *initiators* to evaluate different coalitions, with different members and products.

Since agents are constrained with respect to time and computational power, they cannot evaluate all the possible combinations of products and coalitions. After evaluating each coalition, agents make a conditional decision between invest in it or remaining singleton, and store as optimal the option with highest utility and lowest cost. If a subsequent coalition yields higher utility and lower cost in comparison to the optimal condition stored previously, the decision is updated. At the end of the evaluation process, a final decision is taken. All agents announce separately their optimal decision. If all members of a coalition announce that this option is their optimal decision, the coalition is established. Consequently the common good is adopted.[3] *Adopters* may not take part in future coalition formation processes.

The evaluation of coalitions is a multi-step bargaining process occurring in each time step of the simulation. Negotiation is necessary because agents try to maximise individual utility in coalition, which depends also on what other agents have announced in previous bargaining steps (which determine continuous variations in the value of X_{-i}). In other words, agents adjust behaviour continuously in relation to other agents' announcement and to new opportunities, aiming at improving individual utility and at experiencing cost reduction. Coalition formation, therefore, is modelled as a dynamic and as a long process of continuous interactions among agents because many features evolve over time and agents adapt behaviour accordingly.

The iterative process of coalition formation stops when stability among a group of members is reached. A coalition is stable when Pareto efficiency is reached – each member is better off without making at least one other worse off: (i) all members maximise their utility; (ii) no member has an incentive to move to another coalition; and (iii) no other agent would prefer to enter the coalition. Two more conditions must be satisfied to reach stability among the group of agents. First, the sum of all members monetary contributions has to be at least equal to the investment cost

[3]Annex II describes in detail how the coalition formation works, by means of an illustrative and numerical example.

(I) and not exceeding 110% of its value (Eq.7). Second, the common investment capacity (S) must satisfy the total coalition demand (Eq.8). Formally:

$$I \leq x_i + X_{-i} \leq I * 1.1 \tag{7}$$

$$d_i + D_{-i} \leq S \tag{8}$$

Pareto efficiency and conditions in equations 7 and 8 guarantee coalition stability, and a secure investment. This is also granted by two further conditions: that a member's utility (cost) in coalition is higher (lower) than utility (cost) as singleton: Eq.9 (Eq.10). Formally:

$$U_{i2} > U_{i1} \tag{9}$$

$$c_{i2} < c_{i1} \tag{10}$$

To summarise, at the outset every agent acts as singleton and purchases the service from a central provider. A few *innovators*, interested in purchasing jointly a shared good that could provide locally the same service at a lower cost but which is too expensive to buy individually, contact neighbours to inform about the opportunity. Increasing the size of the network by forming new links, agents interact and explore several coalition options of different size. Once a group of agents cannot improve their utility by changing coalition, and no other linked agent would want to join, or would be accepted by all existing members, they reach a stable coalition. Once they agree to commit to the joint investment, no agent would move to another coalition because this would incur a high sunk costs.[4] We thus assume the good is purchased and the coalition is stable forever.

4 Results and Discussion

4.1 Model Initialisation

The model simulates the co-evolution of coalition formation and diffusion of shared goods in a population of $P = 200$ agents. Tables 1 and 2 report the initial values of the parameters.

Agents are distributed on a regular network, which represents a relatively large neighbourhood (Figure 1). Only 2% are *initiators* (m=4), randomly chosen at the beginning of every simulation (t=0). Each agent has eight potential neighbours

[4]This is in line with the fifth stages of the Innovation-Decision Process in Rogers' theory where confirmation of adoption implementation is a decisional step which comes later in time, once the product reaches its maturity phase (Rogers, 1962).

Parameters		Value
Total population of agents	P	200
Number of *initiators* at t=0	m*	4
Spatially bounded links in the neighbourhood	l*	8
Income	e_i	μ=1000, σ=250
Demand	d_i	μ=45, σ=10
Preference	θ_{i1}=θ_{i2}	μ=0.5, σ=0.1
Preference for proportional division rule (consumption)	α_i	0.5
Preference for proportional division rule (contribution) and equal share division rule (size)	β_i	0.5
Advertising	Adv	0.01
Bandwagon effect	ξ	0.85
Price singleton	p_1	10

* Parameter analysed

Table 1: Model initialisation

($l = 8$) with whom they can tie links (dotted edges in Figure 1) and form a coalition.[5] At the end of this section, two different analyses evaluate whether the diffusion outcome changes in relation to the variation of these two parameters: number of initial informed agent (m) and size of neighbourhood, or network clustering (l).

Agents are heterogeneous in terms of income (e_i), demand (d_i) and preference for income (θ_i) and all values are proportional and compatible. Individual values are assigned randomly from a normal distribution. Agents have the same preference for the service regardless from whether it is bought centrally or produced by the joint investment (θ_{i1}=θ_{i2}). They are homogeneous in respect to the two remaining preferences: proportional division rule based on consumption (α=0.5) and proportional division rule based on contribution and equal share division rule based on coalition size (β=0.5).

Agent's awareness towards the common investment increases at each time step (Adv=1%), meaning that chances for more agents to become *initiators* increase over time. Further, the bandwagon effect related to the share of adopters is almost linear (ξ=0.85). The unit price of the service paid by singletons to a general provider (p_1) is higher than the unit price of the service produced by the shared good (p_2) (Table 2).

[5] Although the degrees of separation between agents in a coalition may be larger then one, as members may invite their own neighbours and so on.

Product	Investment (I)	Capacity (S)	Price (p_2)
q_1	500	200	5.00
q_2	600	250	4.75
q_3	700	300	4.50
q_4	800	350	4.25
q_5	900	400	4.00
q_6	1000	450	3.75
q_7	1100	500	3.50
q_8	1200	550	3.25
q_9	1300	600	3.00
q_{10}	1400	650	2.25

Table 2: Model initialisation: available products

There are 10 capital goods in the market. Each of them has a different cost (I), maximum capacity (S), and price (p_2): the larger the capacity (the higher the investment cost), the larger the economies of scale, the lower the unit price.

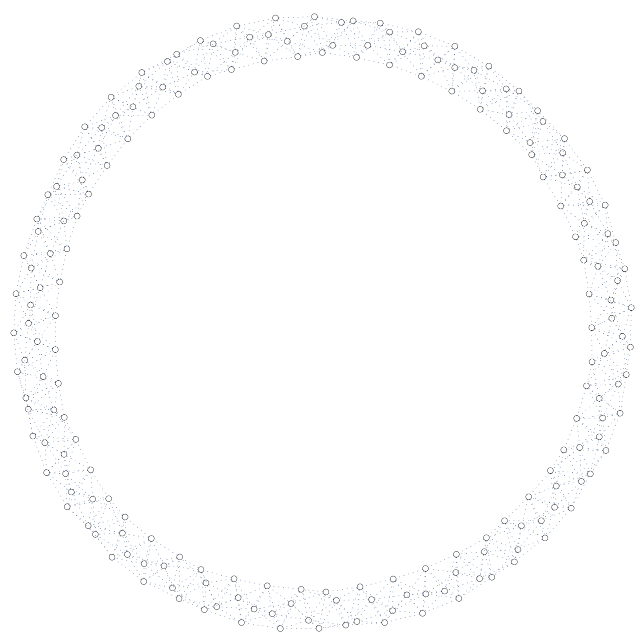

Figure 1: Initial regular network, 200 agents

The model has a time horizon of 200 time steps, where each step defines the time needed to initiate a face-to-face contact and to evaluate investment in coalition. To control for the random effects we show results as averages over 40 simulations with different random seeds.

4.2 Diffusion in Coalition: Emergent Properties

We first discuss the emerging aggregate properties of the model. The model simulates agents' interactions aiming at forming coalition needed to buy jointly a common good to replace service provision from a centralised provider. At the outset, only 2% of the population is aware of the good. The information is spread throughout the network by means of contacts among agents.

