Supply Chain Coordination between Autonomous Agents – A Game Theory Approach

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Abstract— **A supply chain is a network of suppliers, factories, warehouses, distribution centers and retailers, through which raw materials are acquired, transformed, produced and delivered to the customer. A supply chain management system (SCMS) manages the cooperation of these system components. In the computational world, roles of individual entities in a supply chain can be implemented as distinct agents [1]. In this paper we present supply chain coordination between Autonomous Agents. Moreover, we present a cooperative game theory approach to describe the SCM coordination. Numerical and theoretical game examples are detailed in this paper, which help to understand the usefulness of cooperative game theory in SCM.**

I. INTRODUCTION

Coordination between agencies during multi-agency emergency responses, although a key issue, remains a neglected research area [2]. Coordination between the different agencies (enterprises) involved is a major challenge. Most of the components in Supply Chain Management (SCM) work in isolation and achieving coordination among Supply Chain Management partners turns out to be a difficult proposition. A supply chain typically extends across the multiple enterprises including suppliers, manufactures, transportation carriers, warehouses, retailers as well as customers and entails sharing forecast, order, inventory, and production information to better coordinate management decisions at multiple points throughout the extended enterprise [3].

The game theory approach is one of the best tools for modelling this complex system; and for modelling the cooperation between intelligent decision makers, the co-management and the autonomous agents. We know the players of the game, the information and actions are available to each player at each decision point, and the payoffs can be calculated for each outcome. In this paper, the cooperative game theory approach is detailed, through its main features.

The paper is organized as follows: Section (II) discusses the Supply Chain Coordination and co-management. Section (III) discusses the Multi-level Governance. Section (IV) introduces the construction of Supply Chain with the help of an agent. Section (V) presents the different types of games used in supply chain management. In section (VI) discusses the main features of cooperative games. And finally, section (VII) and section (VIII) detail numerical and theoretical SCM examples, in section (IX) can be read the conclusions.

The main goal of the paper is merging the up-to-date knowledge of supply chain coordination and the game theory. So, it contains a large number of reviews, but as an outlook, as an own contribution, it gives a usage example too. This paper integrates the SCM logistic and mathematical modelling knowledge.

II. SUPPLY CHAIN COORDINATION AND CO-MANAGEMENT

Supply chains (SC) are a system with "multiple actors". The supply chain is commonly seen as a collection of various types of companies (raw materials, production, trade, logistics, transport, etc.) working together to improve the flow of products, information and finance [4], [5]. Supply chains are complex systems, dynamic, dispersed and open. Those elements together with other factors (e.g. multiple subjects, independence of cooperating enterprises) determine difficulties in the field of management, or more broadly, of coordination of commonly take up and independently realized actions. The discussed systems are affected, as a whole, by a lack of internal rationality, unverified information and insufficient knowledge. The problem is also posed by uncertainty and a lack of precision [6]; [7], indispensable in the realized projects and complex undertakings.

Co-management is of growing interest among researchers. Centralized, top-down resource management is ill-suited to user participation. Centralized management are limited in their ability to respond to changing conditions, an anachronism in a world increasingly characterized by rapid transformations [8]; [9]. Changing ideas about the nature of resource management, ecosystems, and social-ecological

systems (integrated systems of people and environment) have been catalyzed by insights from complex adaptive systems thinking.

Selected features of adaptive co-management:

- Shared vision, goal, and/or problem definition to provide a common focus among actors and interests;
- A high degree of dialogue, interaction, and collaboration among multi-scaled actors;
- Distributed or joint control across multiple levels, with shared responsibility for action and decision making;
- A degree of autonomy for different actors at multiple levels;
- Commitment to the pluralistic generation and sharing of knowledge;
- A flexible and negotiated learning orientation with an inherent recognition of uncertainty [9].

Plummer and Fennell [10] build upon initial efforts to capture how adaptive co-management is being understood [11, 12, 13] to arrive at the following attributes.

