

A Coalitional Approach for Resource Distribution in Self-organizing Open Systems

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Abstract. This article aims to theorize and explore the distribution problem in the context of self-organizing open systems when they exhibit social behaviors that can be modeled and formalized, applying the interactive decision theory. In this context, the whole system structure is trying to achieve a stable cooperative state at the same time they aim to satisfy the interests of each individual and reach a certain level of social welfare. We analyze these scenarios evaluating the system stability through a formal analysis of coalitional and non-cooperative games and the notions of collective actions and robustness. We used socially inspired computing to propose a negotiation method that allows the members of the system to cooperate and manage common-pool resources without any central controller or other orchestration forms. The model was evaluated using four quantitative moral metrics through simulation techniques. The result showed how a system influenced by ethical behaviors exhibited higher efficiency, symmetry, and invariance over time.

Keywords: Self-organization · Ad hoc networks · Trust · Cooperation · Socially inspired computing

1 Introduction

From the Latin *robustus*, the word robustness refers to the quality of an entity to be strong, vigorous and decided against possible changes in the environment. In general terms, it refers to the ability of an entity to conserve its properties throughout the execution of its functions despite possible variations, interferences, and changes in the operating conditions. For instance, according to Noam Chomsky, in his hypothesis of Universal Grammar, the set of restrictions that exist in every natural language as a group of invariant constraints no matter the context of the Human language, constituted a robust core in his theory of principles and parameters.

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The notion of robustness has been used in the scientific literature to explain, interpret, and state behaviors in biological, economic, and social systems. In the context of Computer Science, robustness is used to describe the capacity of computational systems to deal with adverse operating conditions [1]. In particular, this property is observed in the context of communication and information technologies to describe the decentralized interoperability expected in the Industry 4.0, in which multiple entities interact as a self-organizing open system. Consequently, the notion of robustness leads us to analyze the computational models that we expect to help the next generation of communication networks adapt their structure to unexpected environments.

Additionally, to ease the analysis of this property, it is necessary to understand the mechanisms that produce these behaviors in future technological developments. We use the macro-meso-micro perspective that allows us to analyze the current process of decision making. For example, the case of Perishable Agricultural Supply Chains (CSAP), in which hybrid models of simulation, optimization, and game theory are used to analyze and redesign CSAP effectively, achieve better responses and lower loss of quality derived from logistic flows. A detailed description of this application is described in [2]. This example refers to the principle of autonomy in the context of self-organized open systems, which have been commonly related to the social sciences and philosophy, creating a natural association with human behaviors. Furthermore, in the context of Artificial Intelligence, autonomy concerns the idea that agents do to always act on our behalf; they act with some control over their internal state [3].

In this regard, the purpose of this work is to propose a robust distribution method for self-organizing open systems in scenarios in which the whole system structure is trying to achieve a stable cooperative state at the same time it aims to satisfy the demands of each individual. This proposal is composed of two elements: on the one hand, a coalitional game based on the notions of negotiation and moral metrics. On the other hand, an adaptive technique allows the system to face unexpected operating conditions during the negotiation process. It is essential to mention that this work is an extension of the analysis presented in [4,5]. The result showed how the proposed negotiation model allows the system to achieve higher efficiency, symmetry, and invariance over time.

We structured the document as follows: Sect. 2 shows the related work; both a philosophical background for the idea the collectivism in resource allocation and the notion of moral attitudes are described. Section 3 overviews the agent paradigm and presents robustness as an expected property of a multi-agent system. In Sect. 4, our proposal for resource allocation through coalitional game theory and negotiation is presented. Section 5 presents the experimental results and performance evaluation. Section 6 concludes the article.

2 Related Work

2.1 A Philosophical Background for the Collectivism in Resources Allocation

From Latin *collectivus*, the word collectivism refers to all kinds of plural organization that serves to manage common-pool resources in social systems. In this regard, this concept includes all social artifacts used to manage resources or values (material or immaterial) that can be used by the community members. In modern history, this process is usually represented as the relative value of the material goods exchanged by individuals under assumptions of strict rationality. This scenario was formalized in the Utilitarian Theories of Jeremy Bentham [6], which later derive the Adam Smith's Theory of Moral Sentiments and also the cybernetic proposals of Von Newman & Morgenstern [7]. In these proposals, they show how a moral base could lead to the application of universal ethics centered on an individual who enjoys the privileges of a rational society.

