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Modelling the Triple Helix of university-industry-government relationships with game theory: core, Shapley value and nucleolus as indicators of synergy within an innovation system

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Abstract

The Triple Helix of university-industry-government relationships is a three-person cooperative game with transferable utility. The core, the Shapley value and the nucleolus are suggested as indicators to measure the synergy between innovation actors. The core is the expression of actors' interests and constraints exerted on them; it measures the extent of the synergy. The Shapley value indicates actors' strength to lead to and create synergy; and the nucleolus determines the power of coalitions to maintain synergy. The Triple Helix games of the South Korean and the West African innovation systems are studied, based on bibliographic data collected from Web of Science over a ten-year period (2001-2010). Results show that the core of South Korea is larger than that of West Africa, meaning that synergy occurs more within the South Korean innovation system than in the West African one. University has more power to lead to and create synergy and coalitions involving government work in order to maintain synergy.

Key-words: Triple Helix; innovation ; synergy ; Game theory ; Core ; Nucleolus ; Shapley Value.

1. Introduction

The Triple Helix concept introduced by Etzkowitz and Leydesdorff (Etzkowitz & Leydesdorff, 1995; Etzkowitz, Webster, Gebhardt, & Cantisano Terra, 2000) is one of the variants of the nonlinear model of innovation (Etzkowitz et al., 2000; Leydesdorff, 2012; Meyer, Grant, Morlacchi, & Weckowska, 2014). The model postulates that the interactions between university, industry and government create synergy that leads to innovation (Leydesdorff & Etzkowitz, 2001). The theory has gained attention since it was developed, as illustrated by an increasing number of papers, as registered in the Web of Science (Meyer et al., 2014). Its geographic audience is very broad compared with that of other variants of the linear model of innovation like the Mode 2 (Shinn, 2002, p. 603). The Triple Helix idea has led to a genuine research school with an empirical and conceptual agenda (Shinn, 2002, p. 611). National and international research funding institutions (like the North Atlantic Treaty Organisation, the European Union, National Science Foundation (USA), the Centre National de Recherche Scientifique (France), etc.) are interested in this idea, and researchers from the Third World have contributed to the development and the implementation of the theory; evidence could be established from the nationalities of participants to the annual Triple Helix conferences and authors of papers presented at the conferences (Mêgnigbêto, 2016b, p. 36). Furthermore, innovation programmes have been developed under this paradigm[1] (Park, 2014). As Le Coadic (1994) stated about information science, the Triple Helix is becoming a separate discipline because it has an epistemology (a specific concept, models, methods, etc.), societies (e.g. the Triple Helix Association), journals (e.g. Triple Helix Journal) and scientific events (e.g. the Triple Helix Annual Conference). The Triple Helix is being investigated by researchers from various domains such as sociologists, economists, informetricians, etc.

[1] Shapiro (2007) qualified the Triple Helix as a paradigm.

However, the Triple Helix community is still seeking indicators to measure the synergy between innovation actors. According to Meyer et al. (2014), some papers proposed indicators of science-technology interaction like patent citations or inventor/author analysis, publications counts, patents counts, citations, co-authors and related indicators; others are concerned with measuring information flows especially through entropy measures. The mutual information (Leydesdorff, 2003) or mutual redundancy (Leydesdorff & Ivanova, 2014) and the transmission power (Mêgnigbêto, 2014a), based on information theory, were proposed. They have been used in the literature to analyse various innovation systems, for example, Kwon et al. (2012), Khan and Park (2011), Ye et al. (2013) and Leydesdorff and Sun (2009) who studied mutual information and Ivanova et al. (2014) and Mêgnigbêto (2014b, 2014c, 2015) who studied transmission power.

Innovation systems are complex systems (Katz, 2006, 2016). The university-industry-government relationships constitute a complex system (Leydesdorff, 2003) that can be analysed with techniques and tools from cybernetics, information theory, game theory, decision theory, topology or mathematics of relations or factorial analysis (von Bertalanffy, 1973). Informetric studies having used game theory techniques and tools are scarce: Tol (2012) and Karpov (2014) resorted to Shapley values, the former for assessing research production and impact of schools and scholars, and the latter for allocating publication credit to co-authors; Hayes (2001, 2003) modelled decision-making in library cooperation with cooperative games theory; Schubert and Glänzel (2008) showed that ternary diagram could serve to study research collaboration and citations. Some papers introduced game theory in the study of either innovation systems in general (Baniak & Dubina, 2012 gave a review of them) or the Triple Helix in particular. Carayannis and Dubina (2014) on the one hand, and

Dubina and Carayannis (2015) on the other hand, demonstrated that game theory could help in understanding the behaviour of innovation actors; Dubina (2015a, 2015b) modelled the Triple Helix relationships with game theory; however, the scope of his reflection was limited to project funding. Not only did he not deal with publications, but he did not either propose any indicator to measure the synergy within the Triple Helix framework also. As he wrote, it was a "first attempt to formalize the concept of the Triple Helix of university-government-industry interactions in innovation activities with game theory" (Dubina, 2015a, p. 33, 2015b, p. 40).

The objective of this paper is twofold: i) analyse the Triple Helix relationships using game theory principles, methods and techniques, and, ii) develop indicators to measure the synergy within an innovation system. The article intends to answer the following research questions: i) What are the rules of the Triple Helix game? and, ii) How can the synergy be measured with game theory indicators? It is structured as follows: the second (next) section, gives a background information on game theory; the third section determines the rules of the Triple Helix game, the fourth proposes the core, the Shapley value and the nucleolus as indicators to measure the synergy within a Triple Helix innovation system; the fifth section gives an application to bibliographic data quoted from relevant Triple Helix studies; the last two sections are devoted to the discussion of the findings and the conclusion of our paper.