Diffusion

After 200 periods, still only about 75% of the population is informed (Figure 2), meaning that on a regular network 'contagion' is relatively slow (as discussed earlier). Two more factors are relevant. First, potential direct links are geographically bounded, due to the need to adopt a good that provide a service locally, and an agent can communicate only to the nearest neighbours (l=8). Second, the low number of *initiators* (m=4) slows down the initial 'contagion', since the formation of new links and dissemination of information start from these agents.[6]

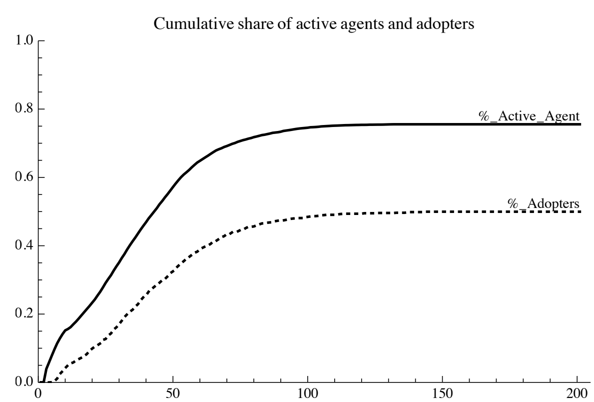

Figure 2: Cumulative share of active agents and agent in coalition

[6]Interpersonal communications are necessary to spread information in social networks (Lin, 1999; Woolcock and Narayan, 2000): these are particularly important for the diffusion of environmental motivations (Ek and Patrik, 2010) and energy-efficiency innovations (McMicheal and Shipworth, 2013).

Awareness, does not imply adoption: only 50% of the population establishes a coalition and adopts the shared good. The cumulative adoption follows the characteristic S-shaped curve, although adoption is higher in the initial time steps compared to traditional diffusion curves. This is due to the fact that in our model, when adoption in coalition reaches a higher utility than buying from the central provider for several agents, this is for certain, reducing the risk of early adopters.[7] 50% adoption rate is not new in the literature on diffusion of capital goods, such as for micro-CHP (Faber et al., 2010) and electric vehicles (Higgins et al., 2012; Shafiei et al., 2012). We will test this outcome against different initial configurations of the network structure (m and l).

Size of coalitions and shared investment

Initiators may choose among ten different products ($q_1 - q_{10}$), where q_1 is the smallest and cheapest, but which provides the service with the highest unit cost; and q_{10} is the largest and most expensive, providing the service at the lowest unit cost. The more a product is adopted, the higher is the probability to be chosen (Ω_q) in new coalitions. Figure 3 shows the value of Ω_q for each of the ten products over time. At the very beginning of the simulation all products have the same probability to be chosen. After a transition period in which probabilities vary rapidly, we observe a long term pattern.

Overall, the most-chosen products are those with a lower investment cost (I), lower capacity (S) and higher unit cost (p_2). Among these, products q_1 and q_2 are those that have the highest rate of adoption during the initial time steps. This is due to both the network structure and to coalition size. At t=0 there are few *initiators* that can tie links with neighbours, the network of connected agents is far from dense, and there are few *active* agents that can enter in coalitions. Therefore, only small coalitions can be evaluated and established, which have a small budget and can afford less expensive goods (as Figure 4 shows).[8]

Figure 4 plots the share of adopters for different coalition sizes (between 3-13) and type of capital good purchased. The figure shows that agents organise themselves

[7] In order to test whether the model is able to reproduce the traditional S-shaped diffusion curve, Annex III presents diffusion outcome when uncertainties are added at the beginning of the process. We show that uncertainty does reduce initial levels of adoption.

[8] These results resonate with notions of group size developed in the collective action literature (Olson, 1971) and in the coalition formation literature (Komorita, 1974). Accordingly, small groups are formed faster than bigger groups and these are more stable than the others. Further, coordination among agents in large-sized groups requires more time and in these formations agents have higher bargaining power and higher opportunity to defect.

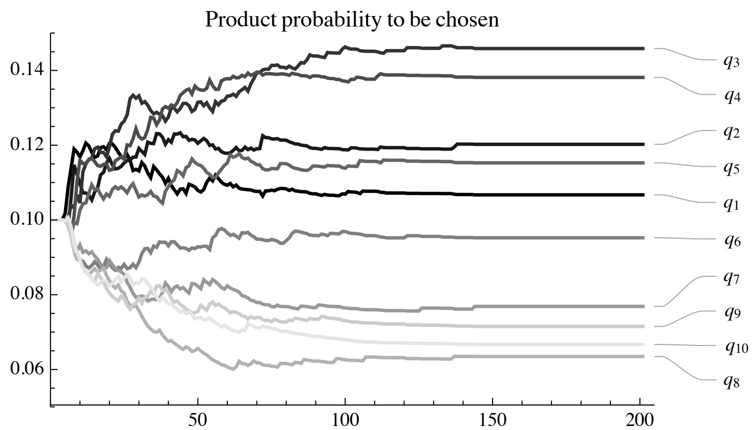

Figure 3: Product probability to be chosen, Ω_q

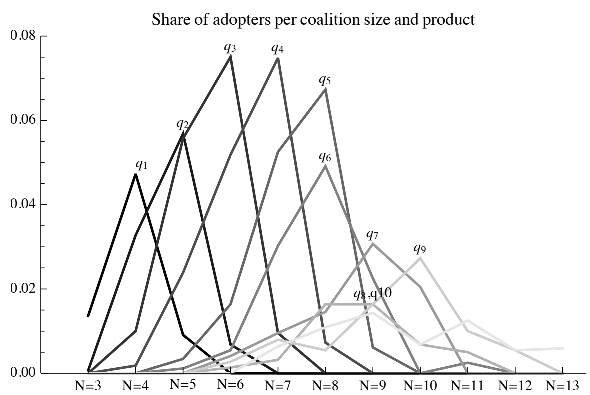

Figure 4: Share of agents in coalition, for each product adopted

in different coalitions to buy specific products. Larger coalitions are established to adopt goods with higher investment cost and higher capacity, whereas smaller coalition are formed to purchase smaller goods. However, depending on the product purchased, some coalitions are more likely to be formed compared to others. For small investments, one type of coalition (small) is markedly more frequent than others. The variability of coalition size increases with I and S, meaning that larger goods are purchased by more heterogeneous types of coalitions (in terms of size).

We then put forward the following propositions.

Proposition 1: *The investment costs (I) and capacity (S) of the shared goods* *adopted in coalition increase with the coalition size.*

Proposition 2: *Coalitions tend to be of homogeneous size (small) when purchasing common goods with low I and S. The heterogeneity of coalition size increases with I and S.*

Figure 5 plots the average number of options evaluated before establishing a coalition and the coalition size: we find a positive significant correlation (r=+0.939, p<0.001).[9] Beside the timing (smaller coalitions are evaluated early in time, when few individuals are *active*), this result suggests that, when agents have the opportunity to choose between smaller and larger coalitions, they opt for the latter; and for larger shared goods with higher I and S (proposition 1).[10]

Proposition 3: *Agents prefer larger coalitions, with larger investments and lowers unit cost, despite they take longer to form.*

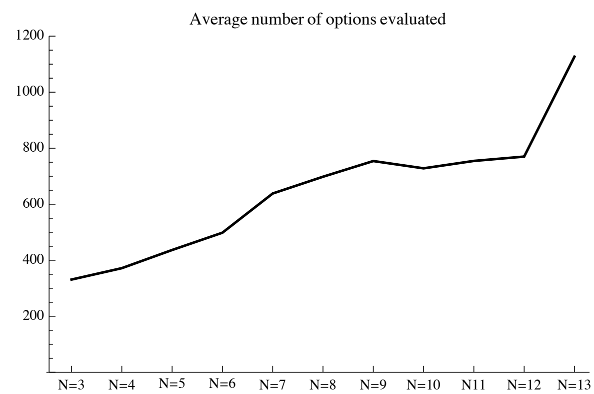

Figure 5: Average number of options evaluated by agents before establishing a coalition

Average contribution to coalition

In the model, agents commit to the common investment a monetary contribution (x_i) that maximises their utility (U_{i2}), and may vary with respect to preferred size

[9] r is the Pearson correlation coefficient and p is the p-value.