Additionally, to support the idea mentioned above, several theories describe the methodological individualism as a form of understanding of social phenomena. However, after these theories were proposed, a famous social dilemma named the tragedy of the commons [8] suggests that maximizing the individual benefits does not respond to the global interests of a social system. In this context, the "Public Good Game" is a clear example of this scenario, requiring a theoretical framework broader than the utilitarian principles. Similarly, there are at least two more theories that try to explain the process of collective decision-making under this scenario. First, the principles of necessity and equality that establish the needs of an individual must be satisfied by the group according to the principle of equality. Second, the principle of equity, which determines that an individual must receive an allocation proportional to his contribution (positive or negative) to the community [9].

2.2 Collectivity and Robustness

For assessing the possible impact of these families in the performance of a self-organizing open system, it is necessary to define and model its structure and behaviors. In this case, the methodological individualism leads us to reduce the complexity of the problem through the representation of capital (goods) according to the preferences and desires of the agents in terms of utility functions. This approach has been explored through the theoretical analysis of social negotiation, extending its concepts towards the holistic idea of social capital [10,11]. On the other hand, the axiomatic analysis of the conceptual bases has been tested in [12] and also important changes were suggested in the context of distributive justice.

Moreover, game theory has been extended its scope towards an evolutionary approach to capture the behaviors throughout the evolution of natural systems

[13]. In such models, robustness is guaranteed as a new mechanism that arises from the collective actions of many individuals that try to achieve a common goal. For example, we can see a sample through the theory of non-cooperative games [4,5,14–16], in which the performance of the model respond as the outcome of the collective behaviors of the agents and not just to the linear addition of the individual actions.

We can adapt economic and political concepts as part of engineering developments to examine the social relationships in multi-agent systems and define the qualities of robustness and connections inside groups of interest. In this regard, the analysis presented in [17] shows how despite asymmetries in power and internal conflicts, agents are promoting the effective treatment of common resources even when it is not possible to guarantee their success in the long term. Furthermore, the proposals presented in [4,5] shows that we can use evolutionary computing to achieve cooperation among agents with different behaviors and also use concepts like sympathy and commitment in non-cooperative games. The results presented above show how a self-organizing system can produce a functionality using cooperation models; In [17], the coffee farming and for [5] a routing service. Without show specific details in each case, we can identify that the evolution of the system behavior converges towards a cooperative group that minimizes asymmetries, even when the individual social tensions of individuals do not disappear.

2.3 Moral Attitudes in Collective Decisions

Collective action demands the participation of multiple individuals who combine their actions to achieve a common goal. During this process, it is necessary to satisfy axiomatic principles that rule the pure distribution problem in common-pool resources. In this regard, to model the individual behavior of the community members, we can consider the different ethical and moral theories related to social systems as an inspiration source for designing and implementing multi-agent systems. Examples of this approach can be found in *The Moral Machine* of MIT [18], the project REINS [19], the project AMA [20] and the project ETHICAA [21]. In general terms, they attempt to explore the inclusion of structure preferences and moral values as part of the behavior of autonomous agents and verify their impact on the collective decision-making process.

Ethical systems define mutually accepted actions that are available for the members of a community. However, although they have been formalized and explored through experimental research, there is insufficient evidence to determine their relevance in the context of collective actions and social goals. As a result, we need a conceptual and computational framework that allows us to evaluate and compare the theories of individual moral behavior in the context of self-organizing systems. For example, [22] explores the impact of multiple moral choices in the decision process in scenarios where different ethical criteria need to be compared to verify the global behavior of the system (Fig. 1).