2. Basic information on game theory

Game theory is a branch of mathematics that deals with how economic actors interact for their interests. Modern game theory and its application in economy originate from von Neumann and Morgenstern (1944). Nowadays, game theory's techniques are used to understand economic, social, political, and biological phenomena (Jackson, Leyton-Brown, & Shohan, 2016; Osborne, 2004). It is concerned with the actions of decision makers who are conscious that their actions affect each other; it “is not useful when decisions are made that ignore the reactions of others or treat them as impersonal market forces” (Rasmusen, 2000, p. 30). According to Aumann (1985), game theory can be applied to all situations where peoples’ actions are both utility maximizing and interdependent.

Game theory defines a game by four elements: the players, the actions, the payoff and the information (Rasmusen, 2000). Players are the individuals who make decisions. An action is a choice made by a player; usually, there is a set of actions a player can choose from. A payoff means either the utility a player receives after the game has been played out; or the expected utility. An information set at any particular point of the game is the reading a player gets from the actions the other players have taken or will take. Once a game is defined, one is interested in the strategies each player elaborates to maximize its utility. Game theory distinguishes two branches: noncooperative games and cooperative games. Noncooperative games focus on the strategies of individual players while cooperative games focus on how players behave mainly by the means of coalitions.

3. Rules of the Triple Helix game

3.1 Players, actions, payoff and information

Defining the rules of a game consists in determining the players, the actions, the payoff and the information (Rasmusen, 2000). In the Triple Helix game, the players are the three main innovation actors: university, industry and government denoted u, i and g[2] respectively; hence, the set of players is N = {u, i, g}. The number of players is therefore, n = 3.

[2] We used small letters to avoid any confusion with the meanings given to capital letters in the Triple Helix literature.

Innovation actors share knowledge in order to exploit it. The exploitation of knowledge requires it to be produced, circulated and be acquired (Mueller, 2006). Doing research is, therefore, a sine qua non or a prerequisite condition for knowledge production. Hence, not publishing is an unconceivable action for actors of the Triple Helix innovation system or the Triple Helix game. Furthermore, while publishing, the Triple Helix innovation actors could negotiate arrangements with one another or not. We conclude that the actions available to the Triple Helix innovation actors are "to collaborate" and "not to collaborate". Because publication is a tangible measure of research, we use the number of papers published by actors or the corresponding percentage shares as payoffs. In publication counting, there are two methods: full counting and fractional counting (Karpov, 2014; Leydesdorff & Bornmann, 2011; Waltman & van Eck, 2015). The full counting method fully assigns a publication to each co-author whereas in the fractional counting case, a publication is fractionally assigned to each co-author; [3] in this paper, we adopt the full counting method as done in bibliometric studies dealing with the Triple Helix relationships (Khan & Park, 2011; Kwon et al., 2012; Leydesdorff, 2003; Mêgnigbêto, 2013). Therefore, we consider such a paper as published by a single author composed of all its co-authors, i.e., they are not counted as the output of any individual author.

3.2 The Triple Helix relations as a cooperative game

By doing research, researchers produce information and knowledge; by collaborating, they increase their productivity (Katz & Martin, 1997) and share information and knowledge (Guns

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[3] With full counting for instance, a publication co-authored by four countries counts as a full publication for each of the four countries. With fractional counting, the weight with which a publication is assigned to a co-author indicates the share of the publication allocated to that co-author, the sum of the weights of all co-authors of a publication equals one. There are many variants of fractional counting (Waltman & van Eck, 2015).

& Rousseau, 2014; Katz & Martin, 1997; Olmeda-Gómez, Perianes-Rodríguez, & Antonia Ovalle-Perandones, 2008). Research collaboration is recognized as crucial for knowledge production and innovation (OECD, 2010); it may cover several aspects. It is often used as synonymous to having multiple authorships or multiple addresses; that is, research collaboration occurs if two or more scientists cooperate and publish (Bordons & Gomez, 2000, p. 198; Katz & Martin, 1997). Even though the measure presents some limitations (Bordons & Gomez, 2000; Katz & Martin, 1997; Subramanyam, 1983), in academia, co-authorship is the most visible indicator of scientific collaboration, and thus, has been frequently used to measure collaborative activity (Abbassi, Liaquat, & Leydesdorff, 2012; Bordons & Gomez, 2000; Katz & Martin, 1997).

Collaboration is one aspect of the interactions between the Triple Helix actors; Leydesdorff advices however against reducing the Triple Helix relations to "collaboration" (Park, 2014). Indeed, Watson (2013) stated that an interaction may be competitive or cooperative. The OECD (2002, p. 15) asserted that the concept of interaction between innovators includes three basic ideas: competition, transaction and networking. Competition is "the interactive process where the actors are rivals and which creates the incentives for innovation". Transaction "is the process by which goods and services, including technology embodied and tacit knowledge are traded between economic actors". Networking "is the process by which knowledge is transferred through collaboration, co-operation and long term network arrangements" (OECD, 2002). According to the Triple Helix theory, "innovation actors who coexisted relatively separately, are now moving in a common direction to stimulate both competition and collaboration" (Leydesdorff & Etzkowitz, 2001); Gibbons et al. (1994) supported that the relations between innovations actors "seeks a balance between competition and cooperation".

