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The dynamics of cooperation in society. The ECHO-EGN Model

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Abstract

Understanding the dynamics of cooperative behavior of individuals in complex societies represents a fundamental research question which puzzles scientists working in heterogeneous fields. Many studies have been developed using the unitary agent assumption, which embeds the idea that when making decisions, individuals share the same socio-cultural parameters. In this paper, we propose the ECHO-EGN model, based on Evolutionary Game Theory, which relaxes this strong assumption by considering the heterogeneity of three fundamental socio-cultural aspects ruling the behavior of groups of people: the propensity to be more cooperative with members of the same group (Endogamy), the propensity to cooperate with the public domain (Civicness) and the propensity to prefer connections with members of the same group (Homophily). The ECHO-EGN model is shown to have high performance in describing real world behavior of interacting individuals living in complex environments. Extensive numerical experiments allowing the comparison of real data and model simulations confirmed that the introduction of the above mechanisms enhances the realism in the modelling of cooperation dynamics. Additionally, theoretical findings allow us to conclude that Endogamy may limit significantly the emergence of cooperation.

1 Introduction

The modelling of the evolution of cooperation in social networks is a consolidated stream of research at the boundary of mathematics and social sciences. The main focus of this line of work is the understanding of how cooperation can

develop in a population of rational agents based on selfish motivations. Evolutionary Game Theory assumed the role of main framework (e.g. [1]), with many studies adopting the Prisoner Dilemma as analytical tool to model the emergence of mutually beneficial interactions among rational decision makers [2–7].

These studies model the population dynamics under the basic assumption of the unitary agent, namely the idea that the social network is comprised by agents following the same model of decision making, based on the optimization of own utility. This assumption finds expression in two main computational settings - first, the invariance of the decision-maker - i.e. all agents follow the same model of choice, based on the maximization of utility; second, the well-mixed population design - i.e. the fact that the agent has generally the same chance of interaction with all others.

It has to be noted that in recent years more complex models of population have been introduced, characterized by spatial structure like lattices [8]. Also more complex organized structures have been taken into account, assuming that agent interactions take place according to the topology of a network of interconnections (e.g. [6,7,9]). However, these innovations concern the second aspect of the unitary agent assumption only - the well-mixed population design - and only partially. Indeed, they imply a variable distribution of connections among agents, yet as a product of the network’s spatial structure, rather than as a function of *a priori* inherently variable agents’ preferences.

The idealized, input-centered, normative approach implied in the unitary agent assumption limits the realism of research and therefore the chance to model natural social settings for the sake of understanding the current and future actual evolution of historically concrete human groups, which are inherently plural (e.g. [10–12]). The latter aim requires an output-centered approach, namely an approach which is mainly interested in understanding the potential evolution of given input states, and to draw from it the identification of structural and individual conditions improving the overall level of cooperation.

The aim of this paper is to present a culturally informed evolutionary game model of network equation, named ECHO-EGN, that provides a decisive contribution to overcome the unrealism of the unitary agent assumption in modelling cooperation evolution. ECHO-EGN integrates the psycho-social theory of the inherent pluralism of social networks in the framework of Evolutionary Game Theory. ECHO-EGN is an output-centered model, which is expected to have both theoretical and application values. From a theoretical perspective, it increases the ecological validity of current models, and in so doing it makes the formal analysis of cooperative dynamics more complete. From an application standpoint, it enables efficacious simulation of evolution of cooperative scenario for the sake of policy decision making.

The purpose of the paper is twofold. First, it intends to present and to validate ECHO-EGN; second, based on this first result, it analyses the model in order to highlight its capacity to identify relevant conceptual properties of the evolution

81 of cooperation in social networks.

82 The paper is organized in the following way. First, we discuss critically
83 the unitary agent assumption in the light of the psycho-social conceptualiza-
84 tion of the relation between mind, culture and society. Second, ECHO-EGN
85 is presented, proposed as an extension of a previous model (EGN) aimed at
86 accounting for the presence of different groups of agents. Third, an empirical
87 validation of the model is provided, based on a simulation design - the observed
88 levels of cooperation in a cluster of actual social networks is compared with
89 the levels obtained by corresponding ECHO-EGN simulations. Fourth, analytic
90 components of the model are developed in order to shed light on the properties
91 of cooperative dynamics. Discussion and conclusions are devoted to highlighting
92 the elements of interest of ECHO-EGN as well as limitations and perspectives
93 of the current stage of its development.

94 2 The cultural variability of social networks

95 The last three-four decades have witnessed the progressive rediscovering of the
96 role culture plays in political and economic affairs by all social sciences (e.g.
97 [13–17]). At the boundaries between psychology, economics, political science
98 and sociology, the concept of social capital [18,19] has provided a view of social
99 behavior, and more in general of the functioning of society and institutions, as
100 depending on the incidence of trust - namely, a factor deeply rooted in cultural
101 contexts.

102 Within this general perspective, several authors have proposed a view of
103 culture as the *source of human variability*. According to this view, culture is
104 a network of complementary and conflicting meanings (e.g. [10,17]); members
105 of a population share the same network of meanings, yet they assume different
106 positions in it - i.e. they adhere to a certain subset of meanings (e.g. a given
107 worldview [20], a system of values [16]), thus rejecting the conflicting ones. As
108 result, each subset of meanings frames the way of thinking and acting of the
109 segment of the population adhering to it. In doing so, the shared network of
110 meanings works as both the basic common ground and what makes members of
111 the social group different from each other.

112 The inherent cultural pluralism of the social group finds expression in three
113 major forms of population variability.

114 *Homophily*. Homophily is the propensity of an individual to prefer to con-
115 nect to members of the same group instead of the out-group. For instance,
116 McPherson and colleagues ([21], p. 416) define it as the tendency for friend-
117 ships “between similar people [to occur] at a higher rate than among dis- similar
118 people”. As it was highlighted (e.g. [22,23]) Homophily is distributed heteroge-
119 neously within the social group, as a result of cultural drivers.

120 *Endogamy*. Here we use this concept in the broad sense, to denote the
121 propensity to be more cooperative with members of one’s group than with mem-
122 bers of other groups. Cultural segments differ as to the degree of Endogamy.
123 Familist cultures [24] as well as cultures fostering identity motives [25] tend

124 to increase the member's Endogamy, namely to make them more inclined to
 125 cooperate with in-group members than with out-group members. In contrast,
 126 universalist values make adherents cooperate with in-group and out-group sim-
 127 ilarly [26].

128 *Civiness.* Any social interaction is embedded in a web of institutions -
 129 formal and informal norms and underpinning meanings that make individual
 130 actions interconnected. As used here, Civiness consists of the valorisation
 131 of such embeddedness [25, 27]. Accordingly, Civiness can be conceived of as
 132 the extension of the propensity to cooperate to the public domain - namely,
 133 to the relation with what is extraneous ([10], chapter 9): it consists of the
 134 actors' capacity of self-regulation, by reason of the rules of the collective game
 135 underlying the production of common goods [28].

136 **3 Evolutionary games for culturally plural so-** 137 **cial groups: the ECHO-EGN Model**

138 **3.1 The starting point. The SR-EGN model**

139 The ECHO-EGN Model is a development of a previous model. In its first ver-
 140 sion - the Evolutionary Game on Network equation (EGN), it was designed
 141 to account for specific characteristics of individuals, beyond the assumption of
 142 the unitary agent. EGN described the dynamical evolution of the coopera-
 143 tion of each player, located inside a network of connections, which is engaged
 144 in several 2-player games with neighbors over time. Thus, EGN introduced a
 145 variable distribution of connections in the mathematical modelling of social net-
 146 works (cf. [29, 30]). A further element able to foster the presence of differences
 147 among individuals was introduced in subsequent papers, where self-regulation
 148 mechanisms were considered in the framework of the prisoner's dilemma [31].
 149 Specifically, the self-regulation mechanisms act as fundamental drivers able to
 150 promote cooperation at the local and global levels [32].

