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Diffusion of Shared Goods in Consumer Coalitions. An Agent-Based Model*

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Abstract

This paper focuses on the process of coalition formation conditioning the common decision to adopt a shared good, which cannot be afforded by an average single consumer and whose use cannot be exhausted by any single consumer. An agent based model is developed to study the interplay between these two processes: coalition formation and diffusion of shared goods. Coalition formation is modelled in an evolutionary game theoretic setting, while adoption uses elements from both 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 and have an impact on the information flow though the population of consumers. Large coalitions are preferred over small ones since 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: D16, D71, E27, O33

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1 Introduction

Diffusion is often studied as a consequence of the individual process of adoption decision, overlooking cases where the decision is taken collectively (Rogers, 1962). Individual adoption implies individual consumption, neglecting cases of collective consumption. Similarly, group consumption (Borcherding and Filson, 2002) and collective action are often studied in isolation (Olson, 1971; Hardin, 1982; Oliver, 1993) with no focus on the prior step of group formation, which, in turn, is mainly examined in the game theory context (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.

Large irrigation systems adopted by groups of farmers (Bardhan, 1993b,a, 2000) is an example of expensive goods that are purchased by a coalition of people that has coordinated themselves beforehand. These goods are common pool resources (CPR) and can be classified as non-excludable and rival (Bowles, 2004). For them *local interactions* among users guarantee a more efficient way of governance compared to both *privatisation* or *external regulation* approaches (Ouchi, 1980; Ostrom, 1990; Ostrom et al., 1994). 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. In this perspective, policies aiming at boosting diffusion of large-sized sustainable goods, requiring a direct involvement of final users, need to consider adoption as a collective decision. And, by studying the processes and dynamics that favourite formation of consumption groups, it is possible to implement instruments to empower citizens whose role is crucial in the transition towards a more sustainable economy.

Group adoption and diffusion of expensive common goods are gaining relevance also in the transportation sector. The automotive industry has started to consider shared ownership as an alternative to the individual car ownership and major manufacturers have already tried to implement fractional ownership programs. This approach is driven by a rapid change in people attitudes (Prieto et al., 2017; de Luca and Di Pace, 2015) and in policy regulations. Cars are becoming expensive goods for many, and the problem of prohibitive prices will be more acute with the introduction into the market of autonomous or driverless vehicles. For these reasons, the promotion of group formation as preliminary step of group adoption may open window of opportunities for shared ownership of next-generation vehicles (Masoud and Jayakrishnan, 2016). Therefore, the process of coalition formation may modify the standard views on the diffusion of new practices and technologies.

This paper develops 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. The model simulates the process of coalition formation that co-evolves with diffusion, which results from the collective decision to adopt an expensive shared good. Coalition formation is modelled in an evolutionary game theoretic setting (Axtell, 1999, 2002), while adoption uses elements from both the Bass and the threshold models. In the agent-based 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. Collective adoption is feasible only when a coalition is stable. Social interactions and individual characteristics play an important role in the bargaining process to form the coalition (Oliver and Myers, 2003). Negotiation is necessary in order to find an agreement before the common investment. The agreement is not only cost-based but it also takes into account aspects of shared ownership and shared consumption. Therefore, the decision to adopt in coalition is related to the overall utility deriving by sharing the common property in its utilisation and ownership. When adopted, the shared good guarantees a more economic and efficient service compared to the existing supply, thereby fostering its diffusion.

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. Diffusion of shared goods crucially depends on the speed at which networks form and information circulates, and on the composition of individual geography. 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.

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

2 The Literature: Diffusion and Coalition Formation

The modelling strategy in this paper builds on two rich literatures: diffusion of innovation (especially in networks) and coalition formation. This section briefly discusses each in turn.

Diffusion of innovation in networks

Innovation diffusion theory often deals with individual adoption decision. It regards the decision-making process in which a potential adopter defines his/her choice throughout time, by gradually increasing awareness of adopting. The role of *initiators* or *early knowers* is pivotal in the diffusion process (Rogers, 1962) since they create the initial *critical mass* (Gersho and Mitra, 1975). Over time, social interactions become important for diffusion, facilitating *imitation effect* (Bass, 1969) and *fashion effect* (Smallwood and Conlisk, 1979; Arthur, 1989). *Later 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 impacts *later adopters* (Abrahamson and Rosenkopf, 1993, 1997). Hence, diffusion process is related to the influence of the social network on potential adopters (Burt, 1987).

To examine the role of social networks, diffusion is also 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 is shown to depend on the network structure (Delre et al., 2010; Peres, 2014), and three structures are often studied. The regular network (or lattice strucutre) 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, as developed by 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 diffusion 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.

The agent-based model developed in this paper is built upon notions from this literature. It uses elements from the Bass and other threshold models, in which the role of *initiators* is central. People awareness is simulated in the model by taking into account both the *bandwagon effect* and interpersonal relations needed to communicate and spread information. The social network is also considered: agents are nodes of a network whose structure is not fixed, but evolves throughout time allowing for the formation of new links spatially bounded. 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).

However, the model in this paper 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).

Coalition formation

Coalition formation has been mainly studied in game theory. Studies on coalitions in triad (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. Negotiation is influenced by the initial distribution of resources and coalition members aim at forming coalitions that guarantee stability. Smaller coalitions are most likely to be formed compared lager coalitions since the probability to reach common agreement 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. In these models the individual payoff depends on own and other members' characteristics and efforts. As a result, members tend to form coalitions that maximise the common utility. *Hedonic coalitions* 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).

The agent-based model presented in this paper embeds features emerging from this literature. It considers the use of individual resources in a common effort and the bargaining mechanism among agents. It also evaluates the impact of the number of players involved in the process and how collaboration and coordination among players takes place. However, whereas game theory helps to understand how rational agents behave when they interact to form a coalition and which features maximise social and individual welfare, organisational transformation are driven by heterogeneous agents and bounded rationality (Simon, 1991; Windrum et al., 2009). Accordingly, evolutionary game theory makes it possible to relax the common assumptions of homogeneity and rationality and to focus more on the agents' behaviour which might bring to stable equilibrium in the whole system. The model in this paper 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.

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. They introduces 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. While Bloch (1995, 1996) assumes a fixed sharing rule of the surplus among agents, Mutuswami and Winter (2002) analyse the formation game with exogenous payoff determination.

The model in this paper allow for singletons, but it differs from previous literature since acting as singleton or joining a coalition are two alternative options to receive a service and to gain some benefit. In the model, agents involved in the bargaining process communicate their demand for the service and the monetary contribution they are willing to commit into the common investment, similar to Axtell (2002). 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 consumption preferences, such as the "preference for income" as proposed by Axtell (1999, p. 9; 2002, p. 1083). Agent's utility in coalition is 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 changes over time.

In this paper the interest is not on how the outcome or surplus is distributed among agents in coalition, as in Bloch (1995, 1996) and Mutuswami and Winter (2002). Contrarily, the focus is on what condition guarantees higher utility to agents, that decide to invest a portion of their income into the common good. Utility, therefore, is not deriving from the division of an outcome or a surplus, but it regards the use in coalition of a good purchased commonly. To do so, the model adapts the utility function proposed by Axtell (2002) where a parameter allows for the combination of both the equal share and proportional division rule of the coalition payoff, which is endogenously determined. This utility function is further developed in this paper, by considering the proportional use of the good.

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.

In conclusion, 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.