- Pluralism and communication. Actors from diverse spheres of society (and at multiple levels) and who have varying principal interests enter into a process to generate shared understanding of an issue or problem. This process is grounded in communication and negotiation. Conflict is viewed as an opportunity.
- Shared decision-making and authority. Transactive decision-making is employed as a basis for achieving decisions. Multiple sources of knowledge are acknowledged. Authority (power) is shared in some configuration among the actors involved.
- Linkages, levels and autonomy. Actors are connected or linked both within levels and across scales. Despite shared interests and commitments, actor autonomy is appropriate at multiple levels. Institutional arrangements therefore encompass multiple levels as well as retain flexibility.
- Learning and adaptation. Actions and policies are considered experiments. Feedback provides opportunities for social learning in which outcomes are collectively reflected upon and modifications to future initiatives are based. Learning may concern routines, values and policies, and/or critical questions of the underlying governance systems; referred to as multiple-loop learning. Develops as trust and knowledge [14].
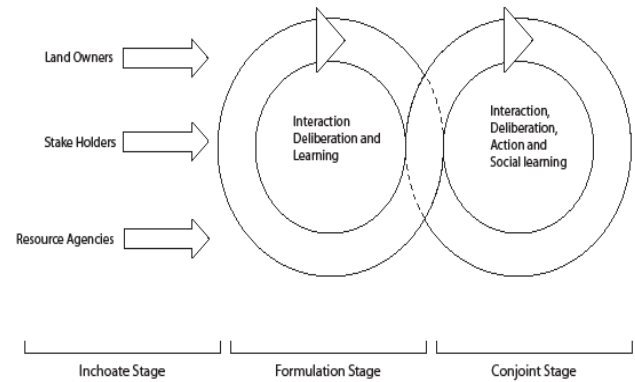

Fig. 1 A model of the adaptive co-management process [14]

Co-management is not a fixed unitary entity, rather it is a set of principles for institutional design that can assume various organizational forms depending on particular circumstances [15].

Coordination defined as the process of managing dependencies among activities. Starting with the individual activity it is easily recognized that the industrial reality contains a multitude of various activities. When focusing solely on individual activities, these might seem to have a generic value, for example considering a production or exchange activity [16].

III. MULTI-LEVEL GOVERNANCE

The chief benefit of multi-level governance (MLG) lies in its scale flexibility. Its chief cost lies in the transaction costs of coordinating multiple competence. The coordination dilemma confronting multi-level governance can be simply stated: To the extent that policies of one competence have spillovers (i.e. negative or positive externalities) for other jurisdictions, so coordination is necessary to avoid socially perverse outcomes. We conceive this as a second -order coordination problem because it involves coordination among institutions whose primary function is to coordinate activity [17]. Type (I.) multi-level governance describes jurisdictions at a limited number of levels. That is to say, they bundle together multiple functions. Type (II.) multi-level governance is distinctly different. It is composed of specialized competence. The number of such competence is potentially huge. They tend to be lean and flexible – they come and go as demands for change [17]. Multi-level governance is the domain of the European Union.

Multi-level governance characterizes the changing relationships between actors situated at different levels. MLG contributes to a growing awareness that many contemporary issues and challenges require analysis that transcends traditional disciplinary boundaries.

Multi-level governance:

- Decision-making competencies are shared by actors at different levels rather than monopolized by executives;
- Collective decision-making significant loss of control for individual executives.

IV. CONSTRUCTION OF SUPPLY CHAIN WITH THE HELP OF AN AGENT

It should be assumed that this is one of the simplest coordination mechanisms. It assumes that the enterprises in the built structure possess a hierarchy, previously provided. In order for it to function effectively, the execution of the following tasks is necessary:

- Initiating the creation of a database of enterprises that will operate within the structure;
- Defining the scope of activities of the individual entities;
- Specifying the rights and obligations of the individual entities (regulations);
- Expanding the database of enterprises through own actions (sending information through the available communication channels, i.e. e-mail, press, internet...);
- Registration of structure participants;
- Approving the participants;
- Agreement;
- Establishing priorities and dependencies between the enterprises.

The agent should be understood and treated as coordinating activities of the organization. The agent should be:

- reactive – agent-coordinator identifies and responds to the tasks; It has current knowledge about the business,
- pro-active – agent-coordinator takes the initiative in order to carry out tasks,
- able to cooperate – agent-coordinator interacts with others in order to carry out the task.