Cooperation, collaboration, competition and transaction contribute to the dynamics within the Triple Helix innovation system. Actions of one actor may determine the behaviour of the others. Besides, throughout their interactions, university, industry and government increase their individual productivity (Katz & Martin, 1997) in terms of number of publications; in other words, each intends to maximize its interests while working for the synergy within the innovation system. Therefore, the Triple Helix relationships as described above can be considered as a game and modelled with game theory. Furthermore, because the Triple Helix actors may bind agreements, the game is cooperative. Cooperative games are defined in a characteristic form by a couple of elements: i) a set of players, and ii) a characteristic function specifying the values created by different subsets of players (Serrano, 2007; Shapley & Shubik, 1973). It implies arrangements between players to form coalitions.

3.3 Coalitions

In cooperative (or coalitional) game theory, a coalition is a group of players that has the institutional structure to plan and perform actions, including the allocation of the generated value over its members (Gilles, 2010). By definition, the empty set and sets of individual players are also considered as coalitions; the coalition that groups together all players is called the grand coalition. Consequently, the number of coalitions in a n-player game is 2^n. Thus, the number of coalitions in the Triple Helix game is $2^3 = 8$ and the set they constitute is $\mathcal{P} = \{\emptyset, \{u\}, \{i\}, \{g\}, \{u, i\}, \{u, g\}, \{i, g\}, \{u, i, g\}\}$. This means that we have the following possibilities: i) there is no actor within the game; in other words, university, industry and government does publish neither individually nor collectively; this is represented by the empty set $\emptyset$; ii) actors publish individually, perhaps only one publishes, or two or all the three, but there is no collaboration; this yields the one-player coalitions represented by the sets {u}, {i}, {g}; iii) there are three bilateral collaborations yielding the three two-player coalitions represented by the sets {u, i}, {u, g}, {i, g}; [4] and, iv) there is one trilateral collaboration resulting in the grand coalition represented by the set {u, i, g}.

3.4 C***haracteristic function***

The characteristic function of a cooperative game determines the payoff of each potential coalition engaged in the game. The basic rules are: i) the total payoff is the payoff of the grand coalition and ii) the empty coalition has a payoff of 0, iii) the payoff of any coalition with at least two members is greater than or equal to the sum of the payoffs of individuals composing the considered coalition (Shapley & Shubik, 1973). Let us consider Figure 1 which represents the basic configuration of the Triple Helix in term of number of publications per sphere as used in the literature (Khan & Park, 2011; Kwon et al., 2012; Leydesdorff & Park, 2014; Leydesdorff & Sun, 2009; Mêgnigbêto, 2013; Ye et al., 2013).

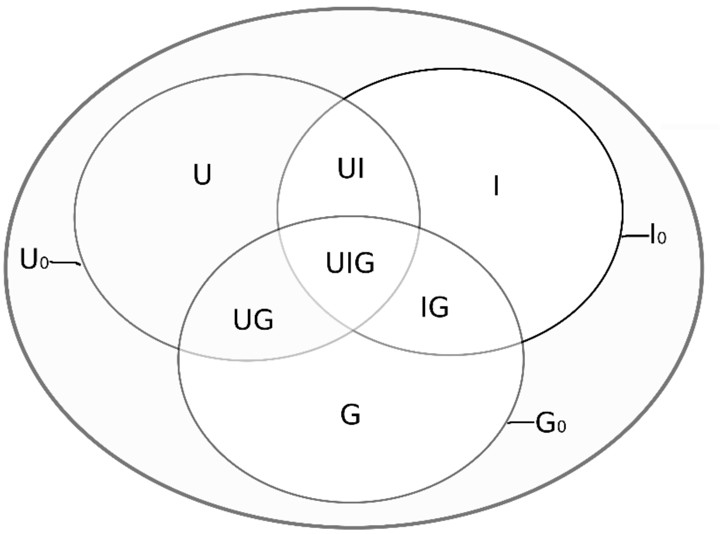


Figure 1. Triple Helix spheres' contributions to the Triple Helix relations

[4] In a set, the order of elements is not meaningful, i.e. the set {u, i} is the same as the set {i, u}.

In Figure 1, U_0, I_0 and G_0 represent the total number of papers university, industry and government published within the considered set of papers, including publications produced throughout bi or trilateral collaborations; U, I, G represent the number of papers university, industry and government published on their own respectively; UI, UG, IG represent the number of papers university and industry, university and government, industry and government co-authored respectively: and UIG the number of papers the three actors co-authored. UI, UG and IG exclude UIG. The total number of publications in the considered set is T = U + I + G + UI + UG + IG + UIG, with U_0 = U + UI + UG + UIG, I_0 = I + UI + IG + UIG and G_0 = G + UG + IG + UIG.

Let υ be the characteristic function of the considered Triple Helix game. It entrusts with each coalition its "interest" in the game, i.e. the number of papers it published or the corresponding percentage share. University produces on its own U papers, industry I papers and government G papers. University and industry produced UI papers jointly. By binding agreements, university expects getting more than U papers and industry more than I papers; the number UI is, therefore, the supplement payoff of which benefit incited the two players to "negotiate" and form a coalition. Because the number UI goes to both players, υ({u, i}) = U + I + UI. By the same reasoning, we deduce υ({u, g}) = U + G + UG and υ({i, g}) = I + G + IG. UIG is the result of the "work" of all three players and should not be attributed to any particular one-player or two-player coalition rather to the grand coalition. So υ({u, i, g) = υ(N) = U + I + G + UI + UG + IG + UIG = T which represents the total number of papers in the considered set. Therefore, the characteristic function of the Triple Helix game follows:

$$\begin{cases} \upsilon(\emptyset) = 0 \\ \upsilon(\{u\}) = U \\ \upsilon(\{i\}) = I \\ \upsilon(\{g\}) = G \\ \upsilon(\{u,i\}) = U + I + UI \\ \upsilon(\{u,g\}) = U + G + UG \\ \upsilon(\{i,g\}) = I + G + IG \\ \upsilon(\{u,i,g\}) = U + I + G + UI + UG + IG + UIG \end{cases} \quad (1)$$

