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Networked Innovation and Coalition Formation: The Effect of Group-Based Social Preferences

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ABSTRACT

In this paper we study the production and dissemination of public knowledge goods – such as technological knowledge – generated by a network of voluntarily cooperating innovators. We develop a private-collective model of public knowledge production in networked innovation systems, where group-based social preferences have an impact on the coalition formation of developers. Our model builds on the large empirical literature on voluntary production of pooled public knowledge goods, including source code in communities of software developers or data provided to open access data repositories. Our analysis shows under which conditions social preferences such as ‘group belonging’ or ‘peer approval’ influence the stable coalition size, as such rationalising several stylised facts emerging from large scale surveys of open-source software developers, previously unaccounted for. Furthermore, heterogeneity of social preferences is added to the model to study the formation of stable, but mixed coalitions.

KEYWORDS

Coalition Formation; Networked Innovation; Open-Source Software (OSS); Public Knowledge Goods; Private-Collective model; Social Preferences.

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1. Introduction

From the seminal work of Powell et al. (1996), a growing debate over the link between the process of innovation and social network formation has taken an important place in the literature on applied sciences.¹ More precisely, this literature has started to distinguish between innovation driven by collaborative relationships, as opposed to more competitive and market-based arrangements (Swan and Scarbrough 2005; Hardy et al. 2003). Along these lines, Phillips et al. (2000) suggest that “networked innovation” of this kind relies on neither market nor hierarchical mechanisms of control, but occurs through more horizontal relationships negotiated in communicative processes. Similarly, Abdirahman et al. (2014) consider networked innovation as intentional, inter-organizational and inter-individual relationships oriented to knowledge creation. Sie et al. (2009) lastly, describe how a network of organisations – or individuals within organisations – will profit from each other’s complementary knowledge by cooperatively sharing information or assets. The resulting partnerships between agents and/or organisations – formed by cooperatively sharing knowledge – are viewed as *coalitions* in this latter paper.

Moreover, as the information communication and technology revolution dramatically expanded the possibilities of this kind of distributed coordination and networked innovation, a tendency towards open development of technological knowledge took wing. Indeed, the functioning of large-scale digital networks highlights the prominent role played by voluntary contributions to the production and management of pools of intangible research resources, such as open source software or large-scale genomic databases. This is especially true in the early stages of research along the innovation and product-development chain, when access to multiple upstream inputs – including materials, literature and data – amongst a large number of decentralized contributors to the research process is essential (Reichman et al. 2016). Also, direct public availability of research results and innovations has proven to provide major socio-economic benefits for society.² As a result, a new type of good, namely public knowledge goods, has emerged in almost all scholarly disciplines and knowledge contexts (Reichman and Uhler 2003; Benkler 2006). In general, these particular public goods, such as technological knowledge, have been defined as goods with non-exclusive access and use conditions, which are widely consumed by various communities or individuals (Hess and Ostrom 2007).

In this paper, we study the process of voluntary coalition-building geared towards the development and dissemination of public knowledge goods.³ Traditionally, the economic literature has mainly focused on the production of public knowledge goods by governmental institutions, whilst less attention was given to the theoretical basis of public knowledge goods produced by *individual* agents contributing voluntarily to communities, such as open source software communities or research exchange networks. As a result, and despite a large body of empirical research which has shown the effectiveness of voluntary mechanisms for the production of public knowledge goods,⁴ the exact ways in which coalitions can overcome the initial free-rider problem undermining technological development are as yet not fully clear. As we will argue, the group-based benefits to knowledge creation which are interlinked with the cooperative, joint process of networked innovation, will play a crucial part in this process.

In short, we approach the process of networked innovation from the point of view of public good theory, where two important features of successful economic and institutional cooperative arrangements stand out. Moreover, and even though both of these features – which we describe in detail below – would apply to a broad set of

voluntary pooled public knowledge goods, we focus on one of the most well studied and prominent cases to illustrate and rationalise our findings: open source software development.

First of all, the importance of reaching an adequate group size for knowledge generation to proceed – often highlighted in public good theory as a necessary condition for voluntary cooperation – also materialises in the open source context. Indeed, as shown in a recent large-scale survey by Schweik and English (2012), the formation of coalitions with a certain minimum size is needed for software developers to effectively pool their efforts and contributions. In other words, only if the aggregate level of the produced public good is high enough – through attracting a sufficient number of contributors with appropriate expertise for selected tasks – will developers be motivated to voluntarily contribute to the development of a project. Furthermore, when such a minimum coalition size is reached, this size will theoretically also be the equilibrium size. Since other agents can free-ride on the public good once it is produced, there is no economic incentive for them to join the contributors’ group. This duality between the core group of user-developers on the one hand and the broader user group on the other, is a well-known pattern that is observed in open source development projects as well (Raymond 1999). In these projects, the group of user-developers grows until the group-size is sufficient for the task at hand, as also described above, while the broader group of software users continues to grow beyond that size.⁵

Second, *private* benefits to knowledge production often influence the willingness of agents to participate in a cooperative process. In the context of open source development, Hippel and Krogh (2003) show that public knowledge generation in effect brings about both aggregate public and non-market, private benefits for developers. The latter private benefits then include problem solving, learning and enjoyment, higher citations for researchers through increased visibility, or access to new personal competencies by joining a community with high-level expertise. As a consequence, developers contributing to public knowledge pools will logically be driven by both the public as well as the private benefits of knowledge production.⁶ It is precisely this latter feature of public good theory which we will extend in what follows, by considering the kind of *social preferences* that are specifically related to the cooperative nature of networked innovation. Allowing for social preferences which can interact with the public and private benefits described above, thus provides our model with its novel feature.⁷

Indeed, the role of public and private benefits when *group-related* social preferences also affect agents’ willingness to join a coalition producing public goods, remains unaddressed in the literature. Public knowledge good development is no exception in this respect, yet there are good reasons to believe that social preferences are an important driver alongside the purely private and public benefits of networked innovation (Dedeurwaerdere et al. 2016). As shown by Dalle and David (2008) in the particular case of open source development for example, reaching a ‘quasi-stable’ stage of a community of contributors generating an evolving code-base, is best explained by the joint involvement of several classes of participants with different mixes of privately *and* socially motivated agents. In three of these classes social preferences play an explicit role, where developers are either driven by peer esteem (so-called ‘kudos’ seekers), group related learning opportunities (so-called social interaction seekers), or both. In other words, when *group approval* or *group belonging* are important to agents, private benefits of knowledge production can transcend the purely individual level studied in earlier work,⁸ and also interact with a group-based dimension. In short, we believe that the process of coalition formation in networked innovation systems also depends

on the characteristics of the network’s members, which are to a large degree given by their various group-based preferences.⁹