[10] This result may support criticisms of Olson's theories of small groups, suggesting that also large groups may favour collective action (Hardin, 1982; Oliver and Marwell, 1988), as in the case of shared goods.

of coalition and shared good. Figure 6 plots the individual average contribution by coalition's size and, within each coalition, by good's size. We shows that, the larger the coalition, the lower the average agent monetary contribution, regardless the level of the investment cost: N and x_i are negatively correlated (r =-0.985, p=0.011). Whereas, for a specific coalition size, the larger the investment cost (and the lower the cost of the service supplied) the higher the average agent individual contribution: I (or S) and x_i are positively correlated (r=0.997, p=0.001). This result conforms with the theory of sharing groups showing that the more the people in coalition, the less the individual costs; further, the larger the quantity purchased in group, the higher the individual cost (Lindenberg, 1982).

Proposition 4: *Average agent's contribution to the shared investment (x_i) decreases with coalition size (N) and increases with the size of the investment (I and S).*

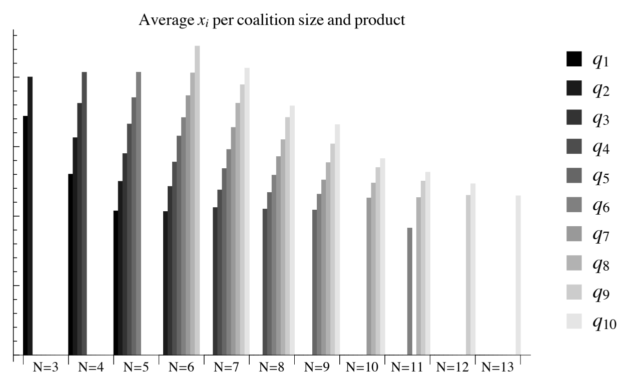

Figure 6: Average agents' contribution in coalition per size and product

Free riding

In large coalitions individual behaviour is non-influential for the whole group: as group size grows, the individual contribution becomes less relevant. This may give raise to free-riding, and explain the tensions in large groups between cooperation and free-riding (Canning, 1995; Glance et al., 1997; Huberman and Glance, 1996; Shehory and Kraus, 1998; Axtell, 2000). In our model we find that this relation is confirmed only partially. Figure 7 plots the share of free riders by coalition size.[11]

[11]Free-riders are coalition members that do not contribute to the common investment (x_i=0), but pay the unit consumption costs (c_{i2}>0).

The aveage share of free-riders in coalitions increases with coalition size up to a point (N=8), to decrease again. This is explained by the fact that large coalitions purchase, on avearge, large and expensive common goods which require commitment of all memebrs: therefore, in agreement with Gächter and Fehr (1999), social approval in collective action reduces the opportunity to have a free-riding attitude.

Proposition 5: *The relation between free-riding and coalition size follows an inverted V shape.*

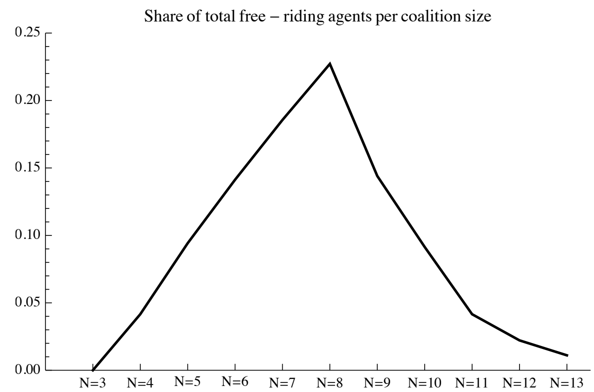

Figure 7: Free-riding agents

4.3 Network analysis

Coalition formation and collective adoption occur in a network of agents whose structure evolves over time. In this section, therefore, we study how adoption and network structure co-evolve, as part of the coalition formation process.

The co-evolution between coalition formation and diffusion

In each time step t, neighbours of agent i can take one of the following alternative status: linked (f_{it}) – can be part of the coalition, not linked (g_{it}) – cannot be part of the coalition, or in coalition (h_{it}). With the current initialisation (see table 1): $l_{it}{=}\sum f_{it}{+}\sum g_{it}{+}\sum h_{it}{=}8$. If w_t is the total number of *active* agents at time t, it is possible to calculate the share of linked neighbours by *active* agent (L_t, Eq.11) and the share of linked and not linked neighbours in the total population (V_t, Eq.12) as follows:

$$L_t = \frac{\sum_{i=1}^{w_t} \frac{\sum f_{it}}{l_{it}}}{w_t} \tag{11}$$

$$V_t = \frac{\sum_{i=1}^{w_t} \frac{\sum f_{it}+\sum g_{it}}{l_{it}}}{P} \tag{12}$$

L_t can be interpreted as the share of potential members (among those already informed) and V_t as the share of agents that could be potentially involved in the process of coalition formation (in the whole population). Figure 8 plots both series over time.

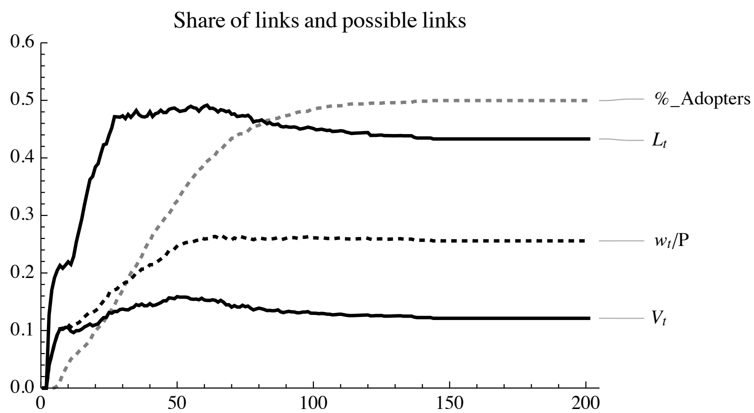

Figure 8: Co-evolution: links, network, coalition and adoption

At the very beginning of the simulation, the share of linked agents (series L_t) and the share of agents that potentially can enter in coalition (series V_t) increase rapidly. When the first coalitions are established, both series stop to grow because the number of *active* agents stabilises (series w_t/P). This is because adopters are no more available for further coalitions, since they break links with neighbours, reducing communication between remaining agents. As soon as information starts to flow again (when the share of *active* agents increases again), the two series start to rise again but with a different slope. L_t grows faster than V_t because while the number of new links (f_{it}) increases (Eq.11), the increasing share of agents in coalition (series %_Adopters) reduces the number of neighbours that could be part of new coalitions ($\sum f_{it}$+$\sum g_{it}$=l_{it}-$\sum h_{it}$ in Eq.12). Both curves reach their maximum when the share of remaining *active* agents (w_t/P) becomes stable, and eventually decrease until a stable state. We can explain this better looking at the actual networks.