3.5 Is the payoff transferable?

In game theory, the benefit of any coalition should go to one partner only – the payoff is not transferable – or shared between the coalition members on the basis of an agreement, so the shares should add up to the benefit – the payoff is transferable. But in publication counting, whatever the method (full or fractional counting) is, a paper resulting from a collaboration accounts for all authors. Let us consider an innovation system consisting of university and industry where these players produced U and I papers on their own respectively and UI papers jointly. The total number of publications within the system adds up to U + I + UI, but overall, university produces U + UI papers and industry I + UI papers. Using game theory language, we will say that the payoff of the coalition formed by university and industry goes to each party entirely (in case of full counting) or partially (in case of fractional counting). Both actors that collaborate in publishing get an utility[5] of their common output. We consider the game as with transferable utility because each player benefits from the utility resulting from the action of coalition he is involved in.

As an illustration, let us consider the USA Triple Helix university-industry system for the year 2001 extracted from Leydesdorff (2003). The total number of papers considered is T =

[5] The utility is measured in terms of number of publications and not in terms of publications use nor the transformation of produced knowledge.

208,437. The repartition per Triple Helix spheres is as follows: university produced alone U = 190,283 papers, industry produces alone I = 8,288 papers, and jointly, university and industry produced UI = 9,866 papers. In fact, the total number of papers university produced is 190,283 + 8,288 = 198,571 and the total number of papers industry produced is 8,288 + 9,866 = 18,154. The number of papers the two actors produced jointly (e.g. 9,866) is added to the one each actor produced on its own to give the number of papers produced totally. The output of their cooperation goes entirely to each other, so the payoff is transferable.

In summary, the Triple Helix is a three-person cooperative game with transferable utility. The players are university, industry and government. They may form coalitions; their interest is the number of publications or the corresponding percentage shares.

4. Measuring synergy

"Synergy is the fusion between different aims and resources to create more between the interacting parties than they had prior to the interactions (…). An object shows synergy when, examining one of various of its parts (or even each or everyone of them) separately, it is impossible to explain or predict the whole's behaviour" (François, 2004). Etzkowitz and Leydesdorff (1995, 2000) considered the synergy in a Triple Helix system as the result of an overlay of exchange among perspectives on the bi and tri-lateral relations. For example, in the USA Triple Helix system for the year 2001 (Leydesdorff, 2003), university, industry and government produced on their own U = 152,449 papers, I = 6,506 papers and G = 24,134 papers respectively; but, the total number of papers within the system is T = 232,571, which is greater than U + I + G = 183,089 papers. The difference (49,482 papers) results from the synergy created between the three actors. Leydesdorff and Park (2014) estimated that synergy can be quantified. The existence of synergy within the Triple Helix innovation system supposes that conditions are fulfilled for actors to agree to work together to achieve the common goal of innovation. It also supposes that actors have the insurance that their interests are secured. In other words, the existence of synergy requires working together for both individual and collective interests, e.g. by the means of collaboration or cooperation to achieve a goal. As the above definition says, with synergy, different parties get more than they would get if they worked alone, justifiying the formation of coalitions. Game theorists developed a certain number of indicators to determine the conditions for individual and collective interests of actors are assured. For cooperative games with transferable payoff, the main indicators are the core, the Shapley value and the nucleolus.

4.1 Core

The core of a cooperative game is defined as the set of actions no individual player has an incentive to deviate from. It is so that it leaves “no coalition in a position to improve the payoffs of all its members” (Shapley & Shubik, 1973, p. 40). Therefore, it is the “state” of the game that ensures both individual and common interests and where “each player individually, and independently from each other maximizes his or her utility” (Stolwijk, 2010, p. 33). The core measures the stability in coalition forming (Gilles, 2010; Shapley & Shubik, 1973; Shapley, 1965, 1971). Outside the core, there may not be any interaction, therefore, no synergy is created, and consequently, innovation could not occur.

To determine the core of the Triple Helix game, one needs to determine the values x_u, x_i and x_g of the utility of players u, i and g respectively, so that they are higher than or equal to the payoff of each player on the one hand, and the sum of the utilities of members of any coalition, on the other hand, is higher than or equal to the value of the coalition, under the condition that the sum of the three values equals the total payoff. Hence, the core of the Triple Helix game is determined by the following system (Maschler, Peleg, & Shapley, 1967, p. 2; Shapley & Shubik, 1973, p. 41):

$$\begin{cases} \boldsymbol{x_u} \geq \boldsymbol{\upsilon}(\mathbf{u}) \\ \boldsymbol{x_i} \geq \boldsymbol{\upsilon}(\mathbf{i}) \\ \boldsymbol{x_g} \geq \boldsymbol{\upsilon}(\mathbf{g}) \\ \boldsymbol{x_u} + \boldsymbol{x_i} \geq \boldsymbol{\upsilon}(\mathbf{ui}) \\ \boldsymbol{x_u} + \boldsymbol{x_g} \geq \boldsymbol{\upsilon}(\mathbf{ug}) \\ \boldsymbol{x_i} + \boldsymbol{x_g} \geq \boldsymbol{\upsilon}(\mathbf{ig}) \\ \boldsymbol{x_u} + \boldsymbol{x_i} + \boldsymbol{x_g} = \boldsymbol{\upsilon}(\boldsymbol{uig}) \end{cases} \quad (2)$$