To study the role of social preferences in this context, we develop a theoretical model of coalition-building in networked innovation systems aimed at technological knowledge production. Also, and as far as we can tell, we are the first to investigate the effect of *group-based* social preferences on this kind of bargaining processes set to overcome social dilemmas. Our approach draws on the private-collective incentive theory of Hippel and Krogh (2003), developed within the wider context of “user-based innovation”. We then complement this perspective by building on the theory of group-related internal motivations, as well as the social psychology literature analysing social preferences, extra-role behaviour and organisational citizenship behavior (LePine et al. 2002). Our main finding is that the private benefits of public knowledge production can have *contrasting* effects on coalition formation. First, and in line with earlier work, private benefits bring about smaller coalitions since the public benefits of knowledge are needed less to overcome its production costs. However, and especially when group approval is more important to developers, larger private benefits – such as private learning and enjoyment, higher citations, increased visibility, or improved competence – can lead to bigger coalitions as well. In this case cooperation in networked innovation systems is perceived more as purely self-interested rather than as a contribution to society, with the result that knowledge production is considered less of an achievement by other developers. Consequently, and given a developer’s sensitivity to the approval of his coalition members, larger public benefits produced by a bigger coalition are needed. This precisely to compensate for the reputational losses suffered by developers which enjoy large private benefits, but find group approval important.

In other words, whether a coalition is made up out of developers deriving large private gains from peer-approved knowledge production – such as the ‘hackers’ discussed further on – or exhibit social preferences for contributing to the group’s social identity – such as the ‘social learners’ introduced below – makes a difference in terms of stable coalition size. Also, as the group-based social preferences become more pronounced across the board, joining the coalition simply becomes too alluring for non-members. Developers then rally around ever higher group-induced welfare levels, up to the point that the grand coalition is the only stable coalition.

Lastly, we study a population composed of multiple developer types, each with different social preferences. We show that, in line with earlier findings by Dalle and David (2008), smaller groups with homogeneous social preferences can overcome the social dilemma by broadening their base. This results in larger, more heterogeneously composed coalitions, made up out of diverse sub-groups.

The rest of the paper is organised as follows. Section 2 provides the basic motivation of our analysis and elaborates on the supporting literature. Section 3 theoretically analyses how social dilemmas of public knowledge production can be overcome through coalition formation in a private-collective model, allowing for social preferences. In Section 4 we present an application of the model assuming heterogeneous social preferences. Section 5 concludes.

2. Motivation

To fully grasp the predictions of our theoretical model introduced below, we first look at the personal attributes and behavioral patterns of real-life open-source software developers. The extensive survey data on socio-psychological motivations in this specific

field allows us to illustrate how the interplay of social preferences and private benefits can influence the process of coalition formation in networked innovation systems, aimed at the generation of public knowledge goods. As in Dahlander and McKelvey (2005), the scope of our model goes beyond existing developer groups, and considers every researcher/innovator with the skills to potentially contribute to a networked innovation system such as a digital development process. The more general question then becomes why the latter would join such a networked coalition of developers to begin with, which determines the stable coalition size.

2.1. *The Case of FLOSS Developers*

The FLOSS-US 2003 survey is a web-based survey, generating a wealth of data on motivations and reasons for developers to begin to work on Free/Libre, Open Source Software (FLOSS) projects (David and Shapiro 2008). Using this data, David and Shapiro (2008) classify the respondents according to their distinct motivational profiles by hierarchical cluster analysis (see figure B.1 in appendix). In addition, whenever possible, the respondents in each cluster are also matched to projects of known membership sizes, revealing that the fractions of respondents from each motivational cluster for the large and the very small project ranges are different (see figure B.2 in appendix). Now, two major outcomes from this study cannot readily be explained in a model without social preferences.

The first point is related to the contrasting effects of social preferences on coalition formation, specifically in the case of low versus high direct *private* returns for the members of the coalition. As can be seen from the study of David and Shapiro (see figure B.2 in appendix), the three clusters where group-based social preferences are at work – the “social learners”, “social programmers” and “user/innovators” – are present both in the small and large ranges of the project sizes. Stable coalitions of the smaller and larger kind are thus equally spread, and this compared to other clusters which are only present in the large ranges. This is consistent with the intuition that group belonging and peer approval foster cooperation in situations of social dilemma. In contrast, the cluster of “aspiring hackers”, which is composed of “[...] *individualist, materially motivated programmers, which take part in FLOSS in the interest of a future career*” (David and Shapiro 2008), is more present in the large-size groups than in the small-size groups. For hackers, the willingness to join a coalition depends more on the purely private benefits from knowledge production – such as job market signaling and human capital accumulation – rather than group-based social benefits (Lakhani and Wolf 2003; Raymond 1999). The question then becomes why these aspiring hackers participate more in the larger projects, whilst the literature on coalition formation would predict the exact opposite outcome given the sizeable private benefits from contributing. Our model provides some intuition here.

The second point concerns the formation of heterogeneous coalitions to overcome social dilemmas, when homogeneous groups are too small to form viable coalitions. Figure B.3 in appendix gives the matrix for developers’ movements among projects of different membership size. In reading these data, it is reasonable to assume that on average developers in their first project derive higher personal learning and problem solving benefits, i.e. higher direct private benefits, compared to the involvement of these same persons in their second and/or most recent project (David and Shapiro 2008). As a result, and on average, developers in second stage projects show a higher probability to go to larger FLOSS projects to compensate for the loss in private ben-

efits, since the individual marginal return on the aggregate public good will be higher in larger projects.