Figure 9 plots the network configuration of agents (left) and the network structure of all established coalitions (right) at the end of one simulation run.[12]

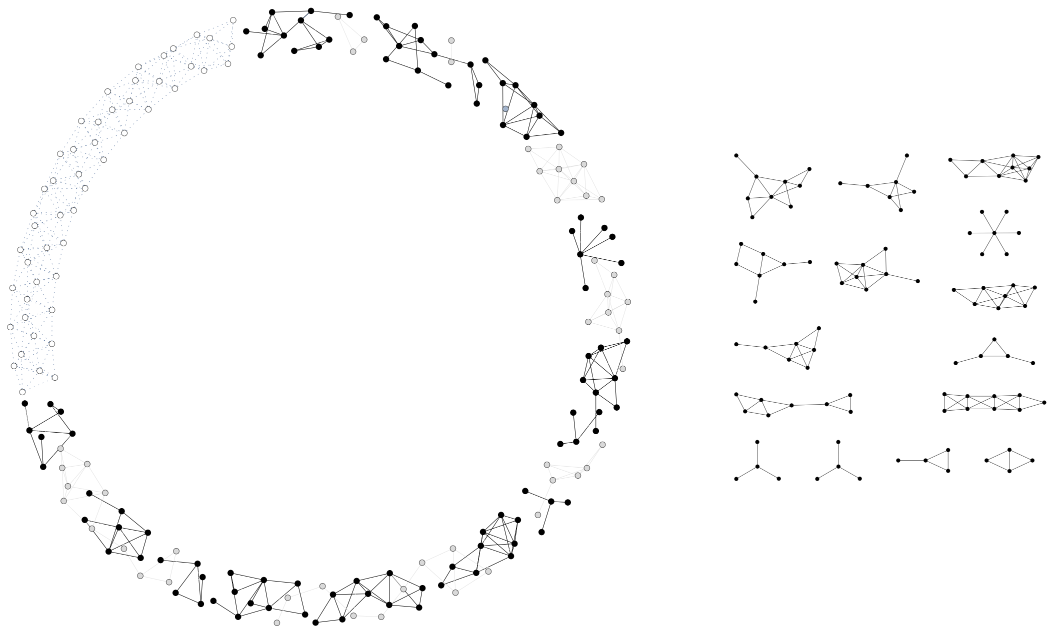

Figure 9: Final configuration: network (left) and coalitions (right)

Black nodes and edges represent connected agents belonging to a coalition that has adopted a shared good (h_{it}). Grey nodes and edges are agents that have been informed and that have participated to the coalition formation process but remained singletons (f_{it}). White nodes connected with dotted edges are neither *initiators* nor *active* (g_{it}), and could not participated in any process of coalition formation. The top-left part of the final network configuration in Figure 9 shows a substantial number of agents that have not been informed during the simulation run, clustered in the same area. Part of the relative low rate of adoption is then explained by a slow information flow.

[12]Because it is not possible to plot an average network configuration over the 40 simulation runs, for illustrative purposes we plot results from a single simulation, representative in terms of average numbers of adopters.

However, there is also a substantial number of singletons, *active*, between established coalitions, with no connections to other individuals. As adopters break their links with neighbours, once they coalesce and adopt, some singletons who did not agree to enter any coalition, are left behind. Figure 10 shows a section of the network in which three agents (69, 71 and 73) are not involved in any of the closest coalitions (64-65-67-68, 59-60-61-62-63-66-70 and the one including agents 73, 74, 75 and others). Since adopters are out of the game, these three isolated agents cannot enlarge further their social contacts and a coalition among them does not improve their utility. This reduces diffusion.

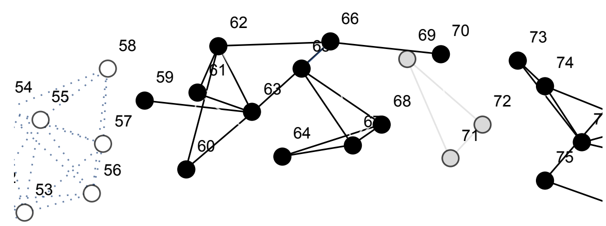

Figure 10: Isolated agents and established coalitions

Proposition 6: *Although coalition formation is necessary for the adoption of shared goods, it may also reduce future coalitions and adoption by reducing the number of available links among remaining agents. Coalition formation and diffusion are co-evolving processes.*

Network properties of coalitions

Figure 11 plots the relation between network metrics (density, radius and diameter, and centrality) and coalition size.

Network radius and diameter (first panel) define the size of networks (the distance between the two most distant nodes). Both measures are not surprisingly positively correlated to N (diameter: r=+0.972, p<0.001; radius: r=+0.968, p=0.009), suggesting that the minimum and maximum absolute shortest paths (or eccentricity) in coalitions increases with size.

Network density (second panel) is the ratio between the number of links over the

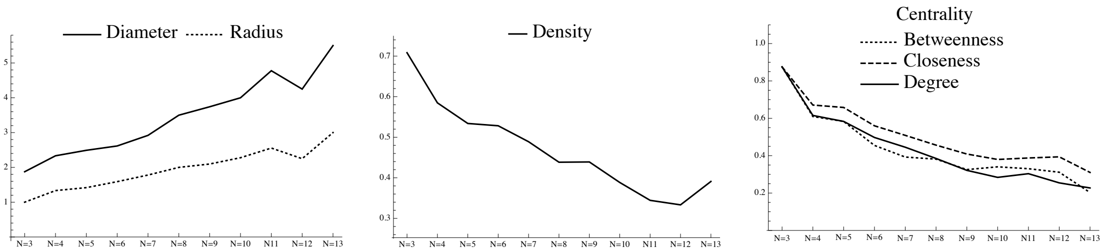

Figure 11: Network metrics

total possible number of links among agents in a coalition.[13] The negative correlation (r=-0.933, p<0.001) suggests that smaller coalitions are more cohesive than large ones, leaving out a lower number of isolated potential users.

The connectivity within coalitions can be measured with network centrality (third panel). The level of connections between agents is inversely proportional to N. This indicates that in larger coalitions the number of links that agents have with others (Degree: r=-0.935, p<0.001), the extent to which agents serve as bridge between other coalition members (Betweenness: r=-0.901, p<0.001), and agents' degree of being connected to all other agents (Closeness: r=-0.934, p<0.001) decrease.

Proposition 7: *Smaller coalitions formed to buy shared goods are more cohesive than bigger ones, and agents' connectivity and centrality is higher.*

4.4 The Role of Geography

The relation between the network structure and coalition formation suggests that the size of the neighbourhood is likely to influence the processes of coalition formation and the diffusion of shared goods. To examine its role, we run the model with different initialisations of parameter l (between 4-14), the number of closest neighbours that an agent can form links with. Figure 12 shows the relation between adoption rates, the % of active agents, and different values of l.

We find a positive and linear relation between the share of adopters and of *active* agents (r=+0.998, p<0.001), and between these two shares and l, and the diffusion of common goods (in brackets) and l (*active* agents: r=+0.971, p=0.001; adopters: r=+0.977, p<0.001; diffusion: r=+0.950, p=0.003). That is, when the good can be

[13] A proxy of structural cohesion (Friedkin, 1981).

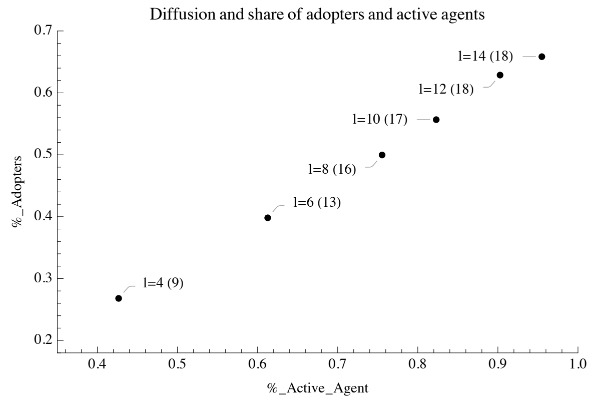

Figure 12: Diffusion, in brackets, and share of adopters and active agents per different values of l

shared between users located at a larger distance, agents have more opportunities to build contacts, form larger coalitions (Figure 13), and increase adoption, than when they can form coalitions with the immediate neighbours.

Figure 13 plots the distribution of coalition size for varying values of l. We find that increasing the number of closest neighbours leads to larger coalitions. The higher the value of l the higher the average number of adopters, and the higher the number of larger coalitions.