151
 152 The extended version of the original model (called SR-EGN) [32] considers
 153 a population of N individuals, $v \in \{1, \dots, N\} = \mathcal{V}$ arranged on an undirected
 154 graph of connections, defined by the symmetric adjacency matrix $\mathbf{A} = \{a_{v,w}\} \in$
 155 $\{0, 1\}^{N \times N}$. When $a_{v,w} = 1$, then v and w are neighbors, while $a_{v,w} = 0$ means
 156 that v and w are not connected. We will refer to the number of neighbors of a
 157 generic player v as its degree, then $k_v = \sum_{w=1}^N a_{v,w}$.

158
 159 The topology of the connection network among individuals is assumed to be
 160 random with a scale-free distribution and average degree $\bar{k}$ [3, 33, 34]. Of note,
 161 the random scale-free distribution makes agents differ as to their connectivity;
 162 this is consistent with the assumption that connectivity is distributed heteroge-
 163 neously over the social group, as a result of cultural norms - (e.g [22, 23]).

164 Each member of the population plays 2-player games with all its neighbors

continuously over time. The games played are assumed to be Prisoner's dilemmas, where the payoff earned by player v against w is described by the matrix:

$$\mathbf{B}_{v,w} = \begin{bmatrix} R_{v,w} & S_{v,w} \\ T_{v,w} & P_{v,w} \end{bmatrix},$$

where $R_{v,w}$ is the reward for mutual cooperation, $T_{v,w}$ is the temptation to defect when the opponent cooperates, $S_{v,w}$ is the sucker's payoff earned by a cooperative player when the opponent is a free rider, and $P_{v,w}$ is the punishment for mutual defection. A Prisoner's dilemma game is characterized by the relation $T_{v,w} > R_{v,w} > P_{v,w} > S_{v,w}$. In this work, we assume that $R_{v,w} = 1$, $P_{v,w} = 0$, $T_{v,w} > 1$ and $S_{v,w} < 0$. Moreover, we assume that the temptation to defect is stronger than the fear of being betrayed, i.e. $T_{v,w} - 1 > -S_{v,w}$.

According to [32], each player plays also a game against himself, which acts as a self-regulatory term. We denote with $\mathbf{B}_{v,v}$ the payoff matrix related to this game, and with β_v the strength of the self game. Notice that the self-game can be different with respect to the standard game [32].

Thus, taken as a whole, the level of cooperation of a generic player v is denoted by $x_v \in [0, 1]$, and its dynamics is ruled by the following equation:

$$\dot{x}_v = x_v(1 - x_v) \left\{ k_v [(1 - T_{v,w} - S_{v,w})\bar{x}_v + S_{v,w}] - \beta_v [(1 - T_{v,v} - S_{v,v})x_v + S_{v,v}] \right\}, \quad (1)$$

where $\dot{x}_v$ denotes the time derivative of x_v , i.e. $\dot{x}_v = dx_v/dt$ and $\bar{x}_v = \frac{1}{k_v} \sum_{w=1}^N a_{v,w} x_w$ is the equivalent player of individual v , i.e. the average cooperation of all its neighbors.

In a nutshell, this equation states that the steady state level of cooperation is one among full defection, full cooperation and intermediate values of cooperation/defection. The effective level of cooperation is then reached according to a selection mechanism ensuring the maximization of the population reward, together with the satisfaction of self-regulation mechanisms depending on parameter β_v . Thus, the latter acts as an inertial factor able to counteract the natural tendency of individuals towards defection.

3.2 The ECHO-EGN group-specific features of cultural variability

In order to represent the cultural variability of the social network - i.e. the culturally driven heterogeneous distributions of Homophily, Endogamy, and Civicness among agents - the ECHO-EGN model adopts a grouped population design.

196 The population $\mathcal{V}$ is assumed to be subdivided into M groups, namely
 197 $\mathcal{G}_1, \dots, \mathcal{G}_M$, such that $\bigcup_{g=1}^M \mathcal{G}_g = \mathcal{V}$, and $\mathcal{G}_g \cap \mathcal{G}_j = \emptyset$, for all $g \neq j$. The size
 198 of group $\mathcal{G}_g$ is N_g . Hence, the share of population belonging to group $\mathcal{G}_g$ is
 199 $\delta_g = \frac{N_g}{N} \in (0, 1)$. Each group is assumed to have a scale-free distribution of the
 200 degrees, with average equal to $\bar{k}_g$.

201 When playing a game, the individual distinguishes between members of the
 202 same (*affine*) and of different (*non affine*) groups. From now on, the corre-
 203 sponding quantities will be indicated by the superscript A for affine players,
 204 and N for non affine players. For example, k_v^A and k_v^N are the number of links of
 205 player v with affine and non-affine players, respectively, i.e. $k_v^A = \sum_{w \in \mathcal{G}_g} a_{v,w}$
 206 and $k_v^N = \sum_{w \in \mathcal{V} \setminus \mathcal{G}_g} a_{v,w}$. Notice that $k_v = k_v^A + k_v^N$.

207 In the following subsections, the ECHO-EGN model specifications of Ho-
 208 mophily, Endogamy, and Civicness will be introduced.

209 3.2.1 Homophily

210 As stated above, Homophily is the propensity of an individual to prefer connec-
 211 tions with members of the same group. In order to account for this property,
 212 a rewiring process has been carried out to modify the initial network of con-
 213 nections, according to a given probability, specific for each group, and denoted
 214 by the Homophily factor $h_g \in [0, 1]$. All details on the algorithm used for the
 215 rewiring phase are given in Appendix A.

216 3.2.2 Endogamy

217 As stated above, Endogamy is the tendency of individuals to be more coop-
 218 erative with members of the same group (affine players). The parameter e_g
 219 affects the structure of the payoff matrix played in games with affine individu-
 220 als. Specifically, given $v \in \mathcal{G}_g$ and $w \in \mathcal{V}$ with $a_{v,w} = 1$, we define:

$$\mathbf{B}_{v,w} = \begin{cases} \mathbf{B}^N & \text{if } w \notin \mathcal{G}_g \\ \mathbf{B}_g^A & \text{if } w \in \mathcal{G}_g \end{cases},$$

where

$$\mathbf{B}^N = \begin{bmatrix} 1 & S^N \\ T^N & 0 \end{bmatrix}$$

221 is the payoff matrix used with non affine players, and

$$\mathbf{B}_g^A = \begin{bmatrix} 1 & S_g^A \\ T_g^A & 0 \end{bmatrix},$$

222 is the payoff matrix used with affine players, where $T_g^A = (1 - e_g)T^N$ and $S_g^A =$
 223 $(1 - e_g)S^N$. Coherently, the payoff matrix of the self-game is $\mathbf{B}_{v,v} = \mathbf{B}_g^A$.

224 3.2.3 Civickness

225 An important assumption of the present model is that different groups show
 226 different levels of Civickness, named c_g . In the SR-EGN model, Civickness is
 227 naturally embodied by parameter β_v , which maps the self-regulation mechanism
 228 constraining the agent's selfish attitude.

229 Moreover, we assume that all members of a given group share the same self-
 230 regulation parameter, which depends on the Civickness value c_g of the group,
 231 according to the following formula:

$$\beta_v = \rho^N \bar{k}_g' \frac{(1 + c_g)^2}{2} \quad \forall v \in \mathcal{G}_g. \quad (2)$$

232 where $\rho^N = \frac{1-T^N}{S^N}$ and $\bar{k}_g'$ is the effective average degree of group g .

Figure 1: Pictorial representation of the function β_v reported in (2) (blue), accounting for the Civickness parameters and its comparison with a linear scaling (red).