3 The Model

The model in brief

The model studies a population of heterogeneous agents that, at the beginning of the simulation, act as singletons and they satisfy their demand for a service through a general provider. However, some agents may have interest to purchase a common good, whose cost is larger than anyone's income, but it can provide the same service as an alternative to the supply of the general provider. This second option requires to form a coalition of consumers. Agents are self-interested and the spontaneous process of coalition formation is driven by the individual interest in reaching a better individual utility and a cost reduction compared to the first option. In the latter, regarding singletons with the general provider, both the cost and the utility are fixed and only depend on individual characteristics. While agents' cost and utility in the second option depend not only on individual characteristics but also on those of the other coalition's members and on characteristics of the coalition itself, such as its size. Driven by their interests, agents interact, attempt to form coalitions and compare the different formations. Agents adjust behaviour in relation to the interactions taking place during the process of coalition formation and their decision is also influenced by external events occurring in the whole population, such as changes in the social network. Agents decides to establish a coalition when it is stable and their individual utility is higher and individual cost is lower compared to the case of acting as singleton. Under these conditions, agents in coalition decide to purchase the common good jointly and to share its utilisation, increasing the rate of diffusion. The adoption decision is then maintained until the end of the simulation, conditioning subsequent coalition formation processes since adoption of the shared good modifies the network structure.

Agents' categorisation

At the outset of the simulation, agents are node of a regular network. They have a maximum of l neighbours with whom they can tie and form a link. Neighbours are spatially limited and they must be within one step from the originating node, because the shared good provides a localised service. In fact, it is assumed that the shared good is non-movable and, once purchased in coalition, it has to be installed in a specific location.

The model distinguishes between regular, *active*, and *initiator* agents. The sequential game of coalition formation starts with m random chosen agents. They are *initiators* and symbolise *innovators* or *early knower* needed for the take off of the diffusion process (Rogers, 1962). In the model, *initiators* have a real interest in purchasing the common good, and this strong motivation gives them three major roles in the game. Action 1: they can contact neighbours and form new links in order to enlarge the network of agents to be involved in the coalition formation process. Action 2: among a set of goods available in the market, they decide which one they want to purchase collectively, and propose this investment to others. Action 3: they start the process of coalition formation, which consist on exploring the possibility to make the investment in cooperation with others.

An *initiator* is always *active*, while the inverse relation is not always valid. A regular agent becomes *active* when s/he is contacted by an *initiator* through Action

1 and a bidirectional link is formed between the two. By means of this interaction information flows among agents and new agents become aware of the opportunity to make the common investment and to replace the centralised service provider. When *active* agents become *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 value is lower than the *visibility* (W_t):

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

where Adv is the level of advertising, exogenously defined, as in the Bass model; $ShareInCoalition_{t-1}$ is the share of agents that have already established 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 are diffused in coalition, *visibility* increases, and more agents may become *initiators*, increasing the likelihood that agents are involved in coalition formation and adoption. However, agents who already belong to coalitions, having switched to the common good, cannot participate in further coalition formation processes, thereby reducing the number of *initiators* and the likelihood that new agents are contacted. For this reason, coalition formation and diffusion are studied as two co-evolving processes.

Process of coalition formation

Agents (i) are heterogeneous in respect to their demand for the service (d_i), income (e_i) and preference for income (θ_i). They are also heterogeneous in respect to their preference towards shared consumption (α_i) and shared contribution (β_i), occurring in coalition. At the beginning of the simulation all agents purchase the service form a general provider at a cost (c_{i1} in Eq.2) which is function of their demand and of the unitary price for the service (p_1). This individualistic consumption option produces an utility to agents which has a Cobb-Douglas structure and is written as in Eq.3. The utility as singleton reduces with the cost (c_{i1}), relative to income, and increases with consumption (d_i). The relative importance of each factor depends on agent's preference (θ_{i1}).

$$c_{i1} = d_i p_1 \tag{2}$$

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

In each time period the process of coalition formation begins with *initiators* 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), maximum amount of service supplied (S) and unitary price for the service (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:

$$\Omega_q = \frac{Diff_q + 1}{(\sum\limits_{q=1}^{Q} Diff_q) + Q} \tag{4}$$

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* start the formation of coalitions and explore the option to invest with others (Action 3). Purchase a shared good in coalition is a common action and therefore agents' cost and utility depend on many more factors and conditions compared to the case of acting as singleton. The individual cost in coalition (c_{i2} in Eq.5) depends not only on agent's demand (d_i) and on the unitary price (p_2), but also on the the monetary contribution that an agent is willing to commit in the joint investment (x_i: $x_i < I$). x_i is the value that maximises agent's utility in coalition, such that U_{i2}: $dU_{i2}/dx = 0$. Also the utility in coalition has a Cobb-Douglas structure and is written as in Eq.6.

$$c_{i2} = d_i p_2 + x_i \tag{5}$$

$$U_{i2}(e_i; c_{i2}; d_i; D_{-i}; x_i; X_{-i}; N; \theta_{i2}; \alpha_i; \beta_i) =$$
$$= (e_i - c_{i2})^{\theta_{i2}} \{(d_i + D_{-i})[\frac{\alpha_i d_i}{d_i + D_{-i}} + (1-\alpha_i)(\frac{\beta_i x_i}{x_i + X_{-i}} + \frac{1-\beta_i}{N})]\}^{1-\theta_{i2}} =$$
$$= [e_i - (d_i p_2 + x_i)]^{\theta_{i2}} \{(d_i + D_{-i})[\frac{\alpha_i d_i}{d_i + D_{-i}} + (1-\alpha_i)(\frac{\beta_i x_i}{x_i + X_{-i}} + \frac{1-\beta_i}{N})]\}^{1-\theta_{i2}} \tag{6}$$

where $\theta_{i2} \in [0;1]$ is the preference for income; 1-θ_{i2} 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); N is the coalition size; X_{-i} and D_{-i} are, respectively, the total monetary contribution and the total demand of the other $N-i$ coalition members belonging to the coalition.

As in Axtell (1999, 2002), this utility function is dependent on the coalition formation process itself and takes into account both agents' characteristics and their willingness to commit part of their income into the common investment.[1] Higher θ_{i2} indicates a higher preference for saving rather than consuming, reducing the propensity to invest in coalition. Contrarily, lower θ_{i2} indicates more inclination to buy the good in coalition, hence more inclination to shared consumption. Utility in coalition is function of others' presence in the group and agent's attitude change accordingly. Higher α_i indicates that an agent gives higher importance to the division rule based on the shared consumption, rather than to the fact that s/he has to share the cost with others and that the coalition has a total of N members. So, parameter β_i discriminates between the proportional division based on cost sharing and the total number of coalition members. Higher β_i gives more importance to the first factor in comparison to the coalition size. The individual utility in coalition also depends on the sum of the contributions and on the demand of the other $N-i$ members. The total coalition monetary contribution is X, where X=$\sum x_i$ and X_{-i}=(X-x_i). In the same way, the total coalition demand is D, where D=$\sum d_i$ and D_{-i}=(D-d_i). X_{-i} and D_{-i} indicate the relationship between agent's utility and others' decisions.[2]

Agents involved in Action 3 evaluate cost and utility of the investment in coalition in comparison to the status of singleton. First, an *initiator* evaluates coalition

[1]Please see Annex I for a complete discussion regarding the properties of equation 6 and its parameters.