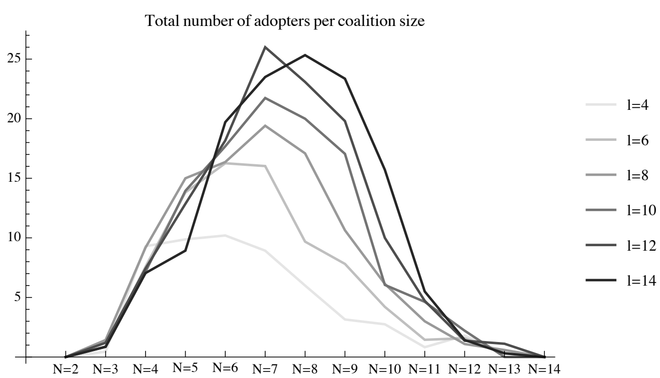

Figure 13: Total number of adopters per coalition size and different values of l

Coalition size is also related to the size of the investment. Figure 14 plots the distribution of shares of adopters per product (where q_1 is a good with low investment cost and high service unit cost, and q_{10} is a good with high investment cost and low service unit cost). For low values of l, on average, coalitions decide to buy common goods that have low investment costs and service supplied. Along with the increase of agents neighbourhood, the share of goods with higher level of I and S increases.

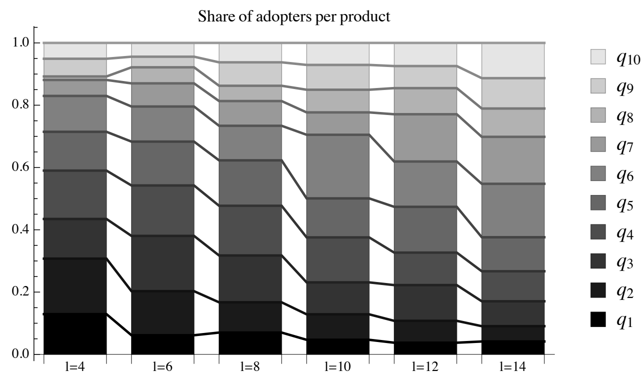

Figure 14: Share of adopters per product and different values of l

Proposition 8: *As the size of the neighbourhood that can share a good increases (the service provided is less tied to the location), information about the shared good flows more rapidly, adoption increases, and established coalitions are, on average, larger, and they buy goods with higher I and S.*

4.5 The Role of Initiators

So far we have investigated a system with few *initiator* agents (m=4, as suggested by the literature). What happens if all agents in the economy are aware of the shared good? In this section, we compare results with the case of all agents being *initiators* (m=200): all agents are connected to their closest neighbours (l=8). This initialisation allows to study diffusion in a complete network. At t=0, agents already know their utility in all possible groups.

Figure 15 compare the share of adopters resulting from the baseline (m=4) and the complete network scenario (m=200). In complete networks, adoption occurs very rapidly and the rate of adoption is higher: after few time steps, the share of adopters reaches its steady state, which is higher than the baseline scenario. This indicates that the absence of communication, which instead occurs simultaneously with the network formation process in the baseline scenario, speeds up the diffusion of shared goods (and is necessary to obtain the S shaped diffusion curve). However, although all agents are informed and connected, differently from many earlier studies, diffusion does not reach 100%. In the case of the complete network, this is because some agents prefer to purchase the service from the central provider, either due to a higher utility or because these remain isolated (Proposition 6).

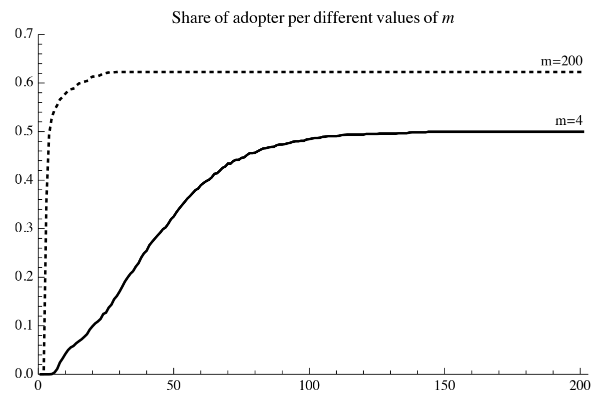

Figure 15: Share of adopter for different values of m

Figure 16 plots the distribution of adopted goods by size. In the complete network, the majority of the coalitions buy the largest product, with the highest value of both I and S (q_{10}). Figure 17 plots the share of adopters per coalition size. Moving from incomplete (m=4) to complete network (m=200) the average size increases. When possible, agents decide to establish larger coalitions (Proposition 3) despite the high level of negotiation and alternative options. Large groups purchase shared goods with higher investment cost, and providing higher quantity of the demanded service (Proposition 1) at a lower cost. In these large groups, in agreement with Proposition 4, agents minimise their individual contribution x_i.

Proposition 9: *In a population of fully informed and linked agents, the share of adopters is higher than in a population where information and connections build as an outcome of diffusion.*

5 Implications for the Diffusion of Sustainable Goods

The literature on the diffusion of sustainable energy has focused on adoption as an individual decision. Hence, it studies mainly small-sized goods which are affordable to the average consumer, such as water-saving technologies (Schwarz and Ernst,

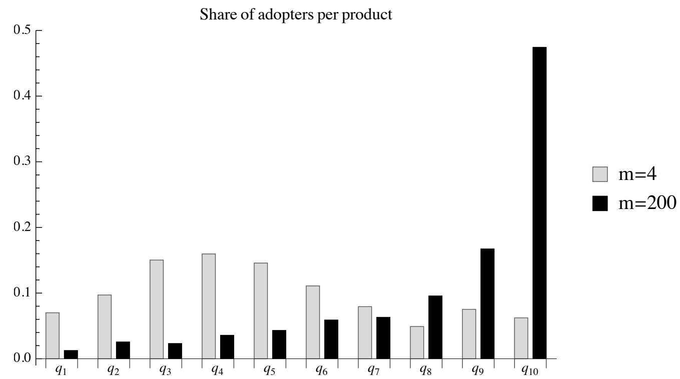

Figure 16: Share of adopters per product and different values of m

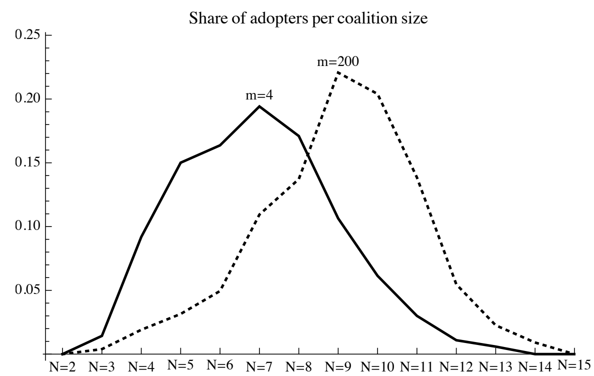

Figure 17: Share of adopters per coalition size and different values of m

2009), micro-cogeneration (Faber et al., 2010), or solar PV panels (Murakami, 2014). Some of these studies examine the role of social interactions and diffusion through networks (Tran, 2012; Bale et al., 2014) and find that networks directly and indirectly influence the individual choices and preferences regarding sustainable goods (Choi et al., 2010; Bollinger and Gillingham, 2012) and might accelerate the diffusion of sustainable energy innovations.

However, to study the diffusion of large-sized sustainable goods, such as smart micro grids, it is necessary to consider adoption as a collective decision. The analysis presented in this paper is suitable to study different cases where a group of individuals may choose to buy a good which is too expensive for a single, such as large-sized decentralised energy systems (DES). DES are too expensive for individual households, but can be purchased by group of neighbours. DES are considered to be indivisible, capital-intensive good with high fixed costs; DES may be beneficial only to users that are connected to it and that share its use; consequently, diffusion of DES is as a case of technology adoption that takes place through collective action; adoption and diffusion of DES requires to first study how such coalitions are formed.