To solve System 2, one should transform each two-variable inequality into a one-variable inequality. For example, $x_u + x_i \geq \upsilon(\text{ui})$ becomes $x_g \leq \upsilon(\text{uig}) - \nu(\text{ui})$ (See Appendix 1). Therefore, the system becomes:

$$\begin{cases} \boldsymbol{x_u} \geq \boldsymbol{\upsilon}(\mathbf{u}) \\ \boldsymbol{x_i} \geq \boldsymbol{\upsilon}(\mathbf{i}) \\ \boldsymbol{x_g} \geq \boldsymbol{\upsilon}(\mathbf{g}) \\ \boldsymbol{x_g} \leq \boldsymbol{\upsilon}(\mathbf{uig}) - \boldsymbol{\upsilon}(\mathbf{ui}) \\ \boldsymbol{x_i} \leq \boldsymbol{\upsilon}(\boldsymbol{uig}) - \boldsymbol{\upsilon}(\mathbf{ug}) \\ \boldsymbol{x_u} \leq \boldsymbol{\upsilon}(\boldsymbol{uig}) - \boldsymbol{\upsilon}(\mathbf{ig}) \\ \boldsymbol{x_u} + \boldsymbol{x_i} + \boldsymbol{x_g} = \boldsymbol{\upsilon}(\boldsymbol{uig}) \end{cases} \quad (3)$$

which leads to the following analytic form of the core: [6]

$$\begin{cases} \boldsymbol{\upsilon}(\mathbf{u}) \leq \boldsymbol{x_u} \leq \boldsymbol{\upsilon}(\boldsymbol{uig}) - \boldsymbol{\upsilon}(\mathbf{ig}) \\ \boldsymbol{\upsilon}(\mathbf{i}) \leq \boldsymbol{x_i} \leq \boldsymbol{\upsilon}(\boldsymbol{uig}) - \boldsymbol{\upsilon}(\mathbf{ug}) \\ \boldsymbol{\upsilon}(\mathbf{g}) \leq \boldsymbol{x_g} \leq \boldsymbol{\upsilon}(\boldsymbol{uig}) - \boldsymbol{\upsilon}(\mathbf{ui}) \\ \boldsymbol{x_u} + \boldsymbol{x_i} + \boldsymbol{x_g} = \boldsymbol{\upsilon}(\boldsymbol{uig}) \end{cases} \quad (4)$$

[6] Equivalent forms of the core may be written with the notations introduced with Figure 1: i) by considering the following equalities: ν(u) = U, ν(i) = I, ν(g) = G, ν(uig) = T, ν(uig) –ν(ig) = U_0, ν(uig) –ν(ug) = I_0 and ν(uig) –ν(ui) = G_0 on the one hand, and ii) by dividing the bounds by T, the total output, and multiply the result by 100 to get percentages, on the other hand. They are: $\begin{cases} \text{U} \leq x_u \leq U_0 \\ \text{I} \leq x_i \leq I_0 \\ \text{G} \leq x_g \leq G_0 \\ x_u + x_i + x_g = \text{T} \end{cases}$ and $\begin{cases} \frac{\text{U}\times 100}{T} \leq x_u \leq \frac{U_0 \times 100}{T} \\ \frac{\text{I}\times 100}{T} \leq x_i \leq \frac{I_0 \times 100}{T} \\ \frac{\text{G}\times 100}{T} \leq x_g \leq \frac{G_0 \times 100}{T} \\ x_u + x_i + x_g = 100 \end{cases}$

Therefore, the core of the Triple Helix game with publication as unit of analysis is determined by the number of publications each actor produced on its own (the lower bound, U, I and G for university, industry and government respectively) and the total number of publications the actor produced, within the system, included in collaboration with other actors (the upper bound, U_0, I_0 and G_0 for university, industry and government respectively), under the condition that the three values should add up to the total number of publications in the considered set. The core of a game can be graphical too. Game theorists use ternary diagram to plot the core of cooperative games (See Appendix 2 for how to read a ternary diagram and plot the core). Along with the core, game theory specialists also use the Shapley value and the nucleolus.

4.2 Shapley value and nucleolus

The Shapley value is considered as a value attributed to players by a fair and impartial arbiter (Jackson et al., 2016). It measures the fairness while allocating the total payoff to players. The Shapley value takes into account the contribution of individual players. It is unique and always exists (Giraud, 2004, p. 67). Shapley (1952, 1953) provides a formula to compute the value, but we will use a simpler alternative (see e.g. Roth, 1988a, pp. 6–7). First, let us consider that the three players have to enter a room, the game area. The number of possible orders of entrance is 3! = 6, listed in column “Order of entrance” of Table 1. The first order is u followed by i and then g. When u enters first, it earns a payoff of υ(u); i on its turn as the second player earns a payoff that equals what it would earn in coalition with u minus the payoff u got as the first player that enters the room, so υ(i) = υ(ui) - υ(u); g the third player would then earn the total payoff minus the payoff coalition ui got, that is υ(uig) - υ(ui). The same logical reasoning permits to fill the cells in Table 1. The Shapley value is the average of the payoffs of each player following its six positions of entrance in the game room (the last row of Table 1). It is the triplet (S_u, S_i, S_g) so that:

$$\begin{cases} S_u = \frac{2v(uig)+2v(u)+v(ui)+v(ug)-2v(ig)-v(i)-v(g)}{6} \\ S_i = \frac{2v(uig)+2v(i)+v(ui)+v(ig)-2v(ug)-v(u)-v(g)}{6} \\ S_g = \frac{2v(uig)+2v(g)+v(ig)+v(ug)-2v(ui)-v(i)-v(u)}{6} \end{cases} \quad (5)$$