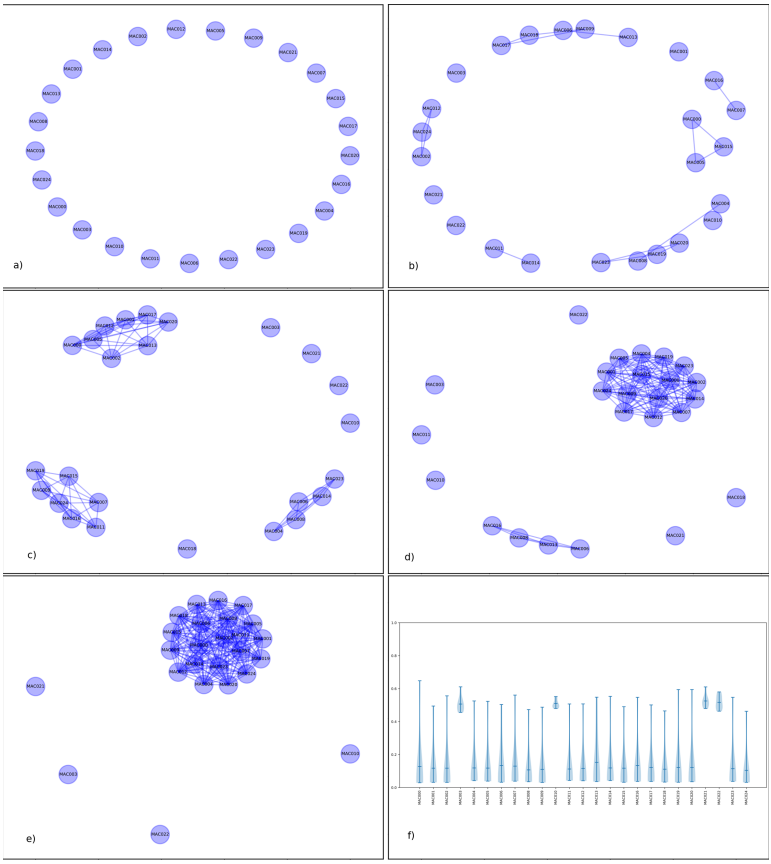

Fig. 1. Formation of a super coalition in 5 successive tournaments: a), b), c), d), e) and distribution of the computational efficiency of each agent f)

3 Robust Multi-agent Systems

To use the approach mentioned above, we need to restrict the possible moral profiles associated with ethical theories to include them as part of the multi-agent systems' behavior and define the cooperation patterns that will exist as part of the desired emergent behavior of a community. In this context, we can consider the Rawlsian principle known as *MaxMin* that can emerge from a deliberation based on the dialogue of common goals and social welfare. This work aims to show some of the mechanisms in the middle of social exchange (modeled as a negotiation process through game theory), in particular, the cooperation process that emerges from the principles of sympathy and social commitment described in [23] (Fig. 2).

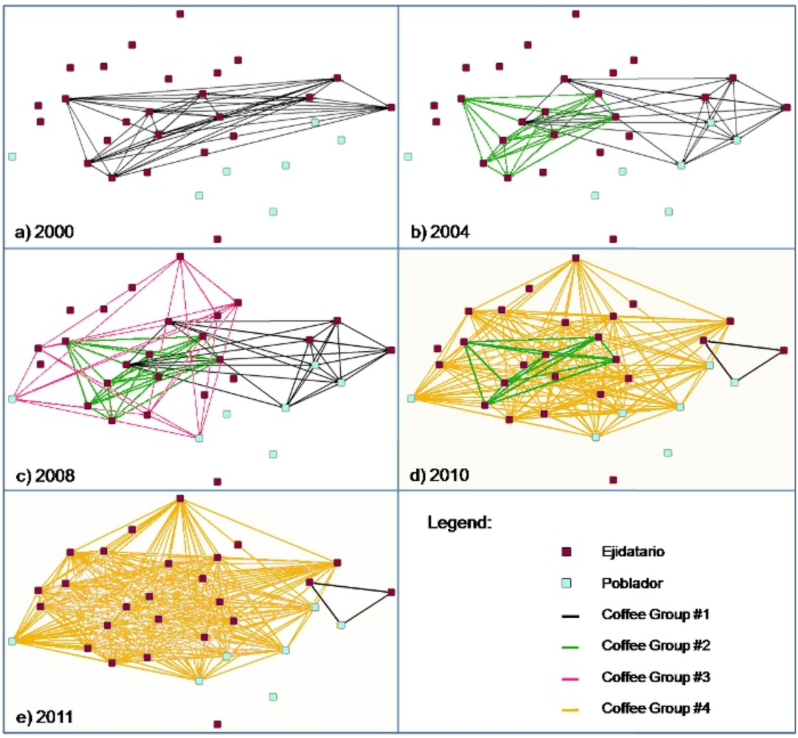

Fig. 2. Formation of a super coalition of coffee producers in 5 different moments: a), b), c), d), e). Source: [17].