There is still an open discussion about which technologies should be considered as DES. Ackermann et al. (2001) propose four categories, distinguishing distributed generation based on the power installed: these are micro, small, medium and large. The model presented in this paper, accordingly, studies agents who can choose among a set of goods available of different size. Overall, DES are considered to be small-scaled electric power sources and, since these are non-movable common goods, they have to be physically installed close to the end users directly connected to them (Hatziargyriou and Meliopoulos, 2002; IEA, 2002). Coherently, a more direct involvement of final users can widely boost diffusion of DES (Sauter and Watson, 2007). They can buy and use these systems independently, and experiencing economic benefits (Watson, 2004).[14] Therefore, as simulated in the present model, the adoption of DES can be seen as an emerging bottom-up process requiring a careful understanding of consumers' behaviour, features and preferences (Groh et al., 2014; Pasimeni, 2017).

Results discussed in section 4 can then provide useful policy advice regarding the diffusion of DES, where an adequate regulation is required (Lopes et al., 2007; Driesen and Katiraei, 2008; Marnay et al., 2008; Agrell et al., 2013). A large diffusion of DES might bring environmental benefits (Hadley and Van Dyke, 2005; Tsikalakis and Hatziargyriou, 2007; Akorede et al., 2010), reduction of transmission losses (Chiradeja and Ramakumar, 2004; Pepermans et al., 2005) and enhancing energy security (Asmus, 2001; Battaglini et al., 2009). As suggested by our model, to facilitate the transition towards a more decentralised energy system, the first requirement is to increase awareness. DES might diffuse more if consumers were sufficiently connected, and DES were able to provide services at higher distance (higher clustering in the neighbourhoods). Under these conditions, large-sized DES (for example those between 50MW and 300MW, as defined in Ackermann et al., 2001) may have a larger probability to be adopted than smaller systems, and, at the same time, consumers might spend less for their energy consumption.

In conclusion the study on diffusion of common goods in consumers coalitions applied to the case of DES permits to analyse what are the factors that can facilitate the direct involvement of final users into the necessary shift towards a less centralised energy system. The importance of consumers' empowering in this transition process

[14] Adoption of DES can also be improved by private and public investments. However, since the focus of this paper in on consumers' coalitions aiming at purchasing (independently) and sharing a common property, these aspects are not considered in the model.

has been recognised by both the scientific community (Hyysalo et al., 2016; Schot et al., 2016) and public organisations (European Commission, 2015a,b). The European Commission clearly endorses this necessity, as communicated in the Energy Union Strategy:

> "To reach our goal, we have to move away from an economy driven by fossil fuels, an economy where energy is based on a centralised, supply-side approach and which relies on old technologies and outdated business models. We have to empower consumers through providing them with information, choice and through creating flexibility to manage demand as well as supply" (European Commission, 2015c, p. 2).

6 Conclusion

This paper has presented and discussed a model developed to study the co-evolution of diffusion of expensive shared goods and the formation of the coalitions required to adopt them. Differently from earlier studies on diffusion, our model considers the adoption decision as a collective action, taken by a group of consumers. These groups are endogenous: consumers organise themselves following a bargaining process, as studied in game theory. Similarly, links between agents evolve over time endogenously by means of interpersonal contacts occurring in the social network. By combining different contributions from diffusion and game theory in one agent-based model, this paper aims at contributing to the discussion on the diffusion of shared goods, for which a collective adoption is required.

Results show that larger coalitions are preferred with respect to small ones, allowing the adoption of more expensive goods that satisfy a larger demand at a lower unit cost for the service provided. Adopters in large coalitions experience a greater cost reduction than in smaller coalitions. Coalition formation and diffusion both depend on spreading information about the good in a given population, which depends on the connectivity among individuals. In networks where the level of clastering is high, information flows rapidly and more people decide to join a coalition and to adopt a shared good. Coalition formation fosters diffusion but the latter reduces future coalition formation and adoption. Coalitions include only some of the neighbours and those who do not enter (because they do not benefit from those coalitions) remain isolated in the network. For this reason, and contrarily to common outcomes in the literature, adoption in coalition does not guarantee full diffusion, also in cases when information the is available to the whole population.

As discussed in section 5, the modelling exercise presented in this paper can be applied to sustainable energy technologies where the role of consumers' ownership is crucial, as for example in relation to investments regarding local energy infrastructures. For instance, the directive 2010/31/EU of the European Parliament provides guidelines towards the *nearly zero-energy building*. These are "building [with] very high energy performance" where the "energy required should be covered to a very significant extent by energy from renewable sources, including energy from renewable sources produced on-site or nearby" (European Parliament, 2010, p.18). The implementation of this directive, together with other propositions supporting direct energy production and consumption, may substantially benefit from our analysis. For instance, as emerges from this paper, when not all users are involved in the transition towards a more sustainable energy infrastructure, some may remain isolated, with a negative impact on social inclusion and on the energy transition itself.

The model may also be extended to study related dynamics, such as network and coalition formation in the international climate agreements (Barrett, 1994; Benchekroun and Claude, 2007; Tavoni et al., 2011; Balint et al., 2017). The model can be extended in different ways, such allowing the reintegration of agents in the game after a certain period after the adoption. Shared goods may be considered as mobile, allowing to study the fifth stages of the Innovation-Decision Process in Rogers' theory where confirmation of adoption implementation occurs once the product reaches its maturity phase. Another relevant modification concerns the possibility to have agents in different network structures, such as random networks or small word.

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Annex I

The utility function related to the shared option (U_{i2}, Eq.4) contains two parameters, α_i and β_i, allowing for the linear combination of three elements. The first, $\frac{d_i}{d_i+D_{-i}}$, is approximately the percentage of the total service, S, provided by the common good and consumed by agent i in coalition (see Eq.8). The second, similarly, $\frac{x_i}{x_i+X_{-i}}$, is approximately the percentage of the value I of the shared good, purchased by agent i in coalition through own monetary contribution x_i, (see Eq.7). The third, $\frac{1}{N}$ represents the equally shared percentage of the service based on the number of coalition members. Therefore, Eq.4 can be rewritten as follow:

$$U_{i2}(e_i; c_{i2}; d_i; D_{-i}; x_i; X_{-i}; N; \theta_{i2}; \alpha_i; \beta_i) = \\ (e_i - c_{i2})^{\theta_{i2}} \{\alpha_i d_i + x_i \frac{d_i + D_{-i}}{x_i + X_{-i}}(1-\alpha_i)\beta_i + \frac{d_i + D_{-i}}{N}(1-\alpha_i)(1-\beta_i)\}^{1-\theta_{i2}} \quad \text{(A1)}$$

Eq.A1 means that, neglecting the effect of α and β, agent's utility function in coalition, along with the money saved from individual income (first part of the equation), depends on the linear combination of (i) the individual demand of the service, (ii) the return of the common investment (total service produced, $d_i + D_{-i}$, divided by the total cost spent to purchase the common good, $x_i + X_{-i}$) multiplied the individual monetary contribution in that investment, and (iii) the total service produced by the common good equally divided to each of the coalition members.

Figure A1 shows how terms in the utility function, *cæeteris paribus*, influence agent's utility in coalition, their relative monetary contribution, and, most importantly, their relation.

High level of θ_i indicates that an agent has a higher preference to save money, while low level of θ_i indicates a higher preference to satisfy the demand for the service. When θ_i=1, the utility depends only on the income saved. In the opposite case, when θ_i=0, agent's utility depends only on consumption. When preference for income is high (high θ_{i2}) (and preference for consumption low), *cæteris paribus*, an agent in coalition maximises utility (U_{i2}) by reducing individual monetary contribution (x_i). When θ_{i2} has a lower value (hence, higher consumption preference), agents in coalition are willing to contribute more in order to maximise utility.