The nucleolus indicates the “more acceptable” distribution of the total payoff among players (Kohlberg, 1971; Schmeidler, 1969, p. 1163); it is a measure of the inequity of the total payoff sharing of the game; it is unique and exists always (Kohlberg, 1971; Schmeidler, 1969). The basic idea behind the nucleolus is to make the least happy coalition ”as happy as possible “ (Brackin, 2002, p. 24; Stolwijk, 2010, p. 62). To know the unhappiest coalition with regard to any particular distribution of the payoff, one should compute the differences between the value of each coalition and the utility it is given, called excesses (Schmeidler, 1969). The largest excess means that the associated coalition is the unhappiest towards the distribution. There is no analytic formula for computing the nucleolus of a game, but a step by step approach leads to finding this indicator. Sziklai (2015) stressed that the computation of the nucleolus is hard; he established several methods as well as the corresponding theory. Nowadays, there are many software applications that allow computing the nucleolus; however, even using the same data, they do not always yield the same results. Guajardo and Jorusten (2015) revealed common mistakes in computing the nucleolus; Cano-Berlanga et al. (2017) claim that the package ‘Game theory’ for the R statistical software (R Development Core Team, 2017) takes into account criticisms and produces robust results.

Table 1. Computing the Shapley value of a Triple Helix cooperative game

Order of entrance			Players: u	i	g	Total
u	i	g	υ(u)	υ(ui) – υ(u)	υ(uig) – υ(ui)	υ(uig)
u	g	i	υ(u)	υ(uig) – υ(ug)	υ(ug) – υ(u)	υ(uig)
i	u	g	υ(ui) – υ(i)	υ(i)	υ(uig) – υ(ui)	υ(uig)
i	g	u	υ(uig) – υ(ig)	υ(i)	υ(ig) – υ(i)	υ(uig)
g	u	i	υ(ug) – υ(g)	υ(uig) – υ(ug)	υ(g)	υ(uig)
g	i	u	υ(uig) – υ(ig)	υ(ig) – υ(g)	υ(g)	υ(uig)
Average			$\frac{2v(uig)+2v(u)+v(ui)+v(ug)-2v(ig)-v(i)-v(g)}{6}$	$\frac{2v(uig)+2v(i)+v(ui)+v(ig)-2v(ug)-v(u)-v(g)}{6}$	$\frac{2v(uig)+2v(g)+v(ig)+v(ug)-2v(ui)-v(i)-v(u)}{6}$	υ(uig)

5. Application

In this section, we consider the innovation systems of West Africa [7] and South Korea; then we determine the rules of the Triple Helix game of these systems and compute the core, the Shapley value and the nucleolus. Bibliographic data of the two areas over a decade (2001-2010) downloaded from Web of Science and treated by Mêgnigbêto **(2015, 2016b)** were used (Table 2). As a simplification we will write ui instead of {u,i} to indicate the coalition formed by players u and i, and similarly for the other cases

5.1 Publication data

Table 2. Scientific outputs of the Triple Helix spheres in West Africa and South Korea over the period 2001-2010.

		U	I	G	UI	UG	IG	UIG	Total
West Africa	Number of papers	17,062	54	3,922	123	8,129	34	112	29,436
	Percentage share	57.96	0.18	13.32	0.42	27.62	0.12	0.38	100
South Korea	Number of papers	228,643	3,504	42,215	7,522	68,703	1,293	2,463	354,343
	Percentage share	64.53	0.99	11.91	2.12	19.39	0.36	0.70	100

Source: Publication counts are extracted from Mêgnigbêto (2015, 2016a) and percentage shares are computed by ourselves.

[7] West Africa consists of the following countries, mentioned in alphabetical order: Benin, Burkina Faso, Cape Verde, Cote d'Ivoire, Gambia, Ghana, Guinea, Guinea-Bissau, Liberia, Mali, Niger, Nigeria, Senegal, Sierra Leone and Togo.

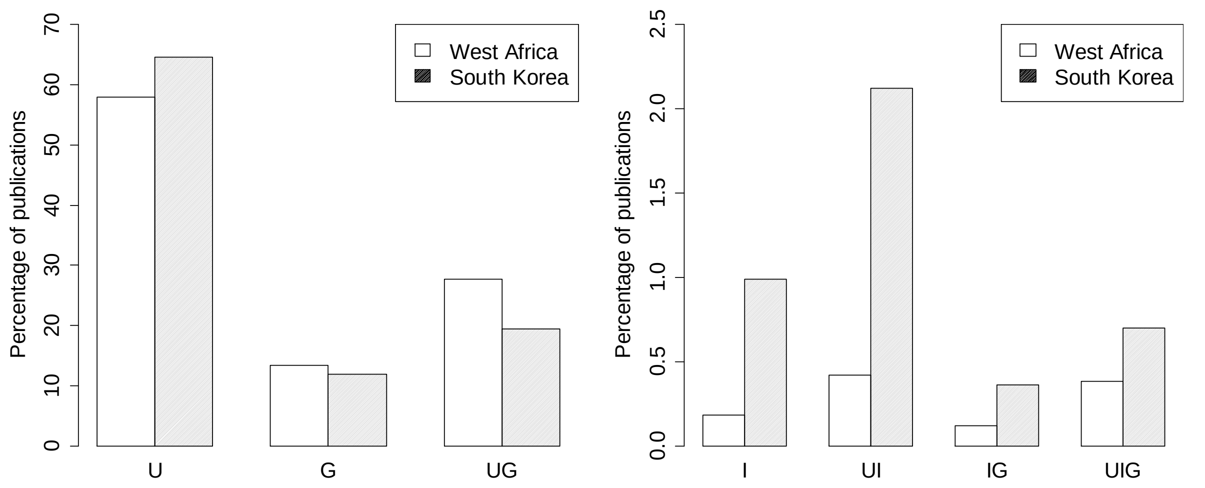


Figure 2. Outputs of Triple Helix spheres in West Africa and South Korea

Note: Industry's percentage shares and contributions are very limited compared with those of other players; therefore, we plotted them separately to allow relevant analyses.