To make a moral analysis of the behaviors considered by autonomous agents in the context of a multi-agent system, the categories proposed by [24] are used. They allow us to describe such behaviors in successive negotiation games based on the prisoner's dilemma. They therefore compare them with a random set of non-deterministic strategies available in [25] as it is showed Sect. 5. Consequently, we analyze the individual behavior of the system members, using a simulation scenario in a distributed virtual environment to produce a robust multi-agent system based on the moral analysis of the agent behaviors [26] .

4 Proposed Model

From the computational model provided in [27], in which four layers are added to produce a stable self-organizing communication system, a negotiation experiment is developed based on the formation of communities of agents that offer computational services through coordination and cooperation patterns. In this context, agents are responsible for managing resources available in the network and provide services to the final user. We analyze a multi-agent system's behavior using a stochastic and evolutionary process based on coalitional game

theory. Once the rational strategies have been chosen, we simulate the system evolution through the execution of negotiation tournaments based on the prisoner's dilemma and the coalitionist meta-strategy proposed in [4]. The game is described in Eq. (1). It is important to mention that this game can produce rational strategies when a group of agents A_g, as part of the evolutionary process [5], incorporate another group of agents A'_g in a coalitionist model.

$$C = (N, S, E, \succeq i) \tag{1}$$

In this regard, N is a non-empty set of agents. S, is a non-empty set of pay outcomes. E is the effectivity function of the payoff set, and $\succeq i$ is a complete preorder over S. This process is assessed through the moral evaluation mentioned above. Also, we compared these results with a negotiation model that described interactions between highly complex social organizations. In particular, we use the moral metrics proposed in [24]:

- Cooperating rating (CR)
- Good partner rating (GPR)
- Eigenjesus rating (EJR)
- Eigenmoses rating (EMR)

Similarly, analyze the moral behavior of our system allow us to study properties like robustness and efficiency, checking the performance of the computational services provided by the agents. The levels of efficiency are measured according to the metric described in Eq. (2).

$$e(i,j) = \frac{f_i(w)}{\frac{f_i(w)+f_j(w)}{2}} \tag{2}$$

In this metric, the relative efficiency $f_i(w)$ is defined as the execution time of the task w in the node i. Also, $E(i)$ represents the total efficiency of the node. Therefore, the moral relationship among the agents is defined as a function that describes the stochastic process related to the addition of the individual ethical metrics in each iteration. This process is repeated until the system achieves a meta-stable state in $t = T$.

$$M(C(t)) = \sum_{0}^{T} \sum_{i=0}^{N} CR_i(t) + GPR_i(t) + EJR_i(t) + EMR_i(t) \tag{3}$$

5 Experimental Results

It is possible to verify how a negotiation process that considers the variability and diversity of the individual's preferences can maintain suitable efficiency levels in terms of the system performance and the agents' utility. These results reinforce the theoretical conception in which it is possible to find a meta-stable equilibrium