[2]To be noted that Eq.3 derives from Eq.6 being N=1 and D_{-i}=X_{-i}=0.

with one of his/her linked neighbours (N=2). Then, one of the two coalition members chooses randomly one of his/her linked neighbours and invites him/her to join the coalition and evaluate the investment proposed by the *initiator* (N=3). After evaluation, one more linked neighbour is invited. Actions 2 and 3 are repeated a number of time in each time step, allowing agents to evaluate different coalitions for different investments. However, given bounded rationality, agents do not evaluate all the possible combinations of products and coalitions.

The evaluation process is a multi-step bargaining process with iterations that happens in every single time step of the simulation.[3] Negotiation is necessary because agents try to maximise individual utility in coalition, which depends on own characteristics and preferences and on others' attitudes. Agents announce their individual contribution (x_i) every iteration, which determines continuos variation 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 long process of continuous interactions among agents because many features evolve over time and agents adapt behaviour accordingly.

The goal of the iterative process of coalition formation is to find stability among group's members. A coalition is stable when Pareto efficiency is reached – each member is better off without making at least one other worse off. More specifically, in a stable coalition (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 (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. This is also granted by two further conditions: members' utility (cost) in coalition is higher (lower) than utility (cost) as singleton (Eq.9 and Eq.10). Formally:

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

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

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

The evaluation process may bring to several stable coalitions, since size determines different cost and utility for agents. Therefore, after each evaluation, agents individually make a conditional decision among the option to invest via a particular coalition or to remain singleton. Among the two, the option that makes an agent better off is stored as optimal. If a subsequent coalition guarantees higher utility and lower cost in comparison to the optimal condition stored previously, the decision is updated. At the and of the evaluation process, a final decision is taken. All agents announce separately their optimal decision. If it regards the common investment, they announce the coalition they aim to set up. If all members of this coalition announce that this option is also their optimal option, then, coalition is established. Under these conditions, the common good is purchased by the coalition and agents adopt. *Adopters*, however, go out of the game, hence they cannot communicate anymore with others and they cannot take part to future coalition formation processes

The shared investment, in fact, provides the service to agents in coalition for the rest of the simulation. This means that agents are *locked-in* and do not modify their choice, under the assumption that a change implies higher infrastructural costs compared to the option to remain.

The model and the diffusion of sustainable goods

The model conceptualisation, as described in the sections above, can be easily linked to the diffusion process of sustainable goods for which large initial investment is needed, as for example decentralised energy systems (DES). These are energy power systems that need to be installed close to final users allowing them to be directly connected to the energy source. Hence, the regular network is the most suitable structure to simulate the social environment where local interactions occur among neighbours. Currently, people living in a neighbourhood satisfy energy needs (d_i) by means of the centralised energy system, for which only a price is paid for the relative consumption (p_1). DES is a more economic alternative option to satisfy the same energy needs. However, because of the elevate infrastructural costs, investment related to DES (I) is only feasible if a group of closed neighbours agrees to do it in cooperation. These local communities need to be stable since the shift to a decentralised and autonomous energy infrastructure requires not only shared investment and ownership of the new common property but also shared consumption, which is bounded by its maximum capacity (S). Therefore, neighbours willing to move to DES have to contribute to the common purchase (x_i) and to pay a price (p_2) for the relative consumption, which is lower than the current electricity price paid to the centralised energy provider. Attitude towards more sustainable options is very much related to people preferences, particularly if they, in order to satisfy consumption needs (1-θ_{i2}), have to share the common resource (α_i and β_i) and their participation implies income reduction (θ_{i2}). Consequently, people participation in energy communities is not only a cost-based decision (Eq.10) but, more importantly, it depends on their overall utility deriving from the sharing experience (Eq.9).

The formation of local communities is not immediate, but it requires time and numerous social interactions among neighbours. When the role of external enabling actors is not considered (i.e. private utilities or public bodies), the spontaneous process of group formation has to start from *early knowers*, having strong motivation towards the shift to a different energy infrastructure. Through continuous interactions, information flows across the neighbourhood, and more and more people is informed on the opportunity to install a DES in their local area. The decision to establish an energy community is the result of a long negotiation process since several constraints and opportunities emerge along with the increase of interested neighbours. When a DES is commonly purchased and installed, people connected to it have committed themselves in a costly investment which implies drastic changes in the energy infrastructure. For this reason, adopters do not participate in further negotiations since replacement would incur a high sunk costs. In conclusion, the process of coalition formation may modify the standard view on the diffusion of sustainable goods, such as DES, for which local communities are instrumental for adoption.

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 and it represents a relatively large neighbourhood (Figure 1). Only 2% are *initiators* (m=4), randomly chosen at the beginning of the simulation (t=0). Each agent has eight potential neighbours ($l = 8$) with whom they can tie links (dotted edges in Figure 1) and form a coalition.[4] Two different sensitivity analyses will 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).

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	$\theta_{i1}=\theta_{i2}$	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

* Parameter analysed

Table 1: Model initialisation

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 from the general provider or produced by the joint investment ($\theta_{i1}=\theta_{i2}$). 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). This setup allows the analysis of the co-evolving phenomena by considering heterogeneity in respect to agents' individual characteristics and homogeneity in relation to their attitudes towards shared consumption and contribution.[5] Agent's awareness towards the common investment increases at each time step (Adv=1%), meaning that chances for more agents to become *initiators*

[4] 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.

[5] In order to test the impact of agents' heterogeneity over these two preferences, the model has been also run with three different initialisations: i) α_i:(0.5;0.1) and β_i:(0.5;0); ii) α_i:(0.5;0) and β_i:(0.5;0.1); iii) α_i:(0.5;0.1) and β_i:(0.5;0.1). Under these conditions, the adoption share increases, on average, by about 8% compared to the outcome with homogeneous agents.

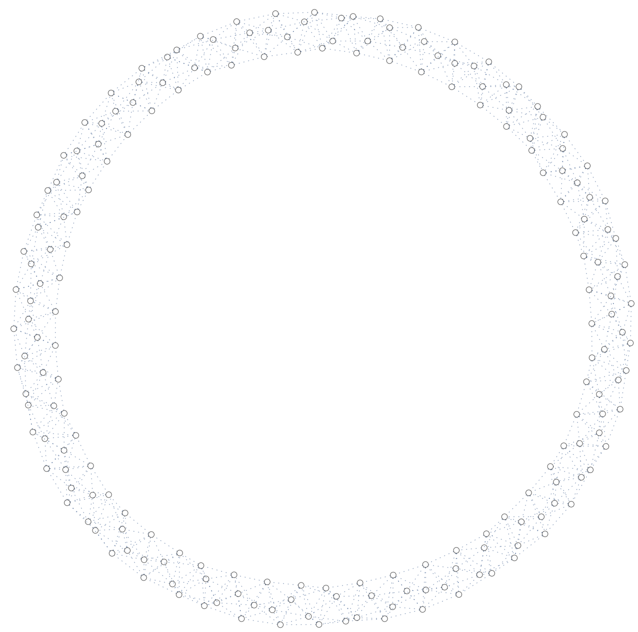

Figure 1: Initial regular network, 200 agents

increase over time. Further, the bandwagon effect related to the share of adopters is almost linear (ξ=0.85).

There are ten shared goods available in the market that *initiator* agents can choose for their common investment (Table 2), as alternative to the singleton option. Each of them has a different cost and a different maximum level of the service that can be provided. These value are strongly correlated: the higher the investment cost (I), the higher the supply (S) and the lower the unit price for the service (p_2). Price that singletons pay to receive the service from a general provider is much bigger than price related to the option concerning the investment in coalition ($p_1 >> p_2$).