The South Korean data are about twelvefold that of West Africa. University is the biggest science producers in both areas, followed by government and then by industry. As far as the bilateral collaborations are concerned, university-government comes first, followed – in this order - by university-industry and then by industry-government. The trilateral relations are registered within the two areas. The percentage shares of the Triple Helix spheres are higher in the case of South Korea than that of West Africa, except for government (G) on the one hand and university-government (UG) on the other hand (**Figure 2**).

5.2 Characteristic functions

For comparison purpose and (also) in order to avoid handling larger numbers characterizing publications data, we prefer using percentage shares for the computations below. In this we ignored the empty coalition utility $\upsilon(\emptyset) = 0$ in the following. The characteristic functions are derived from data in Table 2. They are presented in Table 3. They show that coalitions g, ug and ig have utilities greater in West Africa than in South Korea and that the three coalitions u, i and ui utilities are lower in West Africa compared with those of South Korea.

Table 3. Characteristic functions of West African and South Korean Triple Helix game

Area	West Africa	South Korea
Characteristic function	$\begin{cases} \upsilon(u) = 57.96 \\ \upsilon(i) = 0.18 \\ \upsilon(g) = 13.32 \\ \upsilon(ui) = 58.56 \\ \upsilon(ug) = 98.90 \\ \upsilon(ig) = 13.62 \\ \upsilon(uig) = 100 \end{cases}$	$\begin{cases} \upsilon(u) = 64.53 \\ \upsilon(i) = 0.99 \\ \upsilon(g) = 11.91 \\ \upsilon(ui) = 67.64 \\ \upsilon(ug) = 95.83 \\ \upsilon(ig) = 13.27 \\ \upsilon(uig) = 100 \end{cases}$

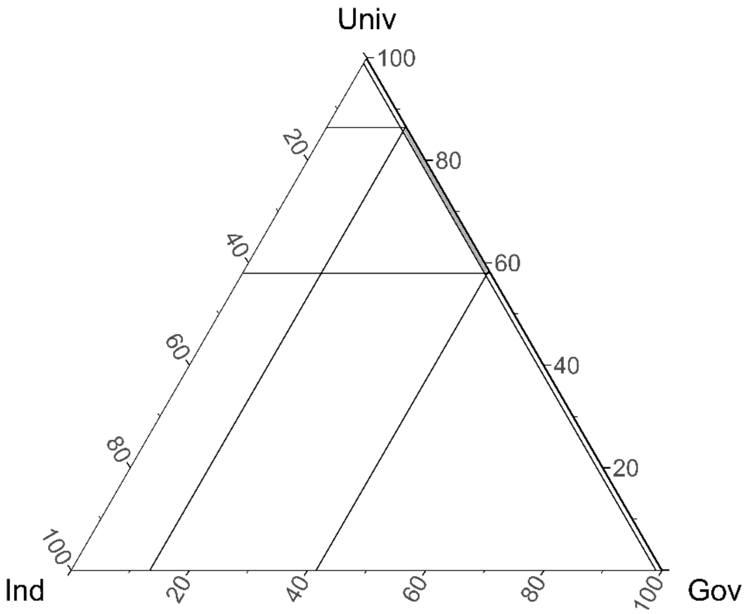
5.3 Cores

The analytic form of the core of the West African and South Korean Triple Helix games is given in Table 4. We used the 'ggtern' package **(Hamilton, 2016)** for the R statistical software **(R Development Core Team, 2017)** to produce the graphical form (Figure 3). The cores are located at the upper side of the diagram, close to the apex labelled University and bordering the side representing the scale 0 of Industry. This position is an illustration of the share of players to the total payoff or the level of production of players. In both areas, university has the largest share (50-90%), government 10-40% and industry less than 5%.

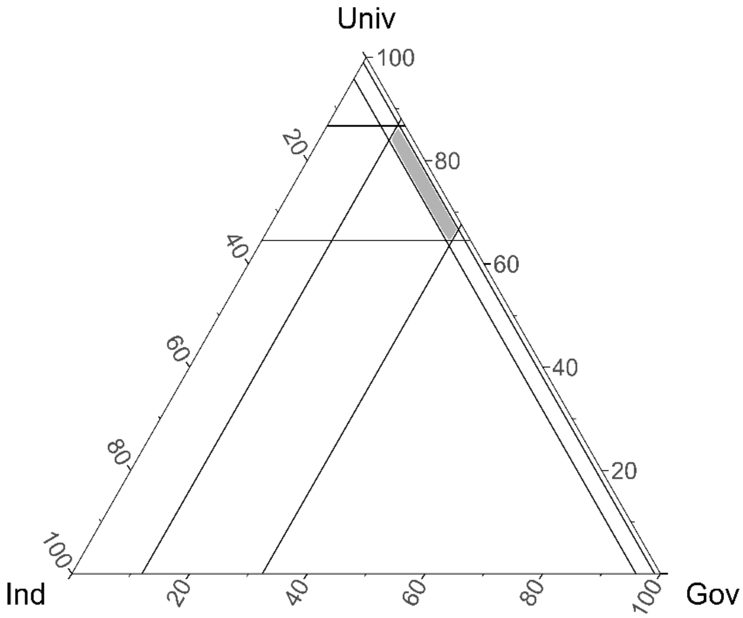
Table 4. Analytic form of the core of West African and South Korean Triple Helix game

	West Africa	South Korea

Core (analytic form)	$\begin{cases} 57.96 \le x_u \le 86.37 \\ 0.18 \le x_i \le 1.1 \\ 13.32 \le x_g \le 41.44 \\ x_u + x_i + x_g = 100 \end{cases}$	$\begin{cases} 64.53 \le x_u \le 86.73 \\ 0.99 \le x_i \le 4.17 \\ 11.91 \le x_g \le 32.36 \\ x_u + x_i + x_g = 100 \end{cases}$



a) West Africa



b) South Korea

Figure 3. Graphical form of the cores of the West African and the South Korean game. Note: The core is the grey-coloured part of the triangle.