The benefit of relations between enterprises defined in such a manner is the legible and explicit indication of the role that each enterprise is to play in the created structure. The building of structures with the help of an assistant most often assume the hierarchical master/slave structure. In such a case the agent master plans and sends out information on the orders to the individual subordinate agents (slave). And each of these agents transfers return information on the status of the completion of their order. The defect of such an approach is the small amount of autonomy for the slave agents. Coordination through the organization works ideally in the coordination of the tasks of agents connected by strong hierarchical relations [18].

Bennett and McCoshan (1993) [19] have suggested a typology of networks (Figure 1) which describes a range of relations between agents at the local or regional level. As they note, the networks A-D are derived from management science, and each has advantages and disadvantages in delivering economic development activities efficiently and sustainably. The introduction of the fifth form, E, is meant to be flexible and responsive to the needs of different agents [20].
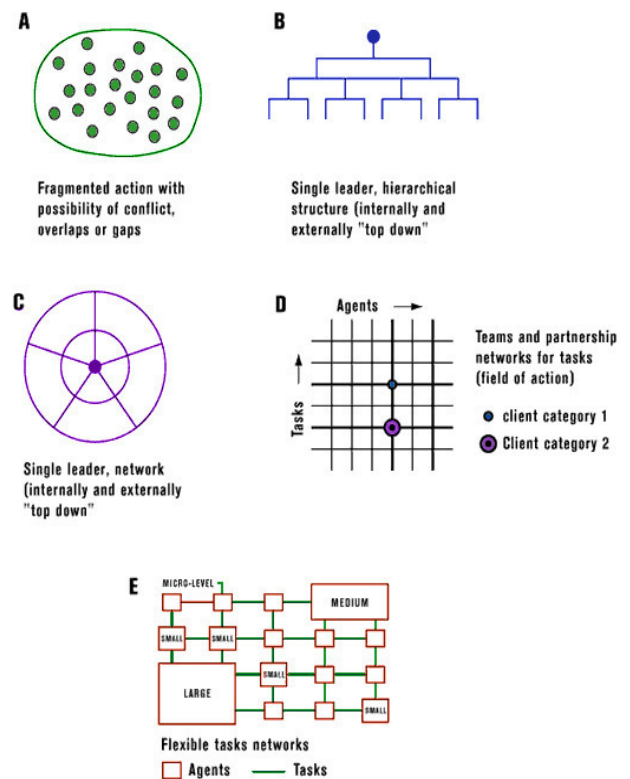

Fig. 1 Network of relations between agents at a local level [20]

V. THE DIFFERENT TYPES OF GAMES USED IN SUPPLY CHAIN MANAGEMENT

Game theory is a powerful tool for analyzing situations in which the decisions of multiple agents affect each autonomous agent's payoff. The elements and rules mentioned in the previous section of this paper are the SCM conceptual basis: the decision-making, the coordination, the governance and the agents are the main subcomponents. The following game theory approach gives the opportunity of the mathematical modelling.

As such, game theory deals with interactive optimization problems. While many economists in the past few centuries have worked on what can be considered game-theoretic models, John von Neumann and Oskar Morgenstern (1944) [21] are formally credited as the fathers of modern game theory. Their classic book summarizes the basic concepts existing at that time. Game theory has since enjoyed an explosion of developments, including the concept of equilibrium by Nash (1950) [22], games with imperfect

information by Kuhn (1953) [23], cooperative games by Aumann (1959) [24] and Shubik (1962) [25].

There are many game theory concepts, but this paper focuses on concepts that are particularly relevant to supply chain management (SCM) and, perhaps, already found their applications in the literature. The main state of the art: Myerson (1997) [29], Friedman (1986) [26], Fudenberg and Tirole (1991) [27], Topkis (1998) [30] and Vives (1999) [31], Moulin (1986) [28]. Some previous surveys of game theory models in management science include Lucas's (1971) survey of mathematical theory of games [32], Feichtinger and Jorgensen's (1983) [33] survey of differential games and Wang and Parlar's (1989) survey of static models [34], Porteus and Whang (1999) [38] survey of screening game. In addition, Fudenberg and Tirole (1991) [27] for more information on Bayesian games, Cachon and Lariviere (2001) [35] survey of signaling game, Brandenburger and Stuart (1996) [39] for more information of business process games, and [40], [41], [43], [44] about the core of the game, [44] about the Shapley value.