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, results are presented as averages over 40 simulations with different random seeds.

4.2 Diffusion in Coalition: Emergent Properties

This section first discuss the emerging aggregate properties of the model. The model simulates agents' interactions aiming at forming coalition needed to buy jointly a

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	2.75
Price singleton (p_1)			10.00

Table 2: Model initialisation: available products

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, about 75% of the population is informed of the opportunity to buy jointly a common good (*active* agents in Figure 2), confirming that on a regular network contagion is relatively slow, as discussed in section 2.[6] Information is spread throughout the network by means of contacts among agents, but not all agents have been aware of the opportunity to invest in coalition and to evaluate this option. Two factors are relevant for this result. First, potential direct links are geographically bounded, due to the need to adopt a good that provide a service locally, and that an agent can communicate only to the nearest neighbours (l=8). This implies that, the limited network clustering reduces the speed of dissemination. 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.

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, when adoption in coali-

[6] In order to test whether the random network impacts positively adoption and information flow, the model is run with this network structure. Accordingly, the final share of adopters is 72%, increasing by 45% compared to the regular network; and all agents in the population are informed.

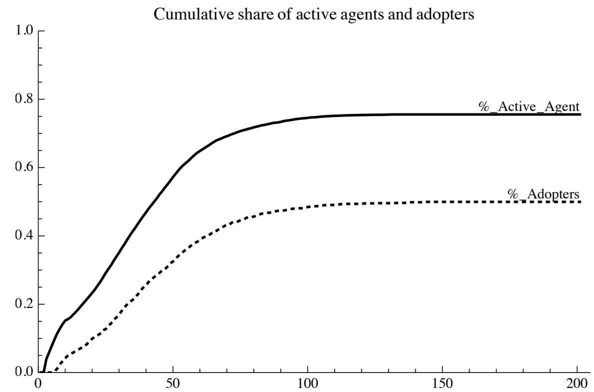

Figure 2: Cumulative share of active agents and agent in coalition

tion reaches a higher utility than buying from the central provider, the common investment certainly reduces the risk of early adopters.[7] 50% adoption rate is not new in the literature on diffusion of capital goods, as for example in the diffusion process of eco-innovations such as for micro-CHP (Faber et al., 2010) and electric vehicles (Higgins et al., 2012; Shafiei et al., 2012).

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. *Initiators* choose randomly the one they want to purchase with others before starting the process of coalition formation. Every time step, a different probability to be chosen is associated to each product (Eq.4): the more a product is adopted, the higher is the probability to be chosen (Ω_q). 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, a long term pattern is observed.

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

[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. It is shown that uncertainty does reduce initial levels of adoption.

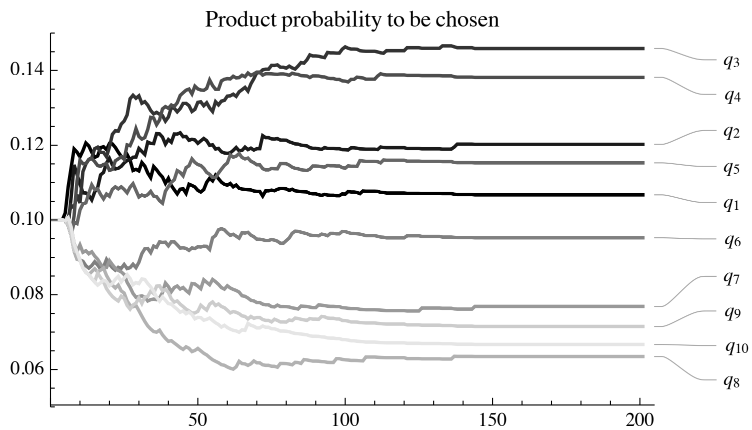

Figure 3: Product probability to be chosen, Ω_q

to both the network structure and coalition size. At the beginning 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]

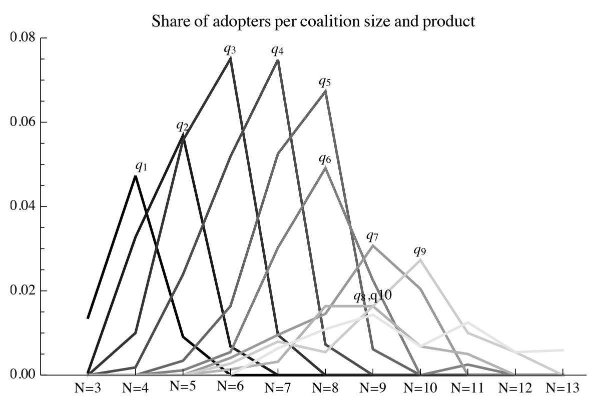

Figure 4: Share of agents in coalition, for each product adopted

[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 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 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).

Based on these results, the following propositions can be put forward.[9]

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 its size: there is a positive and significant correlation between the two. Beside the timing (smaller coalitions are evaluated early in time, when few agents are *active*), this result suggests that, when agents have the opportunity to choose between smaller and larger coalitions, they opt for the latter. In fact, during the decisional process, agents evaluate of all possible coalitions that increase their size incrementally. Therefore, when agents decide to establish large coalitions, they have already evaluated smaller ones. Hence, larger coalitions are preferred over smaller coalitions.[10]

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

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[9]Statistical tests are run for this and for all the other propositions put forward based on the modelling results. Table 3 at the end of section 4 summarises correlation coefficients for these tests.

[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).

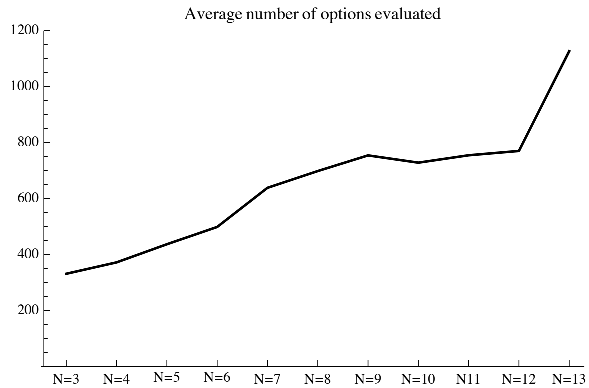

Figure 5: Average number of options evaluated by agents before establishing a coalition

Average contribution to coalition

In the model, agents commit a monetary contribution (x_i) to the common investment that maximises their utility (U_{i2}), and it varies with respect to preferred size of coalition and shared good. Figure 6 plots the individual average contribution by coalition size and, within each coalition, by type of common good. The larger the coalition (N), the lower the average agent's monetary contribution (x_i), regardless the level of the investment cost. Whereas, for a specific coalition size, the larger the investment cost (I) and its maximum supply (S) the higher the average agent's individual contribution (x_i). This result conforms with the theory of sharing groups showing that the more the people in coalition, the less the individual costs, and 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).*

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 explains the tensions in large groups between cooperation and free-riding (Canning, 1995; Glance et al., 1997; Huberman and Glance, 1996;