233 This equation assumes that the Civickness parameters c_g determine an in-
 234 crease (when $c_g > 0.4$), a reduction (when $c_g < 0.4$) and no change (when
 235 $c_g = 0.4$) of the self-regulation parameters β_v with respect to a critical value
 236 $\rho^N \bar{k}_g'$, introduced by Theorem 5 of [32] and discussed in Appendix B of the
 237 present paper. The meaning of the self-regulation parameters β_v is discussed in
 238 Section 5. The choice of a quadratic function, reported in red in Figure 1, is
 239 reasonable under the assumption that the parameters β_v take values lower than
 240 the critical value $\rho^N \bar{k}_g'$, so that individuals are left free to choose their orienta-
 241 tion with respect to cooperation. Furthermore, the quadratic term ensures that
 242 β_v is always lower than a linearly scaled factor, i.e. $\rho^N \bar{k}_g'(1 + c_g)$ (see blue line
 243 of Figure 1), thus making the effect of Civickness weaker.

244

245 Thus, the label "ECHO-EGN" can be intended both to mean the model's
 246 main purpose - the increase of ecological validity - and the reference to the three
 247 parameters of cultural variability - Endogamy, Civicness, and HOMophily.

248 3.3 The ECHO-EGN equation

249 Using these assumptions, equation (1) for player $v \in \mathcal{G}_g$ can be rewritten as
 250 follows:

$$\dot{x}_v = x_v(1 - x_v) \left\{ \begin{aligned} & k_v^A [(1 - T_g^A - S_g^A) \bar{x}_v^A + S_g^A] \\ & + k_v^N [(1 - T^N - S^N) \bar{x}_v^N + S^N] \\ & - \beta_v [(1 - T_g^A - S_g^A) x_v + S_g^A] \end{aligned} \right\}, \quad (3)$$

where

$$\bar{x}_v^A = \frac{1}{k_v^A} \sum_{w \in \mathcal{G}_g} a_{v,w} x_w$$

is the affine equivalent player of v , and

$$\bar{x}_v^N = \frac{1}{k_v^N} \sum_{w \in \mathcal{V} \setminus \mathcal{G}_g} a_{v,w} x_w$$

251 is the non affine equivalent player of v . We also have that the equivalent player
 252 of v is:

$$\bar{x}_v = \frac{1}{k_v} \sum_{w=1}^N a_{v,w} x_w = \frac{1}{k_v} (k_v^A \bar{x}_v^A + k_v^N \bar{x}_v^N).$$

253 Notice that equation (3) is similar to equation (1), provided that the En-
 254 dogamy, Homophily and Civicness parameters have been embedded, as de-
 255 scribed above.

256 4 Model setup and validation

257 In this section we present the empirical analyses developed for testing ECHO-
 258 EGN's ecological validity, namely its capacity to represent natural social net-
 259 works. To this end, we adopted a simulation design - we set a cluster of ECHO-
 260 EGN models up, in order to make each of them simulate a natural social net-
 261 work corresponding to a European regional area; then, we compare the level
 262 and distribution of cooperation of the actual social networks with those of the
 263 corresponding ECHO-EGN simulations. Moreover, in order to test that the
 264 efficacy of the ECHO-EGN simulation was due to the parameters embedding

the cultural variability (i.e. Endogamy, Civicness and Homophily), the performance of the ECHO-EGN simulations was compared with a control condition - namely, a corresponding simulation carried out by a model approximating the unitary agent assumption. In what follows details as to method and findings are reported.

4.1 The set-up of ECHO-EGN

The first step for setting up the parameters of the ECHO-EGN equation consists of the generation of the network of connections among agents. The network is generated in two steps. Initially, for each group g , a scale-free random network of size N_g and average degree $\bar{k}_g$ is generated. Secondly, a rewiring process is implemented for embedding the Homophily property. Further details of this procedure are reported in Appendix A.

In order to avoid any *a priori* bias in the group connectivity other than the diversity due to the natural degree distribution of scale-free networks, we assume that all groups share the same average degree, specifically $\bar{k}_g = \bar{k} = 4$. This can be done without loss of generality using the theoretical findings of [32], for which the thresholds for full cooperation are scalable with respect to the average degree $\bar{k}$.

4.1.1 The set-up of cultural parameters

The three cultural parameters (Homophily, Endogamy, and Civicness) of the ECHO-EGN models were estimated in accordance to the recent cultural map of European societies carried out by Salvatore and colleagues [35]. They surveyed national representative samples of a set of European countries. The investigation led to the identification of five basic worldviews - defined “symbolic universes” - each of them characterizing a cultural group of the population. Moreover, the study provided the distribution of the symbolic universes in each NUTS2 region (see Table 1). The distribution is given in terms of the size of the segments of population, each of them defined by individuals characterized by one of five symbolic universes described below.

1. *Ordered universe group* ($\mathcal{G}_1$). The world is a nice place to live; The positive view concerns every aspect: institutions, services, future, perceived as trustworthy. Endorsement of transcendent values (e.g., justice, solidarity).
2. *Interpersonal bond group* ($\mathcal{G}_2$). Interpersonal bonds and the emotional experience of being involved in them is what matters in life.
3. *Caring society group* ($\mathcal{G}_3$). Institutions are responsive to individual needs. They support people in accomplishing their projects.
4. *Niche of belongingness group* ($\mathcal{G}_4$). The world is a threatening place. The primary network is the shelter from it. Belongingness is the way to survive.

304 5. *Others' world* ($\mathcal{G}_5$). Generalized distrust, hopelessness, lack of agency,
305 anomaly. The world belongs to others, who have power. People have to
306 accept this situation in order to avoid suffering even more.

Region names and acronyms			
Denmark	Netherlands	United Kingdom	Italy
Denmark (DK)	North Netherlands (NL N)	East Midlands (UK EM)	Center Italy (IT C)
	East Netherlands (NL E)	East of England (UK EE)	South Italy (IT S)
	West Netherlands (NL W)	Greater London (UK GL)	North East Italy (IT NE)
	South Netherlands (NL S)	North East England (UK NE)	North West Italy (IT NO)
		North West England (UK NW)	Italian Islands (IT I)
		Northern Ireland (UK NI)	
		Scotland (UK S)	
		South East England (UK SE)	
		South West England (UK SW)	
		Wales (UK W)	
		West Midlands (UK WM)	
		Yorkshire and the Humber (UK YH)	

Table 1: The 22 regions analyzed (NUTS2 territories) divided by country.

307 Symbolic universes are more than beliefs - each of them defines a mode of
308 being-in-the-world that shapes the actor's way of feeling, thinking, and acting -
309 in the final analysis, his/her social identity [35]. Several studies have highlighted
310 the role played by symbolic universes in motivating and channelling social and
311 political behaviour. They proved to orient voting behavior both in Italy [36] and
312 at the Brexit referendum [37]; again, they proved to be associated with the way
313 relevant topics (immigration, Islam, homosexuality, health, participation and
314 democracy, subjectivity) are represented in newspapers [38] as well as with the
315 attitude towards vaccination [39]. Moreover, symbolic universes show different
316 levels of trust in institutions, preference for in-group over out-group members,
317 sense of community, perceived quality of the interpersonal bond, attitudes to-
318 wards foreigners, adhesion to universalist versus self-centered values [35, 40]

r	Acronym	$\delta_{\mathcal{G}_1,r}$	$\delta_{\mathcal{G}_2,r}$	$\delta_{\mathcal{G}_3,r}$	$\delta_{\mathcal{G}_4,r}$	$\delta_{\mathcal{G}_5,r}$
1	DK	0.13	0.34	0.17	0.27	0.09
2	NL N	0.03	0.27	0.27	0.30	0.13
3	NL O	0.09	0.29	0.22	0.30	0.09
4	NL W	0.05	0.28	0.21	0.37	0.10
5	NL S	0.04	0.36	0.16	0.36	0.09
6	UK EM	0.10	0.33	0.05	0.41	0.11
7	UK EE	0.11	0.38	0.06	0.33	0.12
8	UK GL	0.13	0.32	0.06	0.32	0.17
9	UK NEE	0.11	0.34	0.07	0.35	0.13
10	UK NWE	0.10	0.22	0.08	0.49	0.11
11	UK NI	0.16	0.26	0.05	0.37	0.16
12	UK S	0.11	0.17	0.16	0.49	0.06
13	UK SEE	0.13	0.32	0.11	0.25	0.19
14	UK SWE	0.14	0.35	0.08	0.35	0.08
15	UK W	0.05	0.35	0.10	0.39	0.11
16	UK WM	0.04	0.31	0.15	0.34	0.15
17	UK YH	0.16	0.24	0.13	0.32	0.16
18	IT C	0.16	0.26	0.01	0.39	0.18
19	IT S	0.12	0.20	0.00	0.42	0.26
20	IT NE	0.11	0.22	0.02	0.42	0.23
21	IT NO	0.10	0.29	0.02	0.40	0.18
22	IT I	0.12	0.22	0.03	0.36	0.27

Table 2: Distribution of the Symbolic Universes in each of the sampled 22 regional populations. The reported values are approximated to the second decimal place, and hence some rows may not exactly sum up to 1.