In particular, this result is valid both for agents that were involved in the first stage in small groups, which are likely to be homogeneous, or in medium groups, which include both homogeneous and heterogeneous cases. The first case corresponds to homogeneous groups that extend to heterogeneous groups to reach the stable coalition size, which we will explicitly model in section 4 below. The second case corresponds to the increase in optimum group size for heterogeneous coalitions, where the private return component of the contribution to the public good is also decreasing. Either way, the interpretation so far coincides well with the literature on coalition formation: smaller private benefits imply larger coalitions. However, a certain amount of developers in the FLOSS database continues to work on projects of equal, or even smaller size as well. Also here, our model offers an explanation, further rationalising the process of mixed coalition formation.

In short, our model will frame most of these – often seemingly contrasting – dynamics and pinpoint where the private benefits of knowledge production and social preferences can interact. This to provide a fresh perspective on how networked innovations take shape in a private-collective setting.

2.2. *Supporting Literature*

Whilst a large theoretical literature has studied endogenous coalition formation among countries grappling with global environmental problems,¹⁰ or among research units seeking competitive funding,¹¹ we focus on voluntary contribution to *public goods* production.¹² As pointed out in the introduction, and adding to this latter public goods perspective on coalition formation, we focus on public knowledge production in the context of networked innovation systems. From the seminal works of Arrow (1962) and Stiglitz (1999), the global public good character of scientific and technological knowledge has already been largely analysed in the public economic literature. Following the latter, we consider a situation where innovators, such as software developers, face a social dilemma so that – as is the standard initial position in any public good game – their dominant strategy will be non-contribution to the production of the public knowledge good. The aim of the model is then to investigate how *social preferences* influence the bargaining process shaping eventual coalitions, which are set to overcome this social dilemma.

To allow for social preferences, we draw on the private-collective incentive theory developed by Hippel and Krogh (2003). In line with their extensive case study research, we assume that *‘[...] contributors to a public good can inherently obtain private benefits that are tied to the development of that good. These benefits are available only to project contributors and not to free riders and represent a form of selective incentives for project participation that need not be managed by collective action project personnel’* (Hippel and Krogh 2003).

This approach chimes well with the general theory of joint products proposed by Cornes and Sandler (1984, 1994), and further developed by Kotchen (2006, 2009) and Vicary (1997, 2000). One of the main contributions here, is that free-riding over other agents’ contribution to public goods decreases when these same goods also provide contributors with private benefits.¹³ Now, by introducing evidence from social psychology on the role of group behavior, we extend the scope of these private benefits beyond the purely individual frontier, and thus explore their interaction with group-based so-

cial preferences. What is more, since the benefits deriving from such preferences are group-related, they will be *conditional* on coalition-membership.

The literature in social psychology highlights two key dimensions of social preferences that play a prominent role in group behavior: *group identity* related to the collective goals realised by a group or community, and *peer approval* of pro-social attitudes. First, studies provide compelling evidence that the longing for a positive social group identity is a key determinant of engagement in group behavior. Social psychological experiments have shown that social group identity is even in many cases the most important explanatory factor to account for various types of group related motivations such as procedural justice, fairness and supervisor ratings (Blader and Tyler 2009; Wit and Kerr 2002). The second type of social preference that plays an important role in group engagement is the social approval for individual pro-social attitudes and behavior (LePine et al. 2002). These individual pro-social reputation effects have also been studied extensively in the context of overcoming social dilemmas (Suurmond et al. 2004; Bolton et al. 2005).

Lastly, especially this latter dimension of reputation effects is reminiscent of the social exchange approach modelled by Holländer (1990), where voluntary cooperative behavior is assumed to be motivated by social approval. This approval is conceptualised as an emotional activity of appreciations: emotions, feelings, but also verbal expressions are in this sense modelled as having a stimulus power $s(b)$, prompting emotional reactions that measure the subjective value of cooperative behavior b . We will follow a similar approach in what follows, using linear relationships for simplicity.

3. The Model

Consider a community of $n > 2$ developers interacting in a common environment, potentially pooling their efforts in networked innovation systems to produce a certain amount of public knowledge goods, such as technological knowledge, expressed by q_i for each developer i . To model the decision-making driving this innovation process, we follow the approach pioneered by Hoel (1992), Carraro and Siniscalco (1993) or Barrett (1994), which boils down to modelling two stages under perfect and complete information. A ‘contribution’ public good game in the second stage, where each developer decides how much to contribute to the public knowledge good, is preceded by a ‘membership’ game in the first stage, defining coalition formation. The latter should be seen as an announcement game where, by taking into account the behaviour of others, a developer either announces to team up with colleagues in a coalition, or not.¹⁴ We furthermore assume only one coalition can be formed, so that developers who are not joining this coalition are assumed to act as singletons. This is a standard assumption in the economic literature on climate agreement negotiations,¹⁵ and chimes well with the context of voluntary networked innovation, usually clustered around the development of one specific application or idea.

Working towards a subgame perfect equilibrium, we start out with the contribution game in the second stage in what follows, taking the strategic combinations of cooperation decided on in the first stage as given.

3.1. Contribution Game

Depending on whether a coalition of s members ($s = |S|$) is formed in the preceding membership game, and whether developer i is a member of this coalition, his utility

is defined by

$$u_i = \begin{cases} b \sum_j^n q_j - cq_i + \alpha bq_i & \text{if } i \notin S \text{ or if } S = \emptyset \\ b \sum_j^n q_j - cq_i + \alpha bq_i + q_i (\beta + (b - \alpha b)\theta) & \text{if } i \in S \end{cases} \quad (1)$$

where the public good character of the benefits to overall knowledge production $b \sum_j^n q_j$ depends on total production $\sum_j^n q_j$, and the unit cost of production is given by $c > 0$. The purely private, ‘ancillary’ benefits derived from knowledge production – such as problem solving, learning, increased visibility or access to expertise – are then denoted by αbq_i , with $\alpha > 0$ measuring the weight which ancillary benefits receive in developer welfare. For simplicity and mathematical convenience, and following Finus and Rübbelke (2013), we have thus implicitly assumed the same functional form for primary benefits and ancillary benefits, namely $f(q_i) = bq_i$, with $b > 0$ the marginal benefit of producing the knowledge good. For similar reasons, we assume developers are ex-ante symmetric, i.e. they all share the same utility function. However, depending on whether they join the coalition or not, they may enjoy different levels of welfare *ex-post*.