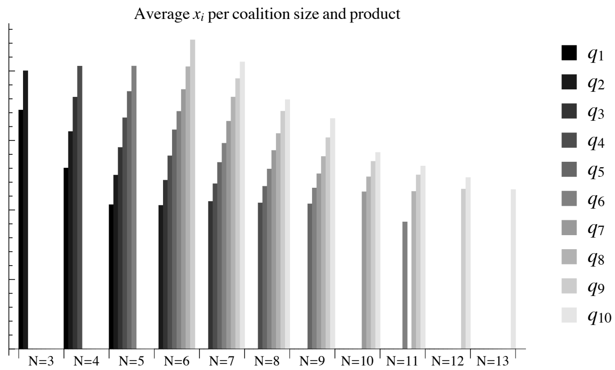

Figure 6: Average agents' contribution in coalition per size and product

Shehory and Kraus, 1998; Axtell, 2000). In the process of coalition formation aiming at purchasing a common good this relation is confirmed only partially. Figure 7 plots the share of free riders by coalition size.[11] The average share of free-riders in coalitions increases with coalition size up to a point (N=8), when it decreases again. Large coalitions purchase, on average, large and expensive common goods which require commitment of all members. This conforms with the idea that the role of certain players is essential to achieve Pareto improvements in group cooperation resulting after negotiation (Elliott and Golub, 2013). And, 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-shaped curve.*

4.3 Network analysis

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

[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).

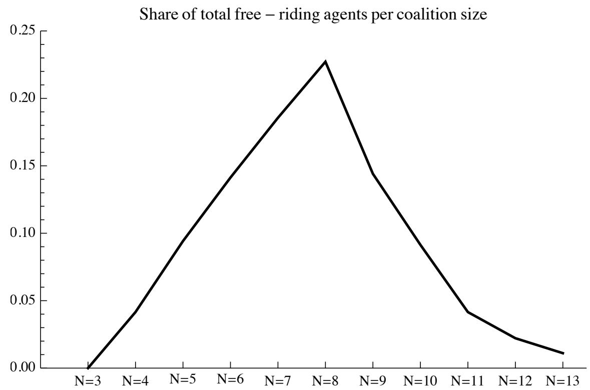

Figure 7: Free-riding agents

The co-evolution between coalition formation and diffusion

In each time step t, neighbours of agent i can assume one of the following status: linked (f_{it}), not linked yet (g_{it}) or in coalition (h_{it}). Hence, based on the model initialisation (see Table 1), $l_{it}=\sum f_{it}+\sum g_{it}+\sum h_{it}=8$. Given w_t the total number of *active* agents at time t, it is possible to calculate the share of linked neighbours for *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 represents the share of links among *active* agents, while V_t represents the share of agents in the whole population that can be potentially involved in the process of coalition formation and evaluation. Figure 8 plots both series over time.

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

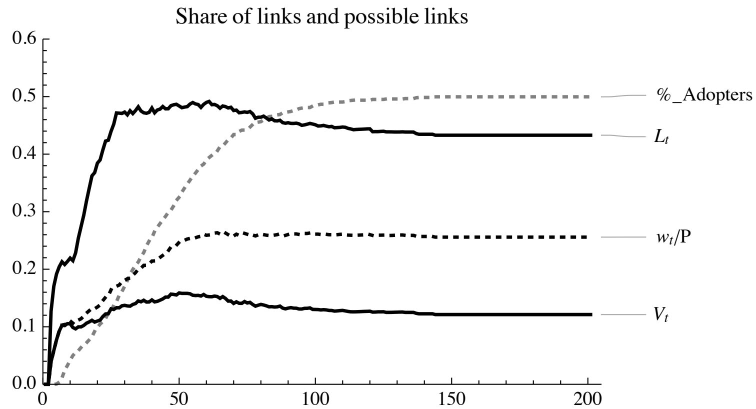

Figure 8: Co-evolution: links, network, coalition and adoption

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. Therefore, constant changes in the social network impact the co-evolution of coalition formation and diffusion of shared goods.

This feature can be explained better by 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]

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.

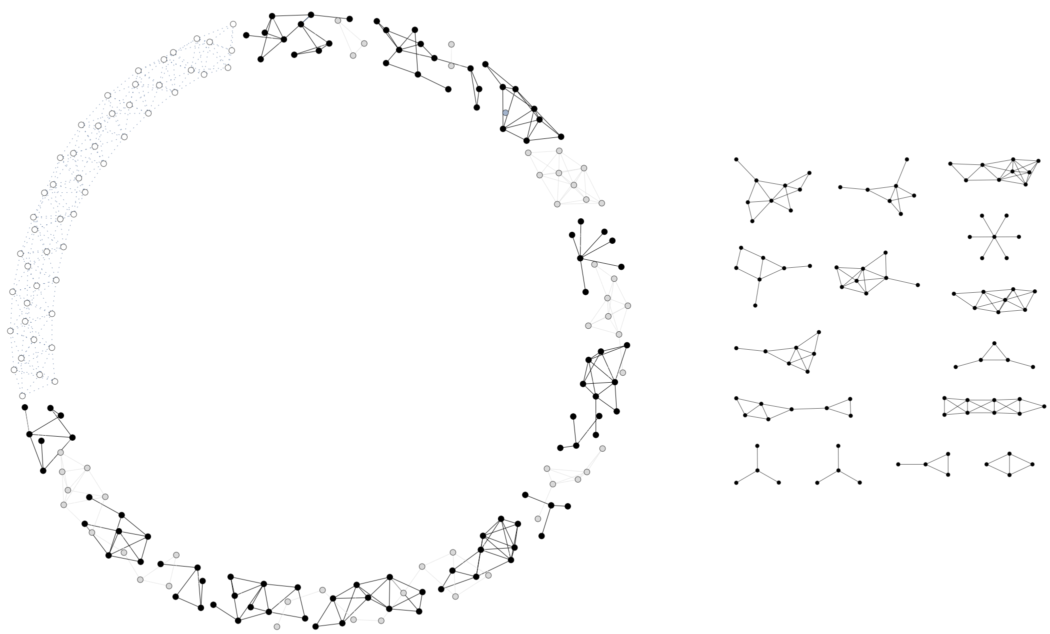

Figure 9: Final configuration: network (left) and coalitions (right)

However, there is also a substantial number of singletons, *active* agents, 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 72) 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. The rate of diffusion is therefore reduced by network externalities (Elliott and Golub, 2013).

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.*

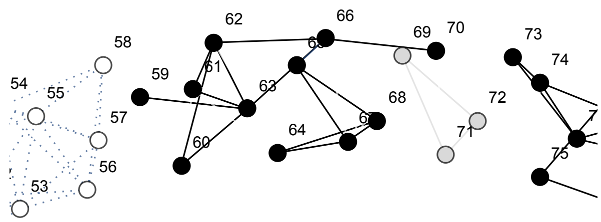

Figure 10: Isolated agents and established coalitions

Network properties of coalitions

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

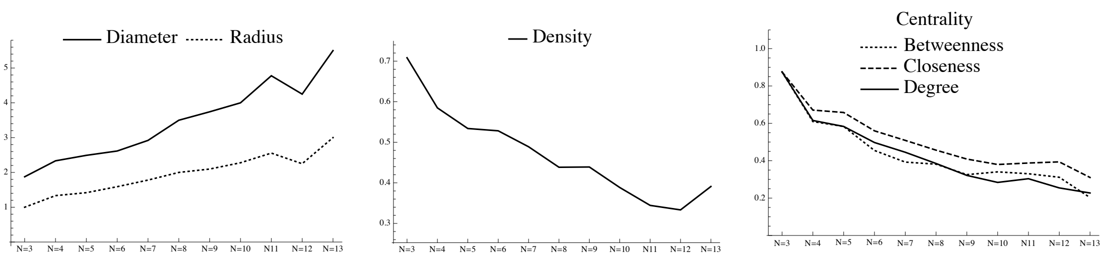

Figure 11: Network metrics

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, suggesting that the minimum and maximum absolute shortest paths (or eccentricity) in coalitions increases with size. Hence, the degree of agents' connectivity in established coalitions decreases with the size of the group. Network density (second panel), a proxy of structural cohesion (Friedkin, 1981), is the ratio between the number of links over the total possible number of links among agents in a coalition. The negative correlation with coalition's size 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), the extent to which agents serve as bridge between other coalition members (Betweenness), and agents' degree of being connected to all other agents (Closeness) 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, the model is run 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 share of active agents, and different values of l.