The relation is similar for d_i on x_i and U_{i2}. A higher demand raises also the cost (c_{i2}=$d_i p_2$), reducing the contribution that maximises utility. Instead, agents in coalition with higher income (e_i) are willing to contribute more, in comparison to those with lower income. This is because savings are higher when the income is higher, and utility increases even if contribution is higher, *cæteris paribus.*

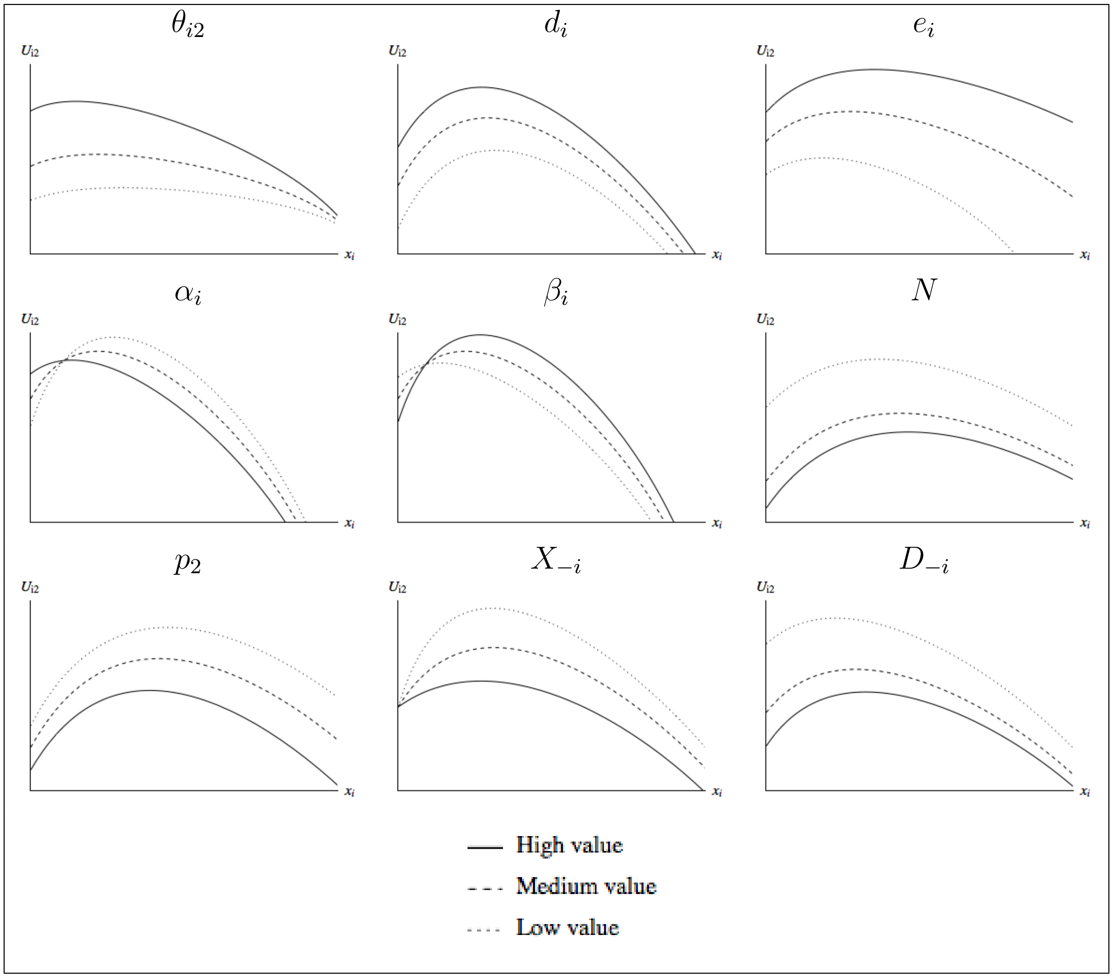

Figure A1: impact of model variables on x_i and U_{i2}

α_i and β_i influence individual utility and contribution in opposite ways. With higher (lower) value of α_i (β_i), utility reaches its maximum at a low levels of monetary contribution. This is because α_i measures the importance given by an individual to the proportional division rule based on consumption. The higher is α_i, the higher is the importance that the individual assigns using only part of the service provided by the common good. Therefore, when this share grows, utility decreases. Parameter α_i, therefore, captures the individualistic perception of the sharing attitude; an agent agrees to share the use with others, but, at the same time, is also reluctant to limit her own consumption. β_i instead measures the importance given by an individual to the proportional division rule based on contribution. Higher value indicates a preference for consuming a lower portion one's income while owning and using part of the common good. Higher β_i also signals that agents attach lower relevance to the number of coalition members. As a result, individuals with high β_i are willing to contribute more to the common purchase, having a higher interest in sharing the cost proportionally with others.

With respect to coalition size (N) individuals participating in smaller coalitions increase their utility by contributing more than in larger coalitions. The last three terms are also straightforward. The higher the price (p_2) of consuming the service in coalition, the lower the utility. The higher is the other members total contribution (X_{-i}), the lower is the individual contribution; the higher is the total demand (D_{-i}), the higher the individual contribution. These two latter characteristics, in combination with other factors in the utility function, might induce members to free-ride.

Annex II

In order to simplify the explanation of the coalition formation process and its co-evolving decisional process, an illustrative example is used. The initial parameters are set as in Table A1. For simplicity, it is assumed that *initiators* can only choose one product. Agents are heterogenous only in respect to their demand (d_i), while all the other parameters (e_i, θ_{i2}, θ_{i1}, α_i and β_i) are set equal to all agents. Because of this heterogeneity, agents acting as singleton have different costs and utilities for option 1 (Table A2).

p_1	10
p_2	5
θ_{i1}=θ_{i2}	0.5
e_i	1000
α_i	0.5
β_i	0.5
S	175
I	200

Table A1: Initial parameters

For graphic purposes, the example represents eight agents only, that are located in a regular lattice. Each of them has four spatially limited potential links in own neighbourhood. Figure A2 below shows an *initiator* agent in the population.

Agent	1	2	3	4
d_i	30	55	35	45
c_{i1}	300	550	350	450
U_{i1}	145	157	151	157

Table A2: Agents' parameters

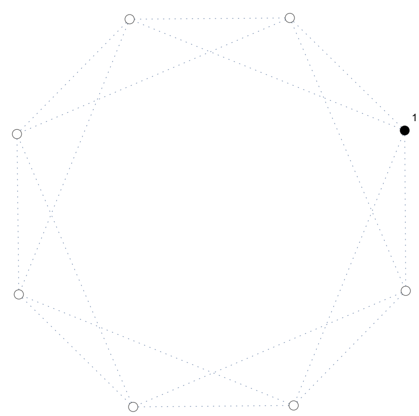

Figure A2: *Initiator* (in black) and the regular network structure

Every time step, the *initiator* ties a link with one of the available neighbours, which is not linked yet. The choice is done randomly among spatially limited links. Links formed are bidirectional. The contacted agent becomes *active* and informed of the opportunity to make the common investment. In this example, as shown in Figure A3, agent-1 contact agent-2 and they establish a link.

In this moment, agent-1 is the *initiator* while agent-2 is not. Both agents, as well as all the other agents in the population, satisfy their demand via the central provider that supplies the requested services. This status is defined as singleton and Eq.1 and Eq.3 calculate cost and utility of this option for each agent. Only the *initiator* (agent-1 in the example) can start the process of coalition formation.

Before doing so, a product is chosen and the relative joint purchase is proposed together with the proposal to form a coalition (in this example only one product is available). Once the product has been chosen, the process of coalition formation can start. The *initiator* contacts one of the linked agent. In the example in Figure A3, agent-1 contacts agent-2 and they evaluate the joint investment in coalition (Eq.2 and Eq.4). Once agent-1 and agent-2 have evaluated the opportunity to invest in

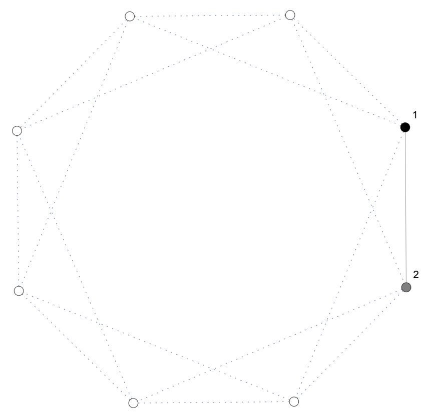

Figure A3: Step 1: *initiator* ties link with agent-2

coalition, they make a conditional decision among the option to invest in coalition or to remain as singleton. The option that makes an agent better off is stored as optimal. When all coalitions have been evaluated (in the example only coalition (1-2) is available to these two agents), all agents announce their optimal conditional decision.