This latter point becomes clear when considering the group-related social benefits we mentioned above, which accrue only to developers working in a coalition producing technological innovation. The sense of ‘belonging’ to a larger group striving to achieve the same goals, which we defined above as contributing to the *group identity*, is given by $\beta > 0$ in (1). The degree to which fellow coalition members appreciate individual contributions to this group effort, what we called *pro-social reputation* building above, is marked by $\theta > 0$. The larger the divide between the marginal ‘social’ benefit of production b and the purely individual benefit captured by αb , the more an individual contribution is perceived as an achievement by group members. Reputation effects of this kind are also modelled by Holländer (1990) as mentioned earlier, where voluntary cooperative behavior is assumed to be motivated by social approval. This approval is conceptualised as an emotional activity of appreciations: emotions, feelings, but also verbal expressions of group members prompt reactions that measure the subjective value of cooperatively developing public knowledge, i.e. as a function of $b - \alpha b$.¹⁶

We can now go over the possible outcomes of the game, given every possible strategic combination decided on in the membership game taking place in the first stage. Assume first that all developers play simultaneously and non-cooperatively. The Nash equilibrium is then derived by computing the fixed point of the developers’ best response correspondence, yielding a unique payoff vector $\mathbf{u}^o = u(\mathbf{q}^o)$.¹⁷ Instead, when developers decide to produce the knowledge good by forming a coalition, we assume a bargaining process works towards the Pareto optimal outcome. This process may result in a coalition of s members, where s goes from 2 to n , in which case the grand coalition forms. The cooperative outcome of this game is given by the Nash bargaining solution,¹⁸ with the non-cooperative equilibrium pay-off vector $\mathbf{u}^o = (u(q_1^o) \dots u(q_n^o))$ as the threat point of the bargaining process.¹⁹

Following Kolstad (2007) or Finus and Rübbelke (2013) – and without loss of generality – we normalise the strategy space to $q_i \in (0, 1)$ so that there are essentially only two possible strategies for each developer i to play: ‘produce knowledge’ ($q_i = 1$) or not ($q_i = 0$). Now, to model a social dilemma, we assume the social optimum where everyone works together is different from the non-cooperative equilibrium, and impose the following two assumptions.

Assumption 1. *When all developers cooperate, a sufficient condition for knowledge production ($q_i = 1$) to be an equilibrium choice in the grand coalition is given by*

$$nb + \alpha b - c + (\beta + (b - \alpha b)\theta) \geq 0. \quad (2)$$

In other words, assumption 1 makes production profitable if all developers cooperate in the grand coalition. To arrive at a social dilemma, the opposite will have to be true when developers do not cooperate.

Assumption 2. *For developers not to contribute ($q_i = 0$) in the non-cooperative Nash-equilibrium, we need that*

$$b + \alpha b - c < 0. \quad (3)$$

Combining both assumptions, we arrive at the typical prisoner's dilemma outcome: production pays from a global, social perspective but not from an individual one. The question then becomes whether developers will choose to cooperate to overcome this social dilemma. We investigate the stability of such a coalition in the next section.

3.2. *Membership Game: Stability and Profitability of Coalitions*

Each individual developer considers the possible choices (cooperative or non-cooperative) of his counterparts, and his subsequent outcomes defined in the contribution game. A coalition of s members can then only form if technology production pays off, i.e. if the benefits of each contributing member u_i^M outmatch the payoffs under the non-cooperative outcome given by u^o . This kind of *profitability* is guaranteed by

$$u_i^M = sb + \alpha b - c + (\beta + (b - \alpha b)\theta) \geq u(q_i^o) = 0, \quad (4)$$

where, because of (3), non-cooperative developers set an equilibrium production choice of $q_i = 0$, and derive zero utility as a result.

Naturally, the fact that cooperative knowledge production is profitable, is only a minimum requirement for any coalition to form. The main issue undermining coalition-formation is free-riding by non-producers. Here, developers have the incentive to let others form the coalition but share in its produce, without contributing themselves. A coalition will by consequence only form if it is both

$$\text{Internally stable: } u_i^M(s) \geq u_i^{NM}(s-1) \quad \forall i \in S, \quad (5)$$

and

$$\text{Externally stable: } u_i^{NM}(s) > u_i^M(s+1) \quad \forall i \notin S, \quad (6)$$

where S again denotes the set of coalition members, and where we assume that if a developer is indifferent between joining the coalition or staying outside, she will join. This notion of stability draws on the oligopoly literature, where a cartel is defined as stable when there are no incentives for any individual members to leave nor any outsiders to join (d'Aspremont et al. 1983).²⁰ In this sense, when a coalition s is internally stable, then coalition $s-1$ is externally instable as outsiders will want to

join. On the other hand, if that same coalition s is externally stable, then coalition $s + 1$ will be internally unstable since coalition members will want to leave.

Employing the notion of stability given by (5) and (6), we can now verify whether a coalition formed in our setup would be stable. Doing so, we first define the following assumption on the group-based preference structure.

Assumption 3. *The group-based social preferences expressed by β and θ in (1) are such that*

$$b + \alpha b - c + (\beta + (b - \alpha b)\theta) < 0. \quad (7)$$

Since we know from (3) that $b + \alpha b - c < 0$, this assumption implies that social preferences will be less pronounced than the individual preferences for the knowledge good itself, captured by the public and private benefits of production, b and αb respectively. The latter assumption is then used in appendix to prove proposition 1 below, summarising our main stability result.

Proposition 1. *If the social benefits of cooperating in group are not too pronounced, so that assumption 1 holds, a stable coalition of $s^* < n$ members forms. Its break-even point of profitability is given by*

$$s^* = \frac{1}{\gamma} - \alpha - \left(\frac{\beta}{b} + (1 - \alpha)\theta \right), \quad (8)$$

with $\gamma = b/c$. *If group-based benefits are larger, and assumption 1 is violated, the grand coalition forms.*

What the proposition shows, is that when social preferences are less pronounced than the preference for the knowledge good itself -as well as for the private benefits αb deriving from it- a stable coalition of size $s^* < n$ will form. In this case, proposition 1 predicts that higher public benefits of public knowledge measured in terms of costs of production $\frac{b}{c}$ ($= \gamma$), lead to smaller coalition sizes. Because of the widening gap between benefits and costs, less developers are needed to make cooperative production profitable. A standard result in the literature.