VI. THE MAIN FEATURES OF COOPERATIVE GAMES

Cooperative game theory focuses on the outcome of the game, where the outcome is measured in terms of the value created through cooperation of a subset of players [35]. In what follows, we will cover transferable utility cooperative games (players can share utility via side payments) and three solution concepts:
- the core of the game;
- the Shapley value;
- and the nucleolus.

A. GAMES IN CHARACTERISTIC FORM AND THE CORE OF THE GAME

The cooperative game consists of the set of players N with subsets or coalitions $S \subseteq N$ and a characteristic function $v(S)$ that specifies a (maximum) value (which we assume is a real number) created by any subset of players in N, i.e., the total pie that members of a coalition can create and divide. A frequently used solution concept in cooperative games is the core of the game. The utility vector $x_1, ..., x_N$ is in the core of the cooperative game if

$$\forall S \subseteq N, \sum_{i \in S} x_i \geq v(S) \text{ and } \sum_{i \in N} x_i = v(N)$$

A utility vector is in the core if the total utility of every possible coalition is at least as large as the coalition's value, i.e., there does not exist a coalition of players that could make all of its members at least as well off and one member strictly better off.

B. SHAPLEY VALUE, NUCLEOLUS

The concept of the core, though intuitively appealing, also possesses some unsatisfying properties. Shapley (1953) offered an axiomatic approach to a solution concept that is based on axioms [45]. One of the most important is that: if v_1 and v_2 are characteristic functions in any two games, and if ϕ_1 and ϕ_2 are a player's Shapely value in these two games, then the player's Shapely value in the composite game, $v_1 + v_2$, must be $\phi_1 + \phi_2$.

An alternative equivalent formula for the Shapley value is:

$$\varphi_i(v) = \frac{1}{|N|!} \sum_R \left[v\left(P_i^R \bigcup \{i\}\right) - v(P_i^R) \right]$$

where the sum ranges over all *INI!* orders R of the players and P_i^R is the set of players in N which precede i in the order R.

Another interesting value function for cooperative games may be found in the nucleolus, a concept introduced by Schmeidler (1969) [47]. The main idea: we look at a fixed characteristic function, v, and try to find an imputation $x = (x_1,...,x_n)$ that minimizes the worst inequity. As a measure of the inequity of an imputation x for a coalition S is defined as the excess:

$$e(x, S) = v(S) - \sum_{i \in S} x_i$$

which measures the amount (the size of the inequity) by which coalition S falls short of its potential $v(S)$ in the allocation x.

VII. NUMERICAL EXAMPLE

There are three enterprises (A, B, C; logistics providers – e.g. freight, storage, complex logistics processes, transhipment processes, with using roads and rails too -), the core of the game based on the following constraints (Fig. 2):

$$v(A)=v(B)=v(C)=0$$
$$v(AB)=3$$
$$v(AC)=5$$
$$v(BC)=4$$
$$v(ABC)=7$$

Here, individually, none of the players can receive any payoff. But if they cooperate, different coalitions result in a positive payoff for each coalition. If they all cooperate, then the grand coalition receives an amount $v(ABC)$ higher than any other coalition. Other words: they have to perform a multimodal logistics task.

The core of a game in characteristics form is defined as the set of all imputations $(x_1, x_2, ... , x_n)$ such that for all

$S \subseteq N$, $\sum_{i \in S} x_i \geq v(S)$. The core is the set of all (x_A, x_B, x_C) satisfying:

$$x_A + x_B \geq v(AB) = 3$$

$$x_A + x_C \geq v(AC) = 5$$

$$x_B + x_C \geq v(BC) = 4$$

$$x_A + x_B + x_C = v(ABC) = 7$$

The set of imputations in this game can be represented by an equilateral triangle with high equal to $v(ABC)=7$. For any point (x_A, x_B, x_C) in the triangle, x_i is the distance to side of the opposite corner, $i=A, B, C$; as indicated in Figure 2.