Taken as a whole, the findings reported above provide convergent support to the conclusion that the map of symbolic universes supplies a reliable way of measuring the three parameters of ECHO-EGN which embed cultural pluralism. For each NUTS2 population, we set the size of the ECHO-EGN groups in accordance to the size of the symbolic universes in that population (see Table 2). Moreover, the levels of Homophily, Endogamy, and Civicness of each ECHO-EGN cultural group was set in accordance to psycho-social and cultural characteristics of the corresponding symbolic universes, as measured by Salvatore and colleagues [38] and Mannarini and colleagues [36].

More particularly, each group’s Endogamy was measured in terms of the corresponding symbolic universe’s average level of *Positive Attitude Towards Foreigners* (PATF). This measure is a 4-item subscale of the Prejudice Scale estimating the self-reported propensity to engage with foreigners in social and work contexts) [41]. Accordingly, we adopt it as a proxy of the propensity to cooperate with out-group members. For the purpose of the model, we computed the scores in accordance to the following formula: $e_g = \frac{1-PATF_g}{2}$. Thus, the higher the value of e_g , the higher the Endogamy.

Homophily was measured in terms of each symbolic universe’s average level on the *Ethnic scale* (ES). The Ethnic scale is one of the two subscales of the National Identity Scale [42]. It measures the view of identity as based on ethnic and blood linkages, juxtaposed to the universalist view of nationality as based on adhesion to rule of law and citizenship. For the purpose of the model, we computed the scores in accordance to the following formula: $h_g = \frac{1+ES_g}{2}$. Accordingly, this index lends itself to be interpreted as a proxy of the propensity to limit the relational contact to the in-group.

Civicness was measured in terms of each symbolic universe’s average level on the *Civic Involvement Scale*(CIS). The Civic Involvement Scale is a measure focused specifically on the estimation of the level of valorization of civic rules. To fit the meaning of the measure, scores were inverted [43].

Table 3 reports the values of Endogamy, Homophily and Civicness parameters for each symbolic universe.

SU name	Endogamy e_g	Civicness c_g	Homophily h_g
Ordered universe ($\mathcal{G}_1$)	0.22	0.38	0.25
Interpersonal bond ($\mathcal{G}_2$)	0.37	0.06	0.48
Caring society ($\mathcal{G}_3$)	0.34	0.64	0.34
Niche of belongingness ($\mathcal{G}_4$)	0.51	−0.22	0.58
Others’ world ($\mathcal{G}_5$)	0.71	0.90	0.52

Table 3: Parameter setting for each Symbolic Universes.

Moreover, a further measure of groups was used: *Individual Propensity to Cooperate* (IPC). It was estimated in terms of each symbolic universe’s average level of *Agreeableness* - a self-report measure of the subject’s propensity to be trustful, open to cooperation (cf. [38], p. 155). Agreeableness is one sub-scale of the TIPI questionnaire [44], a short instrument (10 items) used for assessing the Big Five dimensions of personality. IPC was used for validation purposes, rather than for setting the models’ parameters.

Estimation of the symbolic universes’ levels of attitudes towards foreigners and Agreeableness were retrieved from Salvatore and colleagues ([38], Annex 3, tables 4.3 and 4.10); data concerning the Ethnic Scale and the Civic Involvement Scale were obtained from Mannarini and colleagues [36], a study performed on an Italian sample.

4.2 Validation dataset

We consider populations of $R = 22$ regions, corresponding to 22 NUTS2 territories comprising four European countries - Denmark, Italy, Netherlands, and UK - as reported in Table 1. These populations were selected on the basis of a convenience criterion - populations included are those for which reliable recent information on cultural pluralism were available by Salvatore and colleagues [38] and Mannarini and colleagues [36]

4.3 Indexes of population's cooperation

As proxy of the observable level of cooperation, two *ad hoc* indicators were used: Trust in people and Trust in institutions, according to the European Social Survey (ESS) dataset [45] (cf. Table 2). Hereafter, these two indicators will be referred to as $Y^P = [Y_1^P, \dots, Y_r^P, \dots, Y_R^P]$ and $Y^I = [Y_1^I, \dots, Y_r^I, \dots, Y_R^I]$, where each element stands for one of the R regions considered. More specifically, the value Y_r^P was obtained as the sum of the 3 items concerning the perception of trustworthiness of people - a) people can be trusted, b) people try to be fair, c) people try to be helpful-, in the r -th region, and it ranges in the interval $[0, 30]$, while the value Y_r^I relative to the r -th region, is the sum of the 7 EES items concerning the level of trust in regional, national and supranational institutions - a) country's Parliament, b) legal system, c) police, d) politicians, e) political parties, f) European Parliament, g) United Nations-, and it ranges in the interval $[0, 70]$. Data from all populations were obtained by ESS round 8 (2016-2017), with the exception of Denmark, having round 7 (2015-2016) as source (the 2016-2017 round not being available in that case). For both Y^P and Y^I data, also the corresponding standard deviations, σ_r^P and σ_r^I for the R regions, were considered.

All validation data Y^P , Y^I , σ^P , σ^I and α (IPC) are reported in Tables 4 and 5, respectively.

4.4 Procedure

Using the above setup, for each region, the ECHO-EGN model (1) was simulated until a steady state was reached. For each simulation, cultural parameters were set in accordance to the values of the simulated regions reported in table 3. More particularly, for each region, several numerical experiments were performed by developing 100 numerical solutions of the model. For each solution, the initial condition provided was randomly generated with uniform distribution in the set $(0, 1)^N$. Analogously, in each simulation the random networks were generated according to the procedure described in Appendix A.

4.5 Control experiment

The control experiment was developed by assuming a model of social network approximating the unitary agent assumption. To this aim, Endogamy and Civicness parameters were set equal to the average evaluated over the SUs, thus assuming that all players have the same behavior, independently of the group they belong to. Practically, the Endogamy and Civicness parameters were set equal to the average of the values reported in Table 3 for all SUs.

Finally, in order to enable the control simulation to provide between-regions variability, the Homophily parameter was kept in the control model too. Thus, also in the control model the group differentiation was maintained, but only for setting up the Homophily. In so doing, the control condition enabled a specific estimate to be made of the difference of simulation performance due to two

(a)

Region	Y^P	Y^I	σ^P	σ^I
DK	20.20	42.31	4.44	11.86
NL N	18.83	38.45	4.09	10.32
NL E	18.46	39.23	4.24	10.67
NL W	18.35	39.47	4.21	11.03
NL S	17.70	38.05	4.42	11.03
UK EM	16.99	35.22	4.41	12.39
UK EE	16.79	33.42	4.49	11.92
UK GL	16.84	35.59	5.28	12.06
UK NE	16.97	33.43	5.19	13.12
UK NW	16.20	32.01	4.96	14.01
UK NI	15.99	32.20	6.16	14.63
UK SC	18.50	33.47	4.90	11.17
UK SE	17.09	35.74	4.93	10.98
UK SW	18.30	33.64	4.52	11.87
UK W	16.44	32.50	5.17	12.68
UK WM	15.92	30.45	5.60	13.33
UK YH	16.25	31.99	4.83	13.69
IT C	14.08	27.00	6.04	14.81
IT S	12.83	24.49	5.93	13.74
IT NE	13.66	28.27	6.07	13.04
IT NO	14.06	28.69	5.72	13.16
IT I	12.91	24.63	5.88	12.99

Table 4: Validation data: trust in people Y^P , trust in institution Y^I and the corresponding standard deviations σ^P and σ^I for each region considered.