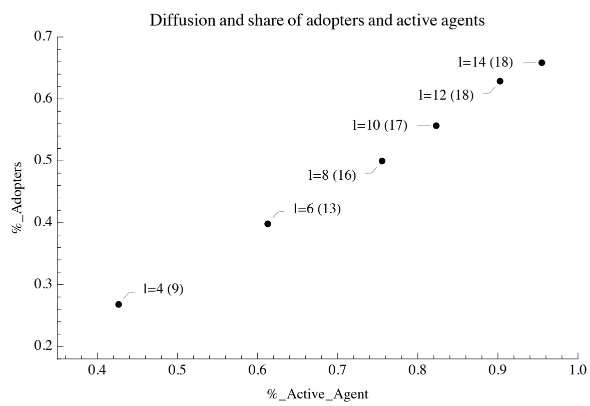

Figure 12: Diffusion, in brackets, and share of adopters and active agents per different values of l

A positive and linear relation is founded between the share of adopters and of *active* agents, between these two shares and l, and between the diffusion of common goods (in brackets) and l. That is, when the good can be shared between users located at a larger distance, agents have more opportunities to build contacts which increase adoption than when they can form coalitions with the immediate neighbours. It implies that the more the connections among nodes, the more the spread of information in the population. This increases agents' awareness and stimulates adoption, as founded in studies of diffusion in networks in relation to adoption of energy innovations (Bollinger and Gillingham, 2012; Tran, 2012).

Figure 13 plots the distribution of coalition size for varying values of l. The increase of 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. It indicates that large number of agents establish bigger coalitions when the network has a higher degree of clustering.

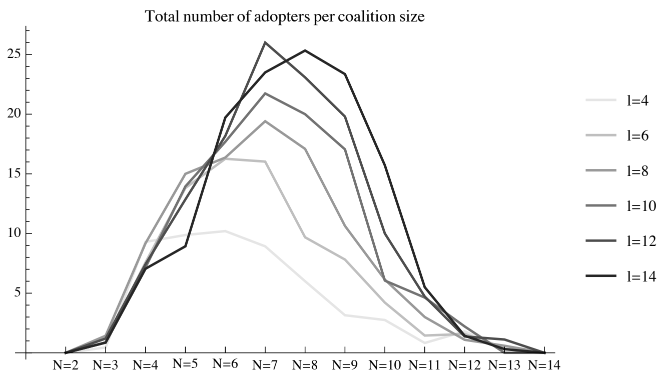

Figure 13: Total number of adopters per coalition size and different values of l

Coalition size is also related to the type of good purchased. Figure 14 shows the distribution of shares of adopters per product. 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.

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 formed to 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 already aware of the shared good with strong motivation towards the common investment? In this

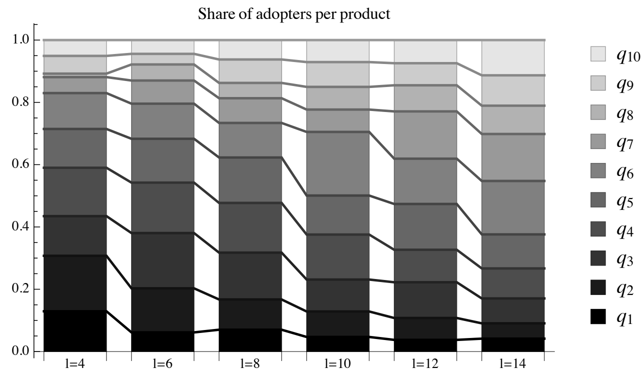

Figure 14: Share of adopters per product and different values of l

section, previous results are compared with the case of all agents being *initiators* (m=200) and all are already connected to their closest neighbours ($l_{it}=\sum f_{it}=8$; $\sum g_{it}=\sum h_{it}=0$). This initialisation allows to study the co-evolution of coalition formation and diffusion in a complete network where agents form and evaluate all possible coalitions. At t=0, agents already know their utility in all possible groups. This condition is different from the baseline scenario where agents only evaluate coalitions that can be formed in a network which is not complete and changes its structure every time step.

Figure 15 compares 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 full information and 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%. This implies that, in the complete network, 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 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

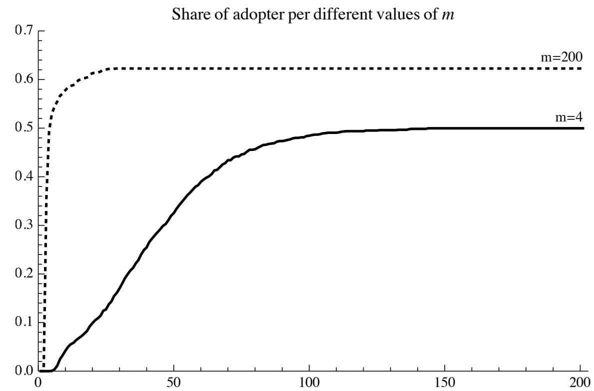

Figure 15: Share of adopter for different values of m

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 unitary cost. In these large groups agents minimise their individual contribution x_i (Proposition 4).

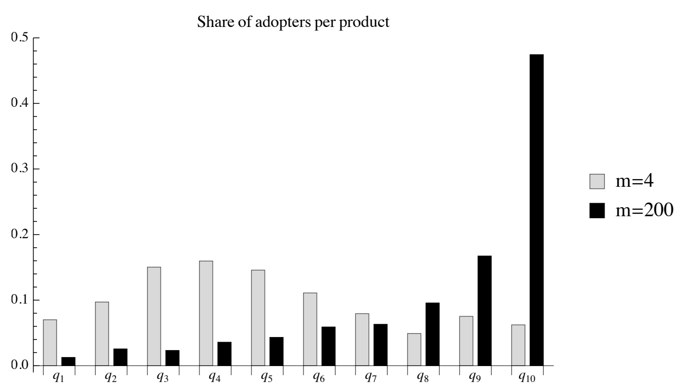

Figure 16: Share of adopters per product and different values of m

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. However, diffusion does not reach the whole population.*