Thus, player i prefers imputations that are close to corner i. Since

$$x_i + x_j \geq v(ij) \leftrightarrow x_k \leq v(ABC) - v(ij)$$

$$for \ i \neq j \neq k$$

the latter inequalities can be drawn to obtain the core – provided that is nonempty.

The core in this game is obtain by drawing the regions

$$x_A \leq 3$$

$$x_B \leq 2$$

$$x_C \leq 4$$

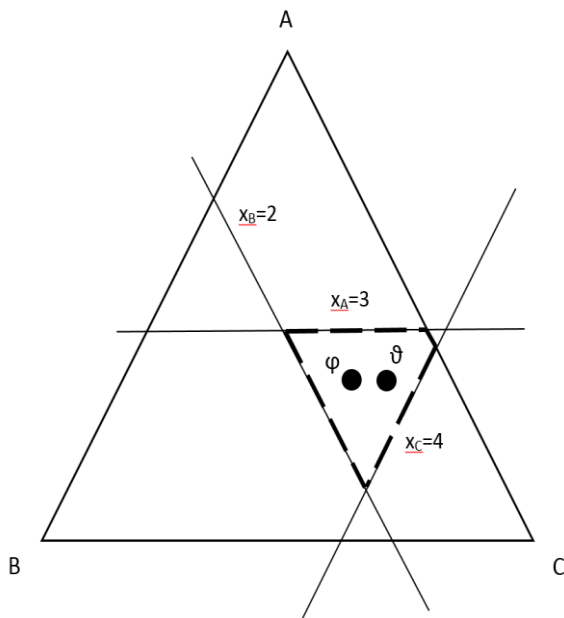These give rise to the area indicated by interrupted lines in Figure 2.

Fig. 2 The core of the game, the Shapley value and the nucleolus

Table 1. shows the marginal contributions of players, based on this, we can calculate the Shapley value.

TABLE I.
THE MARGINAL CONTRIBUTIONS OF PLAYERS

Orders of the players	Marginal contributions of A	Marginal contributions of B	Marginal contributions of C
ABC	v(A)-v(0)	v(B)-v(0)	v(C)-v(0)
ACB	v(A)-v(0)	v(B)-v(0)	v(C)-v(0)
BAC	v(AB)-v(B)	v(AB)-v(A)	v(AC)-v(A)
BCA	v(ABC)-v(BC)	v(ABC)-v(AC)	v(ABC)-v(AB)
CAB	v(AC)-v(C)	v(BC)-v(C)	v(BC)-v(B)
CBA	v(ABC)-v(BC)	v(ABC)-v(AC)	v(ABC)-v(AB)

The Shapley value for the three players are found as

$$\varphi_A(v) = \frac{14}{6} = 2{,}33$$

$$\varphi_B(v) = \frac{11}{6} = 1{,}83$$

$$\varphi_C(v) = \frac{17}{6} = 2{,}83$$

Based on Leng and Parlar (2010), we can use explicit formula to compute the nucleolus [46]:

$$xi = \frac{v(123) + v(ij) + v(ik) - 2v(jk)}{3}$$

$$for \ i,j,k = 1,2,3 \ and \ i \neq j \neq k$$

The nucleolus $\vartheta(x_A, x_B, x_C)$ for the three players are found as (Table 2. shows $e(x,S)$):

$$x_A = \frac{7}{3} = \frac{14}{6} = 2{,}33$$

$$x_B = \frac{4}{3} = \frac{8}{6} = 1{,}33$$

$$x_C = \frac{10}{3} = \frac{20}{6} = 3{,}33$$

TABLE II.
THE E(X,S) IN THE NUCLEOLUS

S	v(S)	e(x,S)	(14/6; 8/6; 20/6)
A	0	$0 - x_A$	-2,33
B	0	$0 - x_B$	-1,33
C	0	$0 - x_C$	-3,33
AB	3	$3 - x_A - x_B$	-0,67
AC	5	$5 - x_A - x_C$	-0,67
BC	4	$4 - x_B - x_C$	-0,67

In this example, the Shapley value and the nucleolus is also in the core. They give solution alternatives of game, which are relatively close to each other.