Contrary to a model omitting social preferences however, the effect of the private benefits $\alpha b q_i$ are ambiguous here. On the one hand, the private benefits bring about smaller coalitions since public benefits of knowledge $b \sum_j^n q_j$ are needed less to overcome production costs. On the other hand, when group approval of individual achievements expressed by θ is important ($\theta > 1$), a larger weight α leads to larger coalitions *ceteris paribus*. Here then, since cooperation is perceived as being based more on self-interest than on altruistic motives, the larger private gains undercut the extent to which knowledge production is considered by peers as a social achievement. Public benefits from technological knowledge will in this latter case be needed more to uphold developer welfare, resulting in larger coalitions. However, more pronounced preferences for group identity building, captured by β , will mitigate this effect.

In other words, if developers incur considerable private gains from public knowledge production in networked innovation systems, and find peer approval to be important, our model predicts larger coalitions. This coincides with the larger presence of the “aspiring hackers” in the bigger projects of the FLOSS data described earlier (see figure B.2 in appendix), since hackers in general are considered to have a lot to gain individually, but care less for group belonging or identity than they do for peer ap-

preciation (David and Shapiro 2008). Indeed, Lerner and Tirole (2002) consider the participation of hackers as driven by the clear objective to create an external reputation of their expertise. Dalle and David (2008) reach a similar conclusion regarding the category of social hackers, drawn by the community recognition and esteem of technically challenging tasks. Conversely, when coalition members also exhibit strong social preferences favouring group identity building, such as the social programmers or learners in the FLOSS database, smaller coalitions are more likely to form alongside bigger ones, depending on the importance attached to peer approval and the size of the private gains.

Lastly, when group based preferences are large enough to switch around condition (3), joining the coalition simply becomes too alluring for all non-members. In this case, more and more non-members would want to join the coalition and enjoy the individual and group-based benefits. This process continues until every single developer has joined the coalition and the grand coalition forms, so that $s^* = n$.

4. Heterogeneous Social Preferences

Importantly, and even when group-based preferences are such that assumption 1 holds, a stable coalition of s^* members – as defined in proposition 1 – will not form if the community in question lacks the numbers, so that $s^* > n$. In this case, the question becomes whether a larger, yet inevitably more heterogeneous community could overcome the social dilemma instead.

Studying the FLOSS survey data given in figure B.3 in appendix, such a process may indeed be taking place. Engaged in their first projects, groups are often smaller and more homogeneous as well as enjoying larger direct private benefits $\alpha b q_j$, since the learning curve will be at its steepest at this point and leads to a higher weight α . Follow-up projects on the other hand mostly expand in size, suggesting that lower private benefits are compensated by forming larger coalitions. However, and importantly, such larger groups have in all likelihood also gained in diversity and heterogeneity. To study these dynamics, we introduce a heterogeneous community in what follows, where developers can differ in terms of their preferences for group belonging β , as well as reputation building θ .

To fix ideas, let us first suppose a coalition of s members forms for a start-up project out of a community of n identical developers. Suppose also that assumption 1 holds, in which case $s = s^* < n$. Then assume that, by moving from the first to the next projects, the weight of private appreciation α goes down considerably because, as described above, the learning curve starts to level off. Now, whether this results in the coalition breaking up because its required size characterised by proposition 1 is larger than the community size itself, also depends on social preferences. If developers are highly sensitive to the kind of group approval captured by θ , we learn from proposition 1 that this mitigates the increase in required coalition size s^* . Indeed, if $\theta > 1$, the required coalition size would even go down *ceteris paribus*. As α drops going from the first to the follow-up projects, producing public knowledge is valued as more of a social achievement by peers so that what a smaller coalition loses in terms of produced public knowledge $b \sum_j^n q_j$, it gains in group approval. Even though they represent a minority in the FLOSS database, this would explain why there are groups that stick to their initial size in follow-up projects in figure B.3 (if $\theta = 1$), or have their numbers shrink (if $\theta > 1$).

Inversely, if peer effects and group approval play a smaller part in developer welfare

so that $\theta < 1$, the required coalition size is more likely to exceed the community's size after a considerable drop in α , leading to a situation where $s^* > n$. But does this mean all further cooperation is ruled out? As mentioned above, The FLOSS data in figure B.3 point in the opposite direction, as cooperation in a majority of cases takes on larger forms in larger coalitions for follow-up projects. Indeed, other communities may join the ranks of our first community, which would come out reinforced as a result. The only remaining question is then whether such heterogeneous, merged communities can support stable coalitions. We investigate in what follows.

Assume a first community of n_1 developers has stronger social preferences for group belonging $\bar{\beta}$ than for group approval $\underline{\theta}$ so that $\underline{\theta} < \bar{\beta} < 1$, where the latter inequality is in line with the intuition underpinning assumption 1. Applying (5), internal stability is then established if for each member of the coalition we have that

$$u_{1i}^M(s_1) = s_1 b + \alpha b - c + (\bar{\beta} + (b - \alpha b)\underline{\theta}) \geq 0 = u_{1i}^{NM}(s_1 - 1). \quad (9)$$

Now consider a second community which, for the sake of simplicity, has exactly the opposite preferences as compared to the first community, so that $\underline{\theta} = \underline{\beta}$ and $\bar{\theta} = \bar{\beta}$. Internal stability for this second community then requires that

$$u_{2i}^M(s_2) = s_2 b + \alpha b - c + (\underline{\beta} + (b - \alpha b)\bar{\theta}) \geq 0 = u_{2i}^{NM}(s_2 - 1). \quad (10)$$