Group	IPC α_g
$\mathcal{G}_1$	10.00
$\mathcal{G}_2$	9.77
$\mathcal{G}_3$	10.28
$\mathcal{G}_4$	9.48
$\mathcal{G}_5$	9.75

Table 5: Validation data: IPC (agreeableness) data for each symbolic universe.

410 cultural parameters (Endogamy and Civicness). Moreover, with this design,
 411 the control model was able to check the alternative hypothesis that the efficacy
 412 of the ECHO-EGN simulation was due to the size of the groups.

413 For each region, the control outputs were obtained by means of the same
 414 procedure used for the ECHO-EGN simulations (i.e. 100 experiments, with
 415 randomly generated initial condition).

416 4.6 Results

417 The average cooperation X_V and its standard deviation σ^{X_V} obtained for each
 418 of the 100 numerical solutions of the ECHO-EGN model were compared with
 419 real dataset Y^P , Y^I , σ^P and σ^I by means of the Pearson correlation coefficient r .
 420 Moreover, the Pearson correlation coefficient was computed as a measure of the
 421 association between the level of cooperation (i.e. the values α of IPC, reported
 422 in Table 5) of each natural group/symbolic universe over the whole $R = 22$
 423 sample, and the corresponding level generated by the simulation models.

424
 425 Figure 2 reports, for each region, the corresponding Y^P value (x -axis) and the
 426 asymptotic simulated cooperation (y -axis) averaged over the whole population
 427 and over the 100 experiments. Different colors have been used to distinguish
 428 among countries: dark blue for Denmark, light blue for Netherlands, green for
 429 UK and yellow for Italy. The black line represents the linear regression, and
 430 its closeness to data reveal the very strong correlation between real data and
 431 model simulations, as will be shown in detail below. It is interesting to observe
 432 the presence of clusters, clearly identifying each country considered on both
 433 real data and model simulations. Denmark and Netherlands exhibit the highest
 434 levels of cooperation, UK shows intermediate levels, while the lowest levels is
 435 observed for Italy.

436 In Figure 3, σ^P , (x -axis) and σ^{X_V} averaged over the 100 experiments (y -axis)
 437 are reported for all regions. Country clusters are present here too; in this case
 438 the highest levels of the standard deviation are shown by the measures refer-
 439 ring to Italy, denoting a higher heterogeneity of the Y^P data and of simulated
 440 cooperation. UK presents intermediate values, while Denmark and Netherlands
 441 prove to have the smallest ones.

442
 443 Similar results were obtained by analyzing Y^I data. Figure 4 reports, for
 444 each region, the Y^I value (x -axis) and X_V averaged over the 100 trials (y -axis).
 445 The regression line is reported in black. The presence of country clusters is ob-
 446 served and again, Denmark and Netherlands exhibit the highest levels of Y^I data
 447 and the average simulated cooperation, UK shows intermediate levels, while the
 448 lowest results are observed in Italy.

449
 450 In Figure 5, σ^I (x -axis) and σ^{X_V} averaged over the 100 trials are reported
 451 for each region. Also in this case, highest levels of the standard deviation are
 452 reached by Italy, denoting higher heterogeneity of data and simulations. UK
 453 shows intermediate values, while Denmark and Netherlands prove to have the

Figure 2: Comparison of Y^P dataset with simulated cooperation X_V . Y^P data ranges in the interval $[0, 30]$, while the X_V belongs to $[0, 1]$. The slope of the regression line (black line) is 0.0128 and the offset is 0.4409.

Figure 3: Comparison of σ^P dataset with σ^{X_V} . The slope of the regression line is 0.0087 and the offset is 0.4284.

Figure 4: Comparison of Y^I dataset with X_Y . Y^I data ranges in the interval $[0, 70]$, while the X_Y belongs to $[0, 1]$. The slope of the regression line (in black) is 0.0051 and the offset is 0.4828.

Figure 5: Comparison of dataset σ^I with σ^{X_Y} . The slope of the regression line (in black) is 0.0037 and the offset is 0.4256.

lowest ones.

The distribution of the cooperation level of each group and of the whole population observed in these experiments are reported in Figure 6, where high concentrations of individuals with a given cooperation level are represented by pink shading. Green and blue arrows denote the average and the mode calculated for each group and over the whole population, respectively.

Figure 6: Distribution of the cooperation level of each group and of the whole population. Data refer to the asymptotic cooperation of players belonging to all 22 regions, obtained by the 100 trials.

An additional validation was carried out by comparing the average cooperation level recorded for each group of each simulation model and the average Individual Propensity to Cooperate (the variable α of Table 5) of each corresponding natural group. The corresponding estimated probability density function of the correlation $r(X_G, \alpha)$ is depicted in Figure 7. The average correlation is $r = 0.69$.

In order to validate the choice of the parameters, we performed a control experiment as described in Section 4.5. In this way, we assumed that all players behave in the same way with respect to the external individual (i.e. constant Endogamy), and with respect to their attitude to self-regulation of defection (i.e. constant Civiness). Figure 8.a reports the estimated probability density function (pdf) of the correlation coefficients $r(X_V, Y^P)$ (blue for the base experiment, purple for the control one) and $r(X_V, Y^I)$ (red for the base experiment, green for the control one), while Figure 8.b shows the estimated pdf of the correlation coefficients $r(\sigma^{X_V}, \sigma^P)$ (blue for the base experiment, purple for the control one)

Figure 7: Probability density functions over 100 experiments of the correlations between the average group cooperation X_G and the IPC dataset α centered on the average correlation.

and $r(\sigma^{X_V}, \sigma^I)$ (red for the base experiment, green for the control one). The average correlation values correspond to the dashed vertical lines. The highest correlations are observed for both the dataset Y^P ($r = 0.93$) and σ^P ($r = 0.75$) in the base experiment (blue), while the control experiment (purple) produces uncorrelated results ($r = -0.22$ for Y^P and $r = -0.15$ for σ^P). High significant correlations are also found for the Y^I ($r = 0.85$) and σ^I ($r = 0.65$) datasets, while in the control experiment we observe low values ($r = -0.22$ for Y^I and $r = -0.15$ for σ^I). It is clear that in all cases investigated, the performances of the control experiment are much lower than those of the base model, where the different values of Endogamy and of Civicism are considered. One can also observe that the dispersion of the distributions reported in panel (a) are lower than the ones reported in panel (b).

4.7 Discussion

The output of the simulation study provided convergent support to the ecological validity of ECHO-EGN. The very high correlations between the level of cooperation of the natural groups and the corresponding ECHO-EGN models showed that the latter is able to simulate natural social networks quite efficaciously. The ECHO-EGN's simulation capacity resulted almost absolute when the trust in people index is used ($r = 0.93$); it is however very high ($r = 0.85$) in the case of the trust in institution index. This difference may be due to the fact that in the latter case the index involves institutions that are transversal

Figure 8: Probability density functions over 100 experiments. Subplot (a): correlations of model simulations and Y^P and Y^I datasets ($r(X_V, Y^P)$ in blue and $r(X_V, Y^I)$ in red). The probability density functions obtained with the control experiments are reported in purple and in green. In this case, $e_g = 0.43 \forall g$ and $c_g = 0.13 \forall g$. Subplot (b): correlations model simulations and the standard deviation of σ^P and σ^I datasets x (blue and red for the base experiment, purple and green for the control one). Dashed vertical lines are centered on the average correlations.

to the territorial populations (e.g. European Union and United Nations) and therefore could be less reflective of the specificity of each local population. The high correlation between the natural and simulated within-population variability of the cooperation ($r = 0.75$ and $r = 0.65$, respectively for trust in people and trust in institutions) provides further support to the ECHO-EGN ecological validity - this result highlights that the ECHO-EGN is not only able to simulate the global cooperation level of the natural social networks, but also, more importantly, its distribution within the population.