Based on this numerical example, we can calculate the tangible benefits of a virtual logistics alliance. Moreover, there are three indicators (core of the game, Shapley value, nucleolus), to evaluate the benefit of this alliance, and the personal effects too. The great advantage of this solution is the quantifiability and the opportunity of the multi criteria decision making.

VIII. THEORETICAL SCM EXAMPLE

The previous numerical example could be good for modelling cooperation in the freight and warehouse exchanges Kovács (2009) [49], Grzybowska and Kovács (2012) [50], Grzybowska and Kovács (2014) [51]. The simplified system model of the supply chain supported by electronic freight and warehouse exchanges is shown in Figure 3.

In this system, the electronic freight and warehouse exchanges perform the supply-demand (freight/storage capacities/tasks) harmonization; the decision supporting, the optimization and the whole software/hardware support. The logistics providers (storage providers, transportation providers, logistics centres) perform the physical freight/storage/transhipment tasks; whereas they have: suitable stock capacities, suitable freight capacities, equipment's, and logistics know-how. The wholesalers are responsible for the information processes; they manage the demands of retailers. This supply chain may be optimal, through using cooperative game theory, pollution or cost point of view. Consequently, green logistics systems, e.g. green city supply chains or combined transportation systems can be realized. In addition, this system is beneficial not only for the individual actors (e.g. retailers, wholesalers, logistics

providers, manufacturers) but also for the national economy (reduce traffic flow, pollution, noise). The future plans include further development of algorithms and tests in real supply chains.
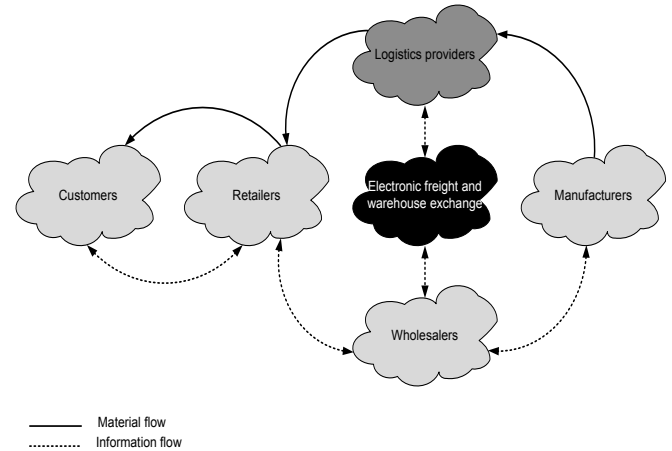

Fig. 3 The simplified system model of the supply chain supported by electronic freight and warehouse exchanges

As another example of potential SCM modelling, research at the Department of Material Handling and Logistics Systems in Budapest is aimed to help logistics processes at the construction industry. This work has been developed in the framework of the project "Development of construction processes from logistical and informatical aspects". This research is part of a project (KTIA-AIK-12-1-2013-0009) financed by the National Development Agency of Hungary. This project concentrates on the logistics aspects, where organization of the material flow is an important task. Based on this research, we can create flowcharts (for top-down modelling and for low-level modelling too), which help to analyse the real construction processes, and thereby we can build up realistic game models too.

IX. CONCLUSIONS

The main result of this article is merging the supply chain coordination and the cooperative game theory approach. By the explanations and the numerical example, this logic modelling is reasonable. The occurring decision supporting problem can be modelled well, the branching points and a variety of outputs can be understood and managed. The main contribution is the combination of SCM and mathematical principal founds, by the addition of numerical and theoretical examples too.

One of most interesting application is the virtual alliances in the supply chain, such as freight exchanges, but other areas also may be promising. The next step in the research will be to make essential progress in the field of supply chains, e.g. a freight and warehouse exchange game model structure.

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