Following proposition 1, both (9) and (10) implicitly define the stable coalition size for each community respectively. Next, we assume these are such that $s_2^* > n_2$ and $s_1^* > n_1$ after completion of a start-up project. This reflects a considerable decrease of α moving towards follow-up or second projects, where the flattening of the learning curve again requires larger public benefits to compensate for smaller private benefits, and thus brings about larger coalitions since we have assumed above that $\theta < 1$. Assuming furthermore that the parameter values of our model implied that $s_1^* = s_2^*$ during the start-up project, we know from proposition 1 that $s_1^* > s_2^*$ after the drop in α , since $\bar{\theta} > \underline{\theta}$. Suppose now that both communities decide to merge for a follow-up project, so that $n = n_1 + n_2$. The stable coalition would then be characterised by

$$s^* = s_1^* = \frac{c - \alpha b - (\bar{\beta} + (b - \alpha b)\underline{\theta})}{b}, \quad (11)$$

if, of course, $s^* < n$. Logically, s^* yields an internally as well as externally stable coalition for the community counting n_1 developers, since (11) follows from (9). For the second community on the other hand, a smaller coalition size s_2^* defined by (10), would already have ensured stability. However, in our merged setting a coalition of size s^* given by (11) is internally stable for this second community as well, since for all coalition members of this community we have that

$$u_{2i}^M(s^*) = s^* b + \alpha b - c + (\underline{\beta} + (b - \alpha b)\bar{\theta}) \geq 0 = u_{2i}^{NM}(s^* - 1), \quad (12)$$

where the last equality, $u_{2i}^{NM}(s^* - 1) = 0$ holds for the simple reason that at size $(s^* - 1)$, coalition members hailing from our first community with n_1 developers will defect without exception. Under complete and perfect information, the n_2 developers of the second community take this potential breakdown of cooperation into account, and act accordingly by contributing. Lastly, because $s_1^* > s_2^*$, the coalition characterised by

(11) will also be externally stable with respect to developers of this second community. We generalise these findings in proposition 2.

Proposition 2. *Let s_1^* and s_2^* be the stable coalition sizes emerging from two communities of developers, which are different in terms of social preferences so that $s_1^* > s_2^*$. Furthermore, assume both communities are insufficiently large for the coalitions to form separately, so that $s_1^* > n_1$ and $s_2^* > n_2$. The merged community $n = n_1 + n_2$ then gives rise to:*

- (1) *A stable coalition of size $s^* = s_1^*$, if $n \geq s_1^*$*
- (2) *Non-cooperation if $n < s_1^*$*

To put our findings in more general terms, proposition 2 predicts that mixed coalitions of heterogeneous agents will be stable, even when smaller, more homogeneous coalitions fail to form. Consequently, smaller groups with homogeneous preferences can overcome the social dilemma by broadening their base, resulting in larger coalitions made up out of diverse sub-groups.

Lastly, we can show under which conditions proposition 2 carries over to a setting where assumption 1 does not hold, in which case we would start off with grand coalitions. Suppose assumption 1 does not hold for both communities, because of very pronounced group-based social preferences. We then get

$$b + \alpha b - c + (\beta + (b - \alpha b)\theta) \geq 0. \quad (13)$$

In this case $s_1^* = n_1$ and $s_2^* = n_2$, and the only stable coalitions would be the grand coalitions. Any difference between the heterogeneous communities at this point, would derive strictly from differences in *community size* n .

As soon as private benefits α decrease after the first start-up projects however, (13) could tilt the other way if $\theta > 1$. In this case, the stable coalition size will no longer be equal to the community size, and the question becomes whether

$$s_1^* \leq n_1 \text{ and } s_2^* \leq n_2. \quad (14)$$

If the required coalition size for follow-up projects exceeds the community size in both cases, which is the premise for proposition 2, we are back in the situation we described before. Of course, in the opposite case coalition sizes would actually shrink in follow-up projects. This would then further rationalise the remaining follow-up flows coming out of the FLOSS data. The same goes for a setting where $\theta \leq 1$ and (13) continues to hold if α decreases, in which case the coalition size remains unchanged going from one project to another.

5. Conclusion

This paper has concentrated on the process of production and dissemination of public knowledge goods in the context of technological innovation generated by coalitions of innovators in networked innovation systems. In particular, we have analysed the ambiguity of private non-market benefits in fostering coalition formation to produce publicly available technological knowledge used in collaborative scientific research, such as open source software or large-scale public databases, which play an important role in contemporary life science research and innovation. Such private benefits to individual innovators contributing to these intangible research assets are considered as an important driver for the proliferation of pooled knowledge goods in distributed innovation networks. Private benefits to contributors that have been partially studied in the literature are of two kinds: (1) direct private benefits such as individual problem solving or higher citation rates for researchers; (2) satisfaction of social preferences such as group belonging, group identity, pro-social individual reputation and status.

In the current literature on coalition formation for public good provision, the effect of these two kinds of benefits tied in knowledge production is mostly considered to bring about smaller, stable coalition sizes. No theoretical explanation of the fact that, in some cases, the increase in focus on private non-market benefits to individual scientists lead to smaller coalitions and, in some cases, to larger ones is provided in the literature. To build a more general model, this paper integrated the theory of public goods and a social psychological model of group related social preferences into coalition theory. This allowed us to show the contrasted effects of social group identity and social approval/disapproval of individual pro-social attitudes on the coalition formation in networked innovation systems. The presence of agents giving high value to their individual pro-social reputation within a social network can make larger coalitions necessary in order to keep coalition formation stable.

Even though we used a dataset from open source software collaborations for testing our model, the model is a general one and therefore the results of the analysis apply to a broad set of voluntary pooled public knowledge goods,. This comparison shows that the integration of social psychology in public good theory is relevant for understanding community formation behavior in this field. In addition, the model predicts that mixed coalitions of heterogeneous agents can be stable even when smaller, more homogeneous coalitions fail to form. This also contains an important lesson for the building of research collaborations in digitally networked life science research. Indeed, building multi-purpose, more heterogeneous, networks might be essential in many cases of up-scaling of voluntary contributed pools of intangible knowledge assets. The latter is also corroborated by the literature on the importance of bridging social capital and the role of knowledge brokers in large-scale science networks (Tortoriello et al. (2012); Phelps et al. (2012)). However, additional empirical research is needed to further corroborate this finding.

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Notes

¹We also refer to Swan and Scarbrough (2005), for an exhaustive literature review on networked innovation.

²As shown by Harison and Cowan (2004), open-source software projects have also become relevant to firms in the sense that a certain degree of disclosure of development processes can boost profit-margins when revenues are responsive to this kind of 'openness'.

³David and Keely (2003) e.g., use the same definition of coalition-building ("network" formation) used in our paper. However, they model the process of coalition formation among research units that seek competitive funding from a supra-regional program, rather than developing new technology.