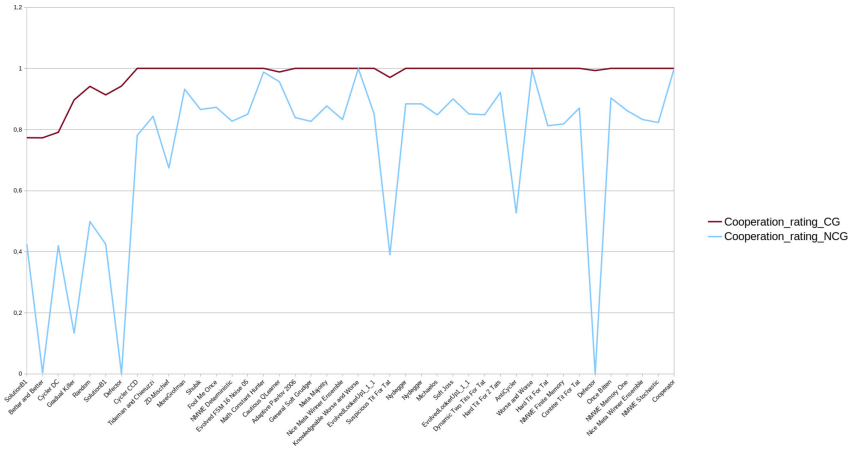

Fig. 3. Cooperation rate between 40 players in a Coalitional Game (CG) and a Non Coalitional Game (NCG)

based on the relationship between the system behaviors and the agents' capacities. As a result, this model is implemented based on the belief that a society can be defined as an association of individuals who form a cooperative coalition to obtain common welfare through collective actions. Moreover, we can describe the emerging behaviors that arise for combining multiple individual strategies in just one negotiation tournament.

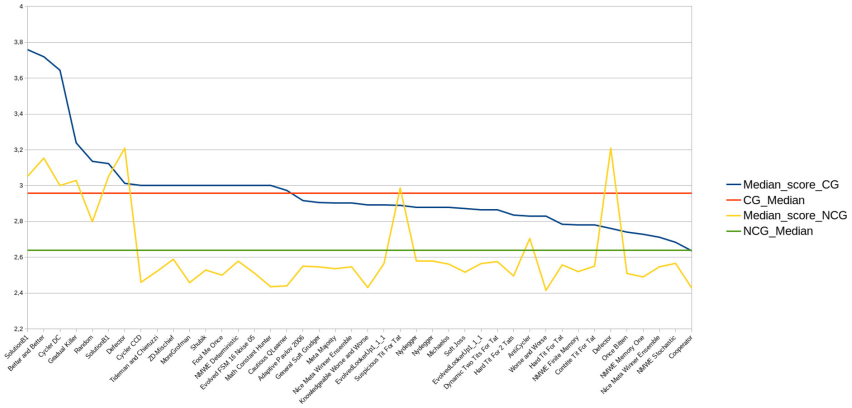

Fig. 4. Median scores for 40 players in Coalitional (CG) and Non-Coalitional (NCG) Game tournaments

Note that the moral metrics of the game confirm an improvement in both: the cooperation level in the system (Fig. 3) and the average profit of the agents

(Fig. 4). As long as the game evolves, the emergent cooperation will increase given the fact that the commitment assumed by the agents limit pure rationality. This behavior allows us to produce emergent cooperation in scenarios in which traditionally the agent would be tempted to defect.

Additionally, this cooperative behavior will maintain its level if the system can continue accepting new players and governing the community through the mentioned logic that, despite the uncertainty in the negotiation process, interprets the individual interests as part of a function of social welfare. Therefore, it is necessary to explore new types of formal logic for modeling complex negotiation scenarios in which many decisions can operate simultaneously as part of the cooperation process. For example, we can use the multi-valued logics of that allow generalizing any common resource allocation method [15].

6 Conclusions

It is possible to assume that through coalitional game theory, in general terms, and in particular, using adaptive techniques, like the ones proposed in [5], the robustness of a self-organizing open system can guarantee the simultaneous operation of the multiple strategies and achieve an equilibria state. This can be understood as the required social foundation for creating agent communities composed of individuals who make decisions and adjust their actions to accomplish common goals in a temporary and morally committed way.

Moreover, the result showed how systems influenced by moral metrics exhibit higher rates of efficiency, symmetry, and invariance over time. These attributes are pursued both philosophical and computational approaches of justice as a requirement for ensuring the sustainability of resources over time. Additionally, it is necessary to explore new scenarios and improve the negotiation rules to analyze this phenomenon in more complex computational systems. We aim to guarantee desirable characteristics and to mitigate the problems and vulnerabilities present in the schemes of self-organizing open systems, which are required in the industry 4.0 and the next generation of communication networks.

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