Again, it is worth noticing that the ECHO-EGN model proved able to simulate quite efficaciously the cooperation of the five segments of natural social groups defined by the symbolic universes ($r = 0.69$) too. This is a further cross-validation of the ECHO-EGN, provided by an indirect source - namely an independent measure (Individual Propensity to Cooperate) which was not involved in the model set-up.

This convergent evidence is still more significant if one considers that no fine tuning of the model parameters was applied; indeed, parameters were set up by means of *a priori* knowledge only - i.e. the data on the size and psycho-social characteristics of the cultural segments analyzed by Salvatore and colleagues [38] and Mannarini and colleagues [36]. In this the findings of the validation test lead to conclude that the ECHO-EGN embeds significantly the psycho-social processes, which drive the emergence of cooperation in social networks.

Finally, the fact that the control model - i.e. the model which embeds two out of three homogeneous cultural parameters - proves to be unable to simulate natural social networks (correlation between control simulations and actual populations is close to 0 or negative in all comparisons) supports the conclusion that the ECHO-EGN ecological validity is due to the parameters mapping the cultural variability of population.

In sum, the main experiment presents significantly higher correlations, thus showing that the introduction of the symbolic universes and the mechanisms of Endogamy, Civicness and Homophily in the mathematical model accounts reasonably well for traits which regulate the cooperative behavior in social networks.

5 Analytical results

5.1 Constraints on cooperation

In this section we report some theoretical results concerning the stability of steady states of the ECHO-EGN equation (3), i.e. constant solutions to which the system dynamics will eventually converge. These states can be found by assuming that $\dot{\mathbf{x}} = 0$, and they embed peculiar properties of asymptotic dynamics of individuals and population as well. In our study, we consider the steady states $\mathbf{x}^{ALLC}$ and $\mathbf{x}^{ALLD}$ of system (3), which represent the situations where all players assume a fully cooperative or fully defective asymptotic behavior, respectively.

Theorem 1. *If $\beta_v > \eta_v \forall v \in \mathcal{V}$, where*

$$\eta_v = k_v^A + k_v^N \frac{1 - T^N}{1 - T_g^A},$$

541 *then the steady state $\mathbf{x}^{ALLC}$ is asymptotically stable.*

542 **Remark 1.** *$T^N > T_g^A$ if and only if $\eta_v > k_v$.*

543 The Theorem essentially states that Endogamy restrains cooperation. In-
544 deed, in a social network without Endogamy, the asymptotic stability of $\mathbf{x}^{ALLC}$
545 requires that the self-regulation parameters β_v exceed the degree of the player
546 (see Theorem 3 in [32]). On the other hand, since $\eta_v > k_v$ in accordance to
547 Remark 1, to guarantee the asymptotic stability of the fully cooperative steady
548 state $\mathbf{x}^{ALLC}$ in presence of endogamic groups, the members of these groups must
549 have stronger self-regulation parameters, although they show a reduced temp-
550 eration to defect when playing with the members of the same group ($T_g^A < T^N$).

Theorem 2. *If $\beta_v < \zeta_v \forall v \in \mathcal{V}$, where*

$$\zeta_v = k_v^A + k_v^N \frac{S^N}{S_g^A},$$

551 *then the steady state $\mathbf{x}^{ALLD}$ is asymptotically stable.*

552 **Remark 2.** *$|S^N| > |S_g^A|$ if and only if $\zeta_v > k_v$.*

553 The Theorem essentially states that Endogamy fosters defection. Indeed, in
554 a social network without Endogamy, the asymptotic stability of $\mathbf{x}^{ALLD}$ requires
555 that the self-regulation parameters β_v is below the degree of the player (see
556 Theorem 4 in [32]). On the other hand, since $\zeta_v > k_v$ in accordance to Remark
557 2, despite the fact that affine players have less fear of being betrayed by indi-
558 viduals belonging to the same group than all other individuals ($|S_g^A| < |S^N|$),
559 their behavior is still defective for larger values of the self-regulation parameter
560 than when all players use the same payoff matrix $\mathbf{B}^N$.
561

562 The proofs of Theorems 1 and 2 are reported in Appendix C.

563 5.2 Theorem interpretation

564 It is interesting to investigate the relationship between values of parameters β_v
565 and the thresholds found in Theorems 1 and 2.

566 To this end, in Table 6 the self-regulation parameters β_v , averaged over
567 the regions and the simulation trials, are reported in column 2 for each group.
568 Moreover, these values are compared to the same averages of threshold η_v , found
569 in Theorem 1 (column 3). Additionally, the Theorem 1 satisfaction is indicated
570 in column 4 for each group. We observe that, on the average, all groups except
571 for $\mathcal{G}_4$ and $\mathcal{G}_5$ satisfy Theorem 1. Columns 5 and 6 report similar results on full

Name	Avg. β_v	Avg. η_v	Th. (1)	Avg. ζ_v	Th. (2)
$\beta_{\mathcal{G}_1}$	16.1	5.5	yes	5.1	no
$\beta_{\mathcal{G}_2}$	9.6	6.2	yes	5.4	no
$\beta_{\mathcal{G}_3}$	15.6	6.5	yes	5.6	no
$\beta_{\mathcal{G}_4}$	5.3	7.8	no	6.0	yes
$\beta_{\mathcal{G}_5}$	10.6	41.4	no	9.8	no

Table 6: Relationship between average self-regulation parameters β_v and the thresholds of Theorems 1 and 2. Col. 2: the value β_v averaged over a given group, over the $R = 22$ regions and over the 100 trials. Col. 3: the value of threshold η_v averaged over a given group, over the $R = 22$ regions and over the 100 trials. Col. 4: Theorem 1 satisfaction (in average). Col. 5: the value the value ζ_v averaged over a given group, over the $R = 22$ regions and over the 100 trials. Col. 6: Theorem 2 satisfaction (on average).

defection, related to Theorem 2. Notice that in this case, “yes” means that the value of column 2 is lower than the value in column 5, and “no” the opposite, as shown in column 6. Only group $\mathcal{G}_4$ satisfies the requirements of Theorem 2. This means that for this group it is not only more difficult to cooperate, but it is also more easier to defect.

5.3 Discussion

The formal analysis of ECHO-EGN leads to a rather counter-intuitive conclusion. The fact that, as Theorem 1 states, Endogamy reduces the global level of cooperation, means that the in-group identity and therefore in-group solidarity promotes cooperation locally (i.e. among in-group members) but prevents it globally (i.e. at the level of the whole society). On the other hand, Theorem 2 ensures that when Endogamy is active, the behavior of individuals can be defective even in the case of high self-regulation. These results have a relevant theoretical implication. Indeed, it is consistent with those that criticize the view of in-group bonds (e.g. conceptualized either as sense of community [46] or bonding social capital [19]) as the lever to increase cooperation and trust in society. In opposition to this rather popular view (e.g. [47, 48]), some authors underline that - when not integrated by universalist and civic attitudes and values - the involvement in the community/in-group bonds can foster identity motives and closure towards the out-group - therefore, paradoxically, to a global reduction of social cooperation and cohesion [49, 50]. Theorems 1 and 2 provide analytical support to this criticism, by showing the role played by the relation with not-affine members and Civicness/self-regulation as strategic resources for cooperation.

6 Conclusion

This paper focused on ECHO-EGN - a model of the evolution of cooperation in social networks designed to go beyond the unitary agent assumption, which greatly weakens the realism of the analysis, reducing the ecological validity of theoretical conclusions and related pragmatic implications.