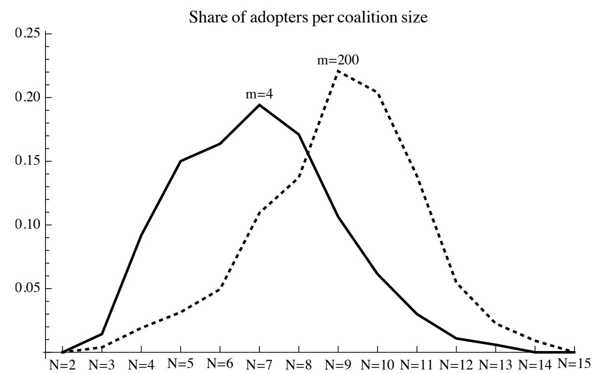

Figure 17: Share of adopters per coalition size and different values of m

Proposition	Variable 1	Variable 2	r
1	Investment	Size	0.735***
2	Investment	Size heterogeneity	0.892***
3	Size	Option evaluated	0.939***
4	Size Investment	Contribution	-0.898*** 0.743*
5	Size	Free riders	-0.412
7	Size	Diameter Radius Density Degree centrality Closeness centrality Betweenness centrality	0.972*** 0.968*** -0.933*** -0.935*** -0.934*** -0.901***
8	Geography	Diffusion Active agents Adopters	0.950** 0.971** 0.977***

r is Pearson correlation coefficient
* p<0.05 ; ** p<0.01 ; *** p<0.001

Table 3: Correlation for propositions

5 Discussion and conclusion

This paper has presented and discussed an agent-based model (ABM) 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, this model considers the adoption decision as a collective action, taken by a group of consumers. These groups are endogenously established in the model: consumers organise themselves following a bargaining process, as studied in game theory. Links between agents evolve over time endogenously by means of interpersonal contacts occurring in the social network. The attempt to combine two streams of literature, the one on diffusion and the one on coalition formation, capturing the complex interplay between the two processes by means of an ABM, brings novelty to the discussion on the diffusion of shared goods, for which a collective adoption is required.

The co-evolution of coalition formation and diffusion of shared good has relevant implications for sustainable goods. The literature on the diffusion of sustainable energy is mainly focused on adoption as an individual decision. It studies mainly small-sized goods, such as water-saving technologies (Schwarz and Ernst, 2009), micro-cogeneration (Faber et al., 2010), or solar PV panels (Murakami, 2014), which are affordable by an average consumer. Other 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.

Instead, to study the diffusion of large-sized sustainable goods, such as decentralised energy systems (DES), it is necessary to consider adoption as a collective decision. DES are energy power sources, scaled to consumers' needs, that have to be physically installed close to final users which are directly connected to them (Hatziargyriou and Meliopoulos, 2002; IEA, 2002). DES are too expensive for individual households, but can be purchased by group of neighbours. These systems may be beneficial only to users that are connected to it and that share its use.[13] Diffusion of DES is as a case of technology adoption that takes place through collective action and it requires to first study how coalitions are formed.

The analysis presented in this paper is suitable to provide meaningful insights to assess conditions under which diffusion of DES can easily take off. In order to facilitate the transition towards a more decentralised energy system, the first requirement is to increase awareness. This is because spreading information is an important enabling action (Lin, 1999; Woolcock and Narayan, 2000), particularly for the diffusion of environmental attitudes (Ek and Patrik, 2010) and energy-efficiency

[13] They can buy and use these systems independently, and experiencing economic benefits (Watson, 2004) 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.

innovations (McMicheal and Shipworth, 2013). DES might diffuse more if consumers are sufficiently connected, and DES can 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 higher probability to be adopted than smaller systems, and, at the same time, consumers might spend less for their energy consumption.

As simulated in this paper, the adoption of DES is as an emerging bottom-up process requiring a careful understanding of consumers' behaviour, features and preferences (Groh et al., 2014; Pasimeni, 2017). A large diffusion of DES might bring environmental benefits (Hadley and Van Dyke, 2005; Tsikalakis and Hatziargyriou, 2007; Akorede et al., 2010), reduce transmission losses (Chiradeja and Ramakumar, 2004; Pepermans et al., 2005) and enhance energy security (Asmus, 2001; Battaglini et al., 2009). Further, it enforces the direct involvement of final consumer and their empowerment, which is determinant not only for the diffusion of DES (Sauter and Watson, 2007) but also for the overall transition process towards a more sustainable economy (European Commission, 2015a,b; Goedkoop and Devine-Wright, 2016; Hyysalo et al., 2016; Schot et al., 2016). But, as emerged from this paper, if someone remains isolated from the transition towards a more sustainable energy infrastructure, this may have a negative impact on social inclusion and on the energy transition itself.

The model has a number of limitations and can be extended in different ways. Firstly, data initialisation is set up randomly following a normal distribution but based on a consistent proportion among parameters but these are not calibrated on any empirical observation. Second, the model currently does not allow for the reintroduction in the game of coalition formation *adopters* agents. Instead, by allowing the reintegration of agents in the game after adoption the model is suitable to study also 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 and possible future extension concerns the impact of different network structures to the co-evolution of coalition formation and diffusion of common goods without local constrains. Eventually, 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).

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Annex I

The utility function related to the shared option (U_{i2}, Eq.6) 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 by committing 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. Eq.6 can be also written 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 implies that, by 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 by the individual monetary contribution committed in the common 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, *cœteris paribus*, influence both agent's utility in coalition and the monetary contribution, and, most importantly, their relation.

High level of θ_{i2} indicates that an agent has a higher preference to save money, while low level of θ_{i2} indicates a higher preference to satisfy the demand for the service. When θ_{i2}=1, the utility depends only on the income saved. In the opposite case, when θ_{i2}=0, agent's utility depends only on consumption. When preference for income is high (high θ_{i2}) (and preference for consumption low), *cœteris 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 between d_i and x_i and U_{i2} is similar. A higher demand raises 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