Now, assuming that the coalition (1-2) is not established because it does not satisfy all the stability conditions, the two agents can contact more neighbours and tie more links, thereby improving and enlarging their network. This activity can be performed only by *initiators*. Nevertheless, at the start of the new time step, all *active* agents check, through Eq.5, if their level of awareness is enough to become *initiators*. Let's assume that also agent-2 becomes *initiator*. In the current situation, therefore, both agents can contact one more neighbour each (Action 1), choose a product (Action 2), and start the process of coalition formation (Action 3). As shown in Figure A4, while agent-1 contacts and forms a bidirectional link with agent-3, agent-2 does the same with agent-4. After that the two *initiators* choose the product they want to buy jointly with others, they start the process of coalition formation as explained before.

The coalition formation starts from *initiators*. First agent-1 and later agent-2 begin this process by contacting one linked neighbour. They firstly evaluate coalition size 2 and then, depending on the available links, evaluate bigger coalitions. In this case, the full coalition, size 4, is the largest they can form. Table A3 below summarises all possible coalitions that can be formed and can be evaluated in this network of agents. There are three coalitions size 2 (1-2, 1-3 and 2-4), two coalitions

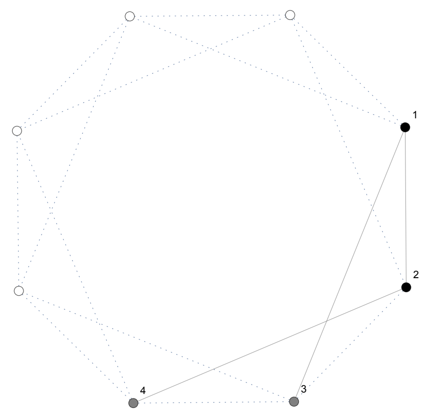

Figure A4: Step 2: *Initiators* tie one link each

size 3 (1-2-3 and 1-2-4) and one coalition size 4 (1-2-3-4).

		Agent									Agent				
Coalition		1	2	3	4	$\sum x_i \geq I$		$\sum d_i \leq S$			1	2	3	4	
1-2	x_i	101	72			173	x	85	✓	stop					
1-3	x_i	97		89		186	x	65	✓	stop					
2-4	x_i		78		88	166	x	65	✓	stop					
1-2-3	x_i	138	76	127		341	✓	120	✓	continue					decision
	c_{i2}	288	351	302						$c_{i2} < c_{i1}$	✓	✓	✓		
	U_{i2}	163	169	164						$U_{i2} > U_{i1}$	✓	✓	✓		
1-2-4	x_i	142	84		108	334	✓	130	✓	continue					decision
	c_{i2}	292	359		333					$c_{i2} < c_{i1}$	✓	✓		✓	
	U_{i2}	167	173		171					$U_{i2} > U_{i1}$	✓	✓		✓	
1-2-3-4	x_i	161	81	145	113	500	✓	165	✓	continue					stop
	c_{i2}	311	365	320	338					$c_{i2} < c_{i1}$	x	✓	✓	✓	
	U_{i2}	163	169	164	167					$U_{i2} > U_{i1}$	✓	✓	✓	✓	

Table A3: Coalitions evaluated

The three coalitions size 2 do not satisfy condition in Eq.7, that is the total monetary contribution added up by the participants is not enough to cover the investment cost. Consequently, these three coalitions are not feasible and they do not provide any optimal conditional decision for the agents involved. Agents stop evaluating these coalitions. Then, agents evaluate the two coalitions size 3. These satisfy both conditions in Eq.7 and Eq.8, so agents continue the evaluation process and consider their individual cost and utility in coalition (Eq.9 and Eq.10). All agents are better off in these two groups, therefore, the two coalitions size 3 are subject to further negotiation in the final decisional step. In the option of the full coalition, size

4, even if it satisfies both initial conditions, agent-1 does not experience improvement compared to the singleton option (cost in coalition is higher). Therefore, agent-1 does not agree to form this coalition, which implies that this is not a feasible solution. Consequently, the full coalition is not further considered by agents.

The four agents involved in the final decisional step have their own optimal conditional decision. Agent-1 and agent-2 want to establish coalition (1-2-4) since their utility is higher than in coalition (1-2-3). On the one hand, agent-3 has coalition (1-2-3) as the only available option to improve individual utility. Agent-4, on the other hand, has coalition (1-2-4) as the only available option to improve individual utility. Based on these considerations that agents make explicit, coalition (1-2-4) is established. This implies that these three agents have coordinated their efforts, agreed on the monetary contribution and that they jointly purchase the common good. Coalition is established, and it means that coalition members are out of the game, making agent-3 isolated in the network. Figure A5 shows how network in Figure A4 evolves after adoption. The three agents in the established coalition (1-2-4) break the existing links, those already formed (e.g. link 1-3) and those potentially available in their neighbourhood (e.g. links 2-3, 3-4, etc.). Agent-3, then, remains isolated. Nevertheless, being *active* agent, in the next time steps agent-3 will check whether or not could become *initiator* (Eq.5). If so, agent-3 can continue the process with the remaining agents in the population.

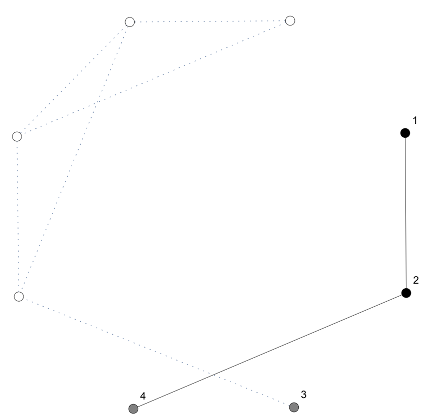

Figure A5: Step 3: coalition established and agent-3 isolated

Annex III

Figure A6 shows a cumulative adoption curve where uncertainties are added at the beginning of the simulation. For the initial times steps, utility in coalition is slightly reduced by means of a coefficient representing a lower utility for early adopters. This produces a lower degree of cumulative adoption in the first stages of the process compared to the case without uncertainties (dotted line, equal to that in Figure 2. However, a slower adoption implies that contacts among agents increase, since more agents are in the game. And, as explained in both sections 4.4 and 4.5, more communication implies higher adoption, as indicated by the higher final share in figure below.

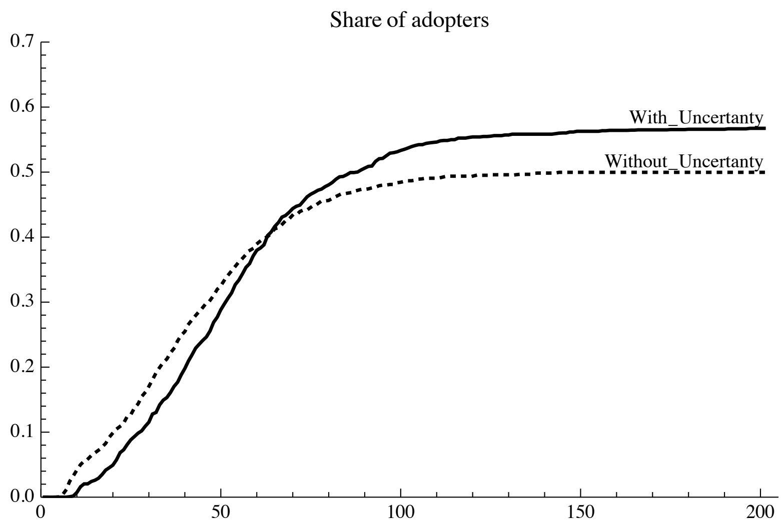

Figure A6: S-shaped diffusion curve