ECHO-EGN models the variability of agents in terms of three major parameters, each of them mapping a cultural component of the inherent pluralism of natural social networks: *Homophily* - i.e. preference to relate with in-group members; *Endogamy* - i.e. the higher propensity to cooperate with in-group members; the *Civiness* - i.e. the propensity to cooperate in the public domain. These components have been conceived as cultural because they are fostered by cultural norms and related psycho-social drivers.

The validation test on ECHO-EGN shows that, thanks to these cultural parameters, the model reaches capacity to simulate the level of cooperation of natural social networks - from almost full to very high, accordingly to the index of cooperation adopted. Moreover, ECHO-EGN proves to be able to simulate efficaciously the within-population distribution of cooperation as well as the average level of the cultural segments' propensity to cooperate.

The high performance on the simulation test leads to two complementary conclusions. On the one hand, it supports the validity of the cultural parameters used by ECHO-EGN, legitimizing them as an effective way to map the cultural and psycho-social processes underpinning the dynamics of cooperation. On the other hand, it provides further evidence of the theoretical and methodological soundness of the notion of symbolic universes [35, 40]. Indeed, this notion underlies the data used to set up the ECHO-EGN models simulating natural social networks. Therefore, the success of the simulation is an indirect proof of the fact that the conceptual and methodological concept of symbolic universe provides a valid and reliable approach to the cultural analysis of a social group.

The formal analysis of ECHO-EGN provides further food for thought. It shows that cooperation is prevented, rather than fostered, by in-group identity and solidarity. This result is theoretically and practically relevant - it integrates the idea of community as the fundamental resource for promoting social cooperation and development. What the analysis specifically suggests is that valorized community bonds have to be integrated by the restoration of forms of universalism in order to make societies more cohesive and inclusive [25].

In general, the realism demonstrated by ECHO-EGN has important implications. At the methodological level, it enables a forecast approach, aimed at mapping the impact of the variation of cultural factors on cooperation. Such an approach could have a practical value too - it paves the way for the use of simulation and formal analysis in the design of policies for social cohesion and cooperation. According to this view, ECHO-EGN can be to estimate and/or to model the impact of cultural factors on the natural social networks' level of cooperation, for the sake of identifying critical drivers and/or setting strategic objectives and/or estimating the consequences of interventions.

Before concluding, it is worth highlighting some limitations of the study.

First, the simulation test was based on a rather small sample of units of analysis, collected on a convenience criterion. Thus, even if the sample proved to incorporate relevant geographical variability (it comprises territories from a Mediterranean country and Northern-European countries as well), further analyses, based on more comprehensive samples of population are required to support the generalization of the current conclusion. Second, the set-up of some of the cultural parameters (more particularly, Homophily and Endogamy) were based on indirect indicators, chosen on a criterion of convenience (i.e the availability of data). Thus, further studies are required to test different, more direct estimations of Homophily, Endogamy. On the other hand, it has to be noted that if the current estimation of these two parameters should be proved to be imprecise, this would mean that ECHO-EGN would have a further chance to empower its ecological validity. Third, the simulation test used only two criteria (trust in people and trust in institutions) to estimate the convergence between simulated and natural social networks. Further studies will be aimed at analyzing the ECHO-EGN's ecological validity through other indicators of cooperation - this will be done both to corroborate its realism and to identify the specific aspects of cooperation the model is sensitive to. Finally, we are aware that other components of cultural pluralism need to be taken into account, in order to enhance the ECHO-EGN ecological validity - e.g. the heterogeneous propensity to socialize, further sources of the inherent differences in the agents' propensity to cooperate, the different temporality agents adopt as the frame of their decisions. The current findings of our work encourage us to see these elements as sources of potential developments of ECHO-EGN, with the prospect of building a mathematical model of the cultural dynamics of cooperation.

Appendix A: Network generation for Grouped Populations

Given the region r in the set of $R = 22$ populations considered in this study, we generated $M = 5$ scale-free networks, each of size $N_g = \delta_{r,g}N$ according to Table 2. The scale-free structure is obtained by employing preferential attachment methods. In a nutshell, given the desired average degree $\bar{k}_g$, an initial fully connected network of $m = \frac{\bar{k}_g}{2}$ is generated. Then, further nodes are added to the network, by connecting it via m links to the already existing nodes. The probability that a new node is connected to one of the existing ones is proportional to the current degree of those nodes. This procedure is repeated until the number of nodes in the networks is equal to N_g .

The networks obtained are not cross connected. In order to create inter-group links and to embed the Endogamy property, a rewiring process is implemented. Specifically, for each couple of connected players v and w , where v belongs to group g , the link is removed with probability $1 - h_g$, and replaced by a new link between v and a random player of a group different from g . Since the Endogamy h_g denotes the probability of one player being connected to an

683 affine one, then the probability of changing an affine link with a non affine one
 684 is $1 - h_g$. It can therefore be seen that, due to the stochasticity of this process,
 685 $k_v^A = h_g k_v$ and $k_v^N = (1 - h_g)k_v$ on the average.

686 Due to the stochasticity of the network, the effective average degree $\bar{k}'_g$ of a
 687 group g is in general slightly different than the average $\bar{k}_g$. To distinguish the
 688 two cases, we introduce the effective parameters $\bar{k}'_g$ and $\bar{k}'$ as $\bar{k}'_g = \frac{1}{N_g} \sum_{v \in \mathcal{G}_g} k_v$,
 689 and $\bar{k}' = \frac{1}{N} \sum_{v \in \mathcal{V}} k_v$.

According to the assumption discussed in Section 3.1, for which the topology
 of the connection network is random with a scale-free distribution, we notice
 that the network obtained by the above procedure is still scale-free. Indeed:

$$\begin{aligned}
 P(k_v = k) &= \sum_{g=1}^M P(k_v = k | v \in \mathcal{G}_g) P(v \in \mathcal{G}_g) \\
 &= \sum_{g=1}^M P(k_v = k | v \in \mathcal{G}_g) \delta_g \\
 &= \sum_{g=1}^M \delta_g \frac{1}{2} \bar{k}_g^2 k^{-3} dk \\
 &= \frac{1}{2} \left(\sum_{g=1}^M \delta_g \bar{k}_g^2 \right) k^{-3} dk \\
 &= \frac{1}{2} \bar{k}^2 k^{-3} dk,
 \end{aligned}$$

690 where δ_g is the share of group g in the considered population and $\bar{k} = \sqrt{\sum_{g=1}^M \delta_g \bar{k}_g^2}$
 691 is the average degree of the resulting complete network.

692 Since in this paper we assume that $\bar{k}_g = 4$, then $\bar{k} = 4 \sqrt{\sum_{g=1}^M \delta_g} = 4$.

693 Appendix B: Civicness

694 Recalling Theorem 5 of [32], and assuming that temptation is stronger than the
 695 fear being betrayed ($T^N - 1 > -S^N$), the quantity $\rho^N \bar{k}'$, where $\rho^N = \frac{1-T^N}{S^N} > 1$,
 696 represents the average threshold for ensuring the global asymptotic stability of
 697 the equilibrium $\mathbf{x}^{\text{ALLC}} = [1, \dots, 1]^\top$ (i.e., the steady state where all individuals
 698 fully cooperate).

699 Based on this result, in the ECHO-EGN model with groups, we assume
 700 the self-regulation parameter of a player v in group g depends on the average
 701 threshold $\rho^N \bar{k}'_g$ and on the Civicness value c_g as reported in equation (2).