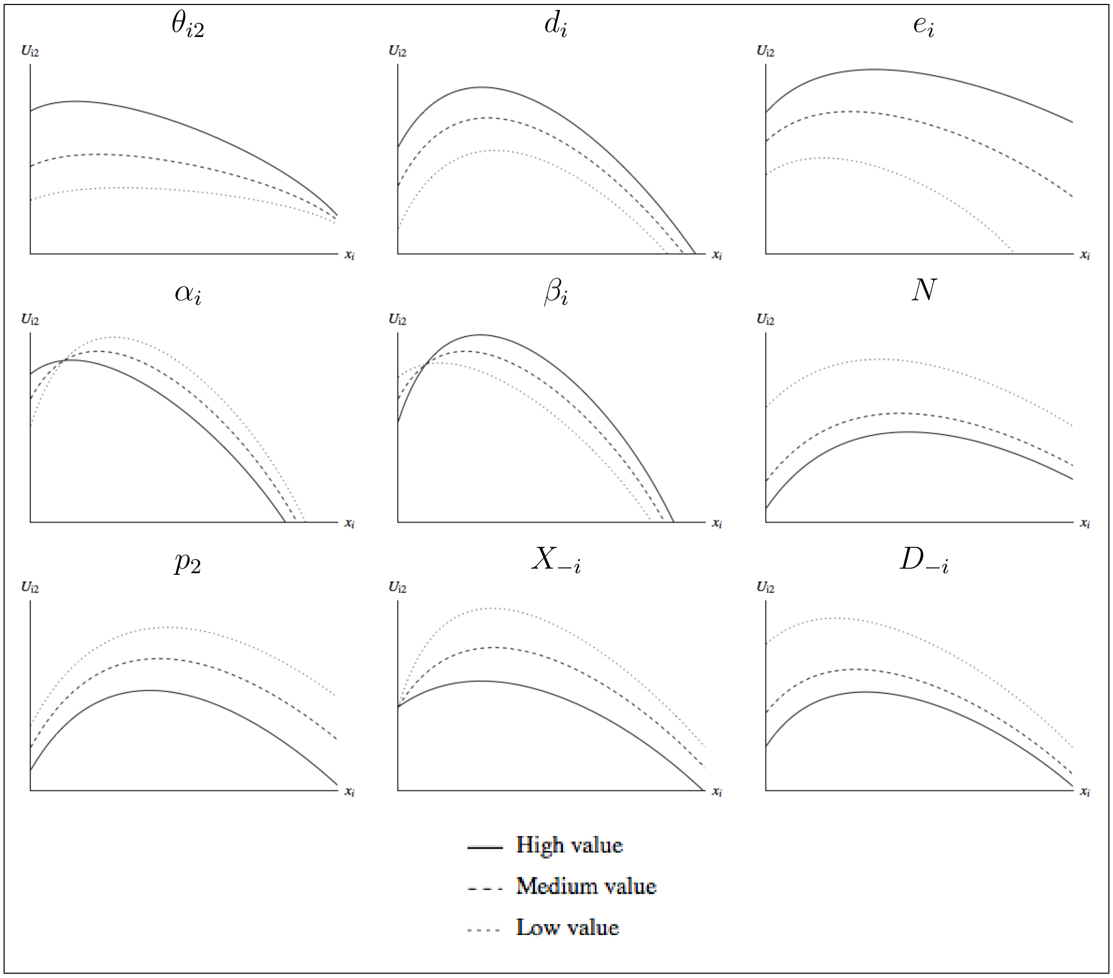

Figure A1: impact of model variables on x_i and U_{i2}

income. This is because savings are higher when the income is higher, and utility increases even if contribution is higher, *cœteris paribus*.

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 agent to the proportional division rule based on consumption. The higher is α_i, the higher is the importance assigned to the fact that s/he is using only part of the service provided by the common good. Therefore, when α_i grows, utility decreases. Parameter α_i 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 portion of own 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 unit price (p_2) of the service in coalition, the lower the utility. The higher is the other members' total contribution (X_{-i}), the lower is the individual contribution as well as the higher is the other members' total demand (D_{-i}), the lower 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 in relation to the first option (Table A2).

Parameters	Value
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

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

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.

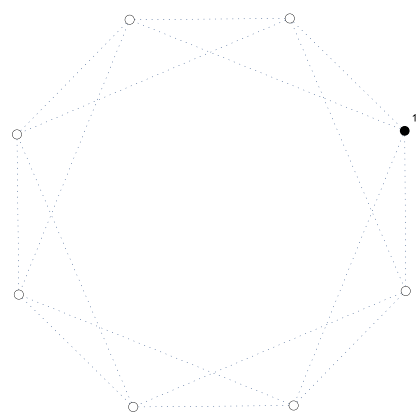

Figure A2: *Initiator* (in black) and the regular network structure

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. Bidirectional links are formed. The contacted agent becomes *active* and is 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. Being singletons, Eq.2 and Eq.3 calculate their individual cost and utility. Only agent-1, the *initiator*, can start the process of coalition formation. Before doing so, a product is chosen (in this example only one product is available) and the relative joint investment is proposed. The process of coalition formation starts: agent-1, the *initiator*, contacts the linked agent-2 (Figure A3) and they evaluate the joint investment in coalition (Eq.5 and Eq.6). The two

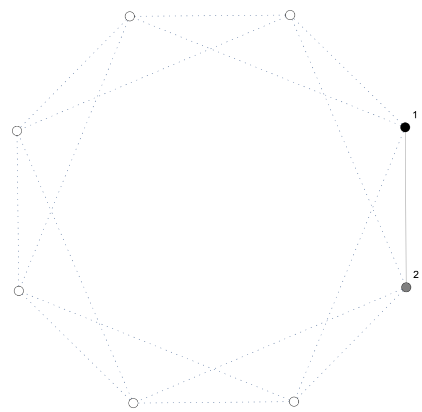

Figure A3: Step 1: *initiator* ties link with agent-2

agents 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.

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. Only *initiators* can do it. At the beginning of each time step, all *active* agents check their level of awareness (Eq.1) to become *initiators*. Assuming that agent-2 becomes *initiator* in this step, the two 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, agent-1 contacts and forms a link with agent-3 and 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 evaluating 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 evaluated in this network of agents. There are three coalitions with size 2 (1-2, 1-3 and 2-4), two coalitions with size 3 (1-2-3 and 1-2-4) and one coalition with size 4 (1-2-3-4).

The three coalitions with 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

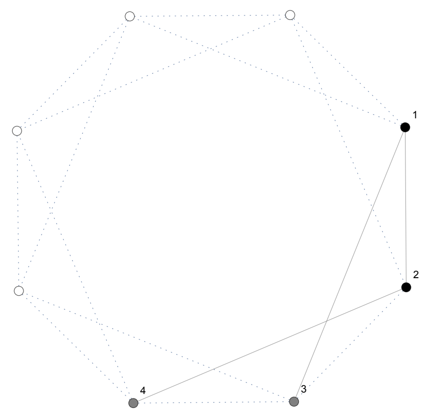

Figure A4: Step 2: *Initiators* tie one link each

		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

not provide any optimal conditional decision for the agents involved. Agents stop evaluating these coalitions. Then, agents evaluate the two coalitions with 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.1). If so, agent-3 can continue the process with the remaining agents in the population.

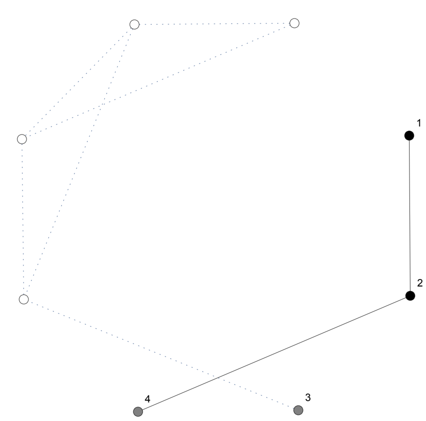

Figure A5: Step 3: coalition established and agent-3 isolated

Annex III

Uncertainty

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.

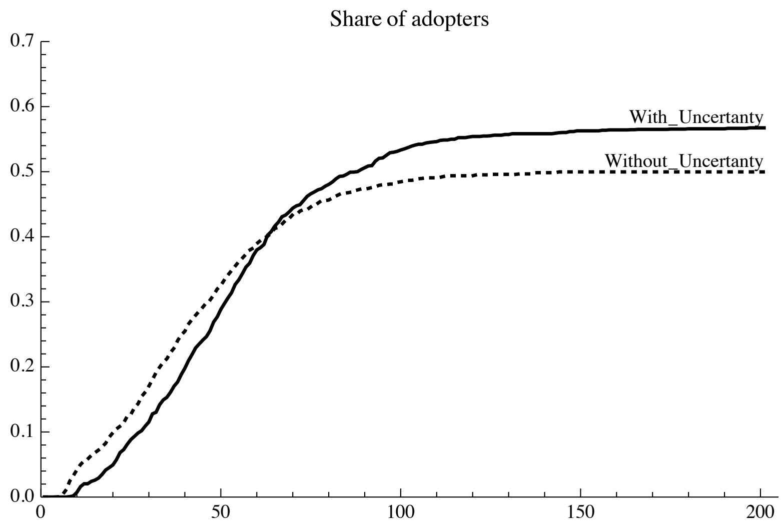

Figure A6: S-shaped diffusion curve

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