⁴See e.g. Lessig (2001), Benkler (2006), Hess et al. (2008), or David (2008).

⁵The latter however does not imply that the core group of developers remains invariably composed of the exact *same* people over time, as shown by Dalle and David (2008) in a simulation model of large-scale open source software projects. Because of this 'turnover' of developers, the core group is more accurately described as a 'quasi-stable' community of agents, which nonetheless always has the appropriate size to intervene in the accessible parts of the code-base requiring further development.

⁶As has been shown elsewhere, this joint public/private character can have different effects on contributions. If the private benefit has a market substitute, the joint character can undermine the willingness to contribute to the public good in situations where the market price of the substitute is sufficiently low (Cornes and Sandler 1984). See also Andreoni (1988), Kotchen (2006, 2009) and Vicary (1997, 2000) for opposite effects in the absence of market substitutes.

⁷More generally, the private benefits to voluntary cooperation in this context are emphasised in many other studies of public knowledge goods. One can think for example of open access databases with tailor-made data management tools that benefit specific communities and individuals (David 2005), or hybrid funding arrangements – including both market and non-market tools – for openly available culture products on the internet (Lessig 2008).

⁸This individual level need not be purely self-interested in the negative sense of the word, but can also have an altruistic quality. See e.g. Gächter et al. (2010) and Garriga et al. (2012) for a discussion on the effects of inequality aversion, fairness and reciprocity in the private-collective context.

⁹Along these lines, (Benkler 2006) has found that, in mixed or complex incentive schemes, such as those at stake in these large-scale digital collaboration networks, participants are driven more by social motivations (especially reputational benefits) and intrinsic motivations (such as ethics, curiosity, and other personal values) than by the prospect of direct monetary rewards alone. In the life sciences, where potential commercial rewards from basic research are always a factor, especially with regard to university-driven research, Allarakhia found that the reciprocity benefits to be gained from participation in research consortia, are often the key motivational factor (Allarakhia et al. 2010).

¹⁰Hoel (1992), Carraro and Siniscalco (1993) or Barrett (1994) laid the groundwork here, followed by e.g. Barrett (2003), Ulph (2004) or Kolstad (2007). Finus (2008) or Hovi et al. (2015) provide a survey of this large body of literature.

¹¹David and Keely (2003) evaluate alternative possible external public R&D funding rules to determine the impact on coalition formation.

¹²See e.g. also Kosfeld et al. (2009) or McEvoy (2010) on this issue.

¹³In Sandler and Arce (2007), such impure public good production is set in the context of international development cooperation. Here, donor countries can also derive private benefits – e.g. through the sale of technology – in addition to the global public good benefits related to the increase in economic development and poverty alleviation. Finus and Rübhelke (2013) go on to study such 'ancillary benefits' of public good provision in a setting of international environmental agreements.

¹⁴A Nash equilibrium in this membership game is therefore a set of announcements for which no developer will do better by unilaterally changing his or her announcement.

¹⁵See e.g. Hoel (1992), Carraro and Siniscalco (1993), Barrett (1994) or Kolstad (2007). For the implications of the formation of multiple coalitions, see Carraro (2003), or Hovi et al. (2015) for a discussion.

¹⁶Note furthermore that under the current specification it is possible for private benefits to outweigh public benefits, to the extent that the reputation effect becomes negative if $\alpha > 1$ in (1). Comparing both equations in (1), developer welfare could consequently be lower when producing inside the coalition as opposed to outside, given certain parameter values. However, since we have modeled the game in such a way that it never pays for developers to produce public knowledge outside of the coalition, this possibility does not affect our equilibrium

results. Indeed, if the coalition is profitable and internally stable – as defined in section 3.2 and resulting from assumptions 2 and 3, and expression (4) – no developer j inside the coalition will have the incentive to leave, whilst no developer i outside of the coalition will want to produce on his own. The situation where e.g. $u_i = \sum_j^s q_j - cq_i + \alpha bq_i$ thus never presents itself. In subgame perfect equilibrium, welfare for developers i outside of the stable coalition is simply $u_i = \sum_j^{s-i} q_j$, and will always be larger than welfare inside the coalition because of the internal and external stability implicitly imposed by assumption 3. If one coalition member were to leave the stable coalition to reap these higher benefits however, cooperation breaks down and overall welfare would be zero. See also footnote 19 on the importance of the threat point to micro-found such an outcome in a non-cooperative setting.

¹⁷By construction of our finite strategy game, the non-cooperative Nash equilibrium will be unique. With $R(\mathbf{q}) = \{\hat{q} = (\hat{q}_1 \dots \hat{q}_n)\}$ the vector correspondence of best responses to the strategy profile $\mathbf{q} = (q_1 \dots q_n)$ – where \hat{q}_i is a best response to $(q_1, \dots, q_{i-1}, q_{i+1}, \dots, q_n)$ for each i – and given that $R(\mathbf{q})$ is upper semi-continuous and convex-valued, we know by Kakutani’s fixed point theorem there is some $\mathbf{q}^o \in R(\mathbf{q})$. Given assumption 2, we also know this equilibrium strategy profile is unique.

¹⁸This assumption is not essential, any bargaining solution in the literature would deliver similar results.

¹⁹As is well known, an outcome under axiomatic Nash bargaining is liable to suppress many details of the decision making process. In order to rationalise such an outcome using a more strategic approach, the disagreement point is of vital importance. The seminal work of Binmore et al. (1986) for example, presents a non-cooperative bargaining model of alternating offers which describes the bargaining process – including initial bargaining positions and motives – explicitly. The bargaining motive identified by Binmore et al. (1986) which arguably resonates the most with our setting of networked innovation, relates to the fear of losing the opportunity to reach an agreement if negotiations are drawn out for too long. In this line of reasoning, the threat point can be thought of in its literal sense: in the event of a breakdown of the bargaining process the opportunity developers jointly strive to exploit will be lost, as not a single developer will produce. The threat of breakdown could for example come from another network of developers reaching an agreement sooner, thus gaining first-mover advantage whilst developers of the first community are still bargaining.