702 Appendix C: Proofs of Theorems 1 and 2

In this appendix the proofs of the theoretical results concerning the stability of the steady states $\mathbf{x}^{ALLC}$ and $\mathbf{x}^{ALLD}$ of the ECHO-EGN equation (3), referred to in Section 5, are reported. To this aim, the equations (3) are linearized locally near $\mathbf{x}^{ALLC}$ and $\mathbf{x}^{ALLD}$ by evaluating the entries of the Jacobian matrix

$$J(\mathbf{x}) = \{j_{v,w}(\mathbf{x})\} = \left\{ \frac{\partial \dot{x}_v}{\partial x_w}(\mathbf{x}) \right\}.$$

703 It is useful to rewrite equation (3) as follows:

$$\dot{x}_v = x_v(1 - x_v) [k_v^A f_g^A(\bar{x}_v^A) + k_v^N f_g^N(\bar{x}_v^N) - \beta_v f_g^A(x_v)], \quad (\text{A.4})$$

where

$$f_g^A(z) = (1 - T_g^A - S_g^A)z + S_g^A$$

and

$$f_g^N(z) = (1 - T_g^N - S_g^N)z + S_g^N.$$

704 In particular, given a player $v \in \mathcal{G}_g$, the diagonal entries of $J(\mathbf{x})$ are:

$$\begin{aligned} \frac{\partial \dot{x}_v}{\partial x_v} &= (1 - 2x_v) [k_v^A f_g^A(\bar{x}_v^A) + k_v^N f_g^N(\bar{x}_v^N) - \beta_v f_g^A(x_v)] \\ &\quad - \beta_v x_v(1 - x_v)(1 - T_g^A - S_g^A). \end{aligned} \quad (\text{A.5})$$

705 On the other hand, the off-diagonal entries of $J(\mathbf{x})$ are:

$$\frac{\partial \dot{x}_v}{\partial x_w} = \begin{cases} x_v(1 - x_v)(1 - T^N - S^N) & \text{if } w \notin \mathcal{G}_g \\ x_v(1 - x_v)(1 - T_g^A - S_g^A) & \text{if } w \in \mathcal{G}_g \end{cases}. \quad (\text{A.6})$$

706 From the theory of nonlinear dynamic systems, the stability of a steady state
707 $\mathbf{x}^*$ depends on the sign of the real part of the eigenvalues of the corresponding
708 Jacobian matrix $J(\mathbf{x}^*)$ [34]. For $\mathbf{x}^{ALLC}$ and $\mathbf{x}^{ALLD}$, since $x_v \in \{0, 1\}$, then the
709 off-diagonal entries reported in (A.6) are identically null. Therefore, the Jaco-
710 bian matrix has a diagonal structure, and hence its eigenvalues coincide with
711 the expressions reported in (A.5), i.e. $\lambda_v = j_{v,v}(\mathbf{x}^*) = \frac{\partial \dot{x}_v}{\partial x_v}(\mathbf{x}^*)$. In the following
712 Theorems, we find the sufficient conditions to have negative $\lambda_v \forall v \in \{1, \dots, N\}$.

713

Theorem 1. *If $\beta_v > \eta_v \forall v \in \mathcal{V}$, where*

$$\eta_v = k_v^A + k_v^N \frac{1 - T^N}{1 - T_g^A},$$

714 *then the steady state $\mathbf{x}^{ALLC}$ is asymptotically stable.*

Proof. Considering a player $v \in \mathcal{G}_g$, from equation (A.5) we get that:

$$\begin{aligned}
\lambda_v = j_{v,v}(\mathbf{x}^{\text{ALLC}}) &= -(k_v^{\text{A}} f_g^{\text{A}}(1) + k_v^{\text{N}} f_g^{\text{N}}(1) - \beta_v f_g^{\text{A}}(1)) \\
&= -(k_v^{\text{A}}(1 - T_g^{\text{A}}) + k_v^{\text{N}}(1 - T^{\text{N}}) - \beta_v(1 - T_g^{\text{A}})) \\
&= -(1 - T_g^{\text{A}}) \left(k_v^{\text{A}} + k_v^{\text{N}} \frac{(1 - T^{\text{N}})}{(1 - T_g^{\text{A}})} - \beta_v \right) \\
&= -(1 - T_g^{\text{A}}) (\eta_v - \beta_v).
\end{aligned}$$

715 Since $T_g^{\text{A}} > 1$ and $\beta_v > \eta_v$, then $\lambda_v < 0$. This holds for any v . Hence, all
716 eigenvalues are negative, and $\mathbf{x}^{\text{ALLC}}$ is asymptotically stable. $\square$

In accordance to Theorem 3 in [32], we know that, considering a population which uses only the payoff matrix $\mathbf{B}^{\text{N}}$, then $\mathbf{x}^{\text{ALLC}}$ is asymptotically stable if

$$\beta_v > k_v \quad \forall v.$$

Comparing the thresholds obtained in Theorem 1 of this paper and in Theorem 3 of [32], we notice that:

$$\eta_v > k_v \iff T^{\text{N}} > T_g^{\text{A}}.$$

Indeed:

$$\begin{aligned}
k_v^{\text{A}} + k_v^{\text{N}} \frac{1 - T^{\text{N}}}{1 - T_g^{\text{A}}} &> k_v && \iff \\
k_v^{\text{N}} \frac{1 - T^{\text{N}}}{1 - T_g^{\text{A}}} &> k_v - k_v^{\text{A}} = k_v^{\text{N}} && \iff \\
\frac{1 - T^{\text{N}}}{1 - T_g^{\text{A}}} &> 1 && \iff \\
T^{\text{N}} &> T_g^{\text{A}}.
\end{aligned}$$

717 This corresponds to Remark 1.

718 Despite the fact that players have lower temptation to defect towards mem-
719 bers of their own group than towards all other individuals ($T_g^{\text{A}} < T^{\text{N}}$), they must
720 possess a stronger self-regulation parameter β_v with respect to the case where
721 all players use always the same payoff matrix $\mathbf{B}^{\text{N}}$ to guarantee the asymptotic
722 stability of the fully cooperative steady state $\mathbf{x}^{\text{ALLC}}$.

723

Theorem 2. If $\beta_v < \zeta_v \quad \forall v \in \mathcal{V}$, where

$$\zeta_v = k_v^{\text{A}} + k_v^{\text{N}} \frac{S^{\text{N}}}{S_g^{\text{A}}},$$

724 then the steady state $\mathbf{x}^{\text{ALLD}}$ is asymptotically stable.

725 *Proof.* Considering a player $v \in \mathcal{G}_g$, from equation (A.5) we get that:

$$\begin{aligned}
\lambda_v = j_{v,v}(\mathbf{x}^{\text{ALLD}}) &= k_v^A f_g^A(0) + k_v^N f_g^N(0) - \beta_v f_g^A(0) \\
&= k_v^A S_g^A + k_v^N S^N - \beta_v S_g^A \\
&= S_g^A \left(k_v^A + k_v^N \frac{S^N}{S_g^A} - \beta_v \right) \\
&= S_g^A (\zeta_v - \beta_v).
\end{aligned}$$

Since $S^A < 0$ and $\beta_v < \zeta_v$, then $\lambda_v < 0$. This holds for any v . Hence, all eigenvalues are negative, and $\mathbf{x}^{\text{ALLD}}$ is asymptotically stable. $\square$

In accordance to Theorem 4 of [32], we know that, considering a population which uses only the payoff matrix $\mathbf{B}^N$, then $\mathbf{x}^{\text{ALLD}}$ is asymptotically stable if

$$\beta_v < k_v \quad \forall v.$$

Comparing the thresholds obtained in Theorem 2 of this paper and in Theorem 4 of [32], we notice that:

$$\zeta_v > k_v \iff |S^N| > |S_g^A|.$$

Indeed:

$$\begin{aligned}
k_v^A + k_v^N \frac{S^N}{S_g^A} &> k_v && \iff \\
k_v^N \frac{S^N}{S_g^A} &> k_v - k_v^A = k_v^N && \iff \\
\frac{S^N}{S_g^A} &> 1 && \iff \\
|S^N| &> |S_g^A|.
\end{aligned}$$

This corresponds to Remark 2. Hence, even if affine players have less fear of being betrayed by affine players than all other individuals ($|S_g^A| < |S^N|$), their behavior is defective also for larger values of the self-regulation parameter with respect to the case where all players use the same payoff matrix $\mathbf{B}^N$.

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