²⁰Building on d’Aspremont et al. (1983), Donsimoni et al. (1986) shows that stable coalitions exist under fairly general conditions. Alternative notions of stability leading to potentially larger coalitions, such as ‘farsighted stability’, are considered by Osmani and Tol (2009) and in Carraro (2003).

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Appendix A. Proof of proposition 1

First, suppose one coalition member leaves a coalition of s members formed in our setup, and that the $(s-1)$ members continue to produce because $u_i^M(s-1) = (s-1)b + \alpha b - c + (\beta + (b - \alpha b)\theta) \geq 0$ so that the free-rider receives a payoff of $u_i^{NM}(s-1) = (s-1)b$. Now, as defined in (5), internal stability requires

$$u_i^M(s) = sb + \alpha b - c + (\beta + (b - \alpha b)\theta) \geq (s-1)b = u_i^{NM}(s-1), \quad (\text{A1})$$

which boils down to

$$u_i^M(s) = b + \alpha b - c + (\beta + (b - \alpha b)\theta) \geq 0, \quad (\text{A2})$$

and which we have ruled out under assumption 1.

We can then move on to the second case, where the $(s-1)$ remaining members cease production once the free-rider leaves because $u_i^M(s-1) = (s-1)b + \alpha b - c + (\beta + (b - \alpha b)\theta) < 0$, with $u_i^{NM}(s-1) = 0$ as a result. Internal stability now requires that

$$u_i^M(s) = sb + \alpha b - c + (\beta + (b - \alpha b)\theta) \geq 0 = u_i^{NM}(s-1), \quad (\text{A3})$$

which holds by our initial condition of profitability (4), in effect rendering cooperation profitable in the first place. As a result, it is this second case which characterises an internally stable coalition. Setting $s = s^*$ in (A3) and re-working, internal stability thus implies that

$$s^* \geq \frac{c - \alpha b - (\beta + (b - \alpha b)\theta)}{b} \quad \text{and} \quad s^* - 1 < \frac{c - \alpha b - (\beta + (b - \alpha b)\theta)}{b}. \quad (\text{A4})$$

Otherwise put, s^* is the largest integer of the relation $\frac{c - \alpha b - (\beta + (b - \alpha b)\theta)}{b}$, or, $s^* = I\left(\frac{c - \alpha b - (\beta + (b - \alpha b)\theta)}{b}\right)$. For any $s > s^*$, members would continue to produce after one member left the coalition, which cannot be an equilibrium as argued above. Contrarily, when $s < s^*$, members would not produce at all since production is not profitable, so no coalition would form.

Now, in order for the same coalition to be externally stable, (6) has to apply so that

$$u_i^M(s+1) = (s+1)b + \alpha b - c + (\beta + (b - \alpha b)\theta) < sb = u_i^{NM}(s), \quad (\text{A5})$$

where the case of an internally stable coalition of $(s+1)$ forming initially is again ruled out because of (7). Re-writing (A5) furthermore, we arrive at the initial condition given by (7). Consequently, and re-working (A4), the stable break-even point of profitability s^* in our setup is given by

$$s^* = \frac{1}{\gamma} - \alpha - \left(\frac{\beta}{b} + (1 - \alpha)\theta\right), \quad (\text{A6})$$

where we write the marginal public benefit b of knowledge production in terms of costs of production $\frac{b}{c}$ ($= \gamma$), and where we approximate $I\left(\frac{c - \alpha b - (\beta + (b - \alpha b)\theta)}{b}\right)$ by $\frac{c - \alpha b - (\beta + (b - \alpha b)\theta)}{b}$.

Suppose now that social preferences are so pronounced that assumption 1 is no longer valid. In this case, internal stability is still guaranteed for every possible coalition $s \leq n$, as (A2) would hold across the board. External stability on the other hand, would be violated for every but one coalition: the grand coalition. Indeed, (A5) breaks down at every coalition size $s < n$ in this case, as more and more non-members would want to join the coalition and enjoy the individual and group-based benefits. This process continues until every single developer has joined the coalition. ■

Appendix B. Figures: the case of FLOSS developers

Figure B1. Key characteristics of motivational clusters

Cluster	Profile	Key characteristics
1	Professionals	Non-ideological, expert, self-employed or company-sponsored to collaborate on FLOSS projects
2	Aspiring hackers	No need to modify existing code but like fixing bugs and learning new programs
3	Social learners	Become better programmers, learn how programs work, work with like-minded, "give back to community," support FLOSS ideology
4	Social programmers	Experienced, employment related needs to use, modify existing code and fix bugs; project choice influenced by social connections with other developers
5	"User-innovators"	Modifying existing software unimportant, learning and interacting with like-minded others unimportant; wanted to "give back to community," and launched own project

Source: David and Shapiro, 2008, p. 384.

Figure B2. Distribution of small and large project participants by motivation profiles identified by cluster analysis of FLOSS-US survey respondent

Cluster	Small project and large project populations only			
		Small (1-2)	Large (>29)	Total
1 (<i>Professionals</i>)	%	5.2	5.5	5.3
	N	22	10	32
2 (<i>Aspiring hackers</i>)	%	7.6	16.7	10.3
	N	32	30	62
3 (<i>Social learners</i>)	%	49.1	45.0	47.8
	N	207	81	288
4 (<i>Social programmers</i>)	%	14.0	12.8	13.6
	N	59	23	82
5 (<i>User-innovators</i>)	%	24.2	20.0	22.9
	N	102	36	138
Total	%	100.0	100.0	100.0
	N	422	180	602
Pearson chi-squared(4)			11.09	
Prob > chi-squared			0.03	
Chi-squared goodness-of-fit(4)			60.75	
Prob > chi-squared			0.00	

Source: David and Shapiro, 2008, p. 394.

Figure B3. Transition matrix for developers' movements among projects of different membership sizes

Current/most recent project	First project		
	Small 1-2	Medium 3-29	Large >29
<i>Panel A: all developers</i>			
Small	111	42	32
Medium	30	80	22
Large	13	7	47
Pearson chi-squared(4)	140.58		
Prob > chi-squared	0.00		
<i>Panel B: developers for whom first and current/most recent projects were different</i>			
Large	51	42	32
Medium	30	29	22
Small	13	7	18
Pearson chi-squared(4)	7.96		
Prob > chi-squared	0.09		

Source: David and Shapiro, 2008, p. 389.