5.4 Shapley values and nucleoli

Applying formula in Equation (5) gives the triplets (72.11, 0.58, 27.32) and (75.52, 2.47, 22.02) as the Shapley values for West Africa and South Korea respectively. We used, however, the package "GameTheory" (Cano-Berlanga et al., 2017) for the R statistical software (R Development Core Team, 2017) to compute the Shapley values and the nucleoli (**Table 5**). In both areas, the Shapley value and the nucleolus rank players the same as their total output. However, the university or industry Shapley value in West Africa is lower than that of university or industry in South Korea; the governement Shapley value is larger in West Africa than in South Korea. As far as the nucleolus is concerned, university and government values in West Africa are higher than those of the same players in South Korea; the industry nucleolus is lower in West Africa than in South Korea.

Table 5. Shapley value and nucleolus of the West Africa and South Korean innovation systems.

Player	West Africa		South Korea	
	Shapley value	Nucleolus	Shapley value	Nucleolus
University	72.107	85.58	75.515	83.92
Industry	0.576	0.64	2.465	2.58
Government	27.316	13.78	22.020	13.50

6. Discussion

6.1 Core expresses existence and extent of synergy

In both West Africa and South Korea, university is the biggest science producer, followed by government and industry; the industrial output is very limited compared with that of university or government. Consequently, the cores are close to the apex University – representing scale 100 for University – and border the side of the triangle opposite to the Industry apex – representing scale 0 for Industry axis.

The formation of the core (cf. its analytic form) reveals constraints on players' interest by giving their lower and upper bounds. The lower bound is the production of a player on its own; the upper bound – which is the marginal contribution – includes outcomes of collaborations. The marginal contribution of a player is the amount by which the total payoff will shrink if that player withdraws or the value the great coalition loses if player is not part of it (Stolwijk, 2010, p. 10). It reflects the "power" of that player in the game. It appears like the threat a player exerts on its partners while negotiating coalitions, or the power of negotiation of a player (Stolwijk, 2010). In both areas, university has more power than government to form coalition, in turn, government has more power than industry. The difference between the bounds of a player's interest represents the contribution of that player to the formation of the core. University and government have larger contributions in West Africa as compared to South Korea; the reverse is, however, true in the case of industry (cf. **Figure 4**). The explanation of such a result may be found in publications data (cf. **Figure 2**): industry published less in West Africa (see e.g. Mêgnigbêto, 2013, 2014c, 2016b) and therefore, has less opportunity to collaborate. As an illustration, industrial publication share is 0.18 and rises to 1.1 with collaboration. In the case of South Korea, industry has a percentage share of 0.99 (about 6 times the one of West Africa), but it rises to 4.17 when the collaborations shares are included. In summary, university and government has more facilities to collaborate and to form coalitions in West Africa when compared to South Korea; however, West African industry does not have enough power to form coalitions as compared to the situation in South Korea.

"The core of a game may be interpreted as the set of sociologically stable outcomes, in that no coalition can upset any one of them." (Shapley, 1965, p. 15, 1971). In other words, outside the core, at least one coalition "must fail to realize its full potential" (Shapley, 1965, p. 15, 1971), e.g. there is no way that all players get more than they will in the core; that is, no agreement may be found on the sharing of the total payoff. Such a situation would lead to the lack of interaction between innovation actors, and as a result, to the lack of synergy within a Triple Helix innovation system. Therefore, the core may be interpreted as the range of all possible compromises players could reach based on their interests and the constraints on these interests, with the target of creating synergy. The contributions of players to the formation of the core give the extent of the core, which is the margin players have to share the total payoff; these margins may be measured by the surface area of the core as fraction of the surface area of the triangle supporting the ternary diagram.[8] The surface area of the core of South Korea (1.3%) is larger than that of the core of West Africa (0.5%)[9] meaning that South Korean innovation actors have more margin in allocating outcomes of collaboration than West African ones; they have more margin to form coalition and lead to and create synergy than West African ones. We consider the core as the indicator of synergy and its surface area as the extent or the level of synergy.

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[8] The core of a n-person game, if it exists, is a polyhedron with at most n –1 dimensions (Lloyd S Shapley, 1965, p. 6). Therefore, the core of a 3-person game is a polygon, or a segment or a point.
[9] We used the TU_game software application (Caplan & Sasaki, 2006).

6.2 Shapley values represent the strength of player to lead to synergy

The analysis of the Shapley values leads to the conclusion that university has the largest value, followed by government and industry. Mathematically, the Shapley value is the expected marginal contribution of a player (Roth, 1988a, p. 6); it can be interpreted as the "expected utility of playing a game" (Roth, 1988b) ; therefore, it is the expected interest that incites a player to form coalitions. The image of the Shapley value that arises from the applications is that it is an index of strength of a player (Aumann, 1985), the strength of the coalitions he belongs to and the ones he does not (Stolwijk, 2010). We interpret the Shapley value as the strength of a Triple Helix actor to build and drive coalitions with the final goal of creating synergy. That explains the ranking of coalitions according to their payoff in this order: ug, ui, u, ig, g, i, the empty and grand coalitions excluded: university has the highest Shapley value so that the coalitions it is involved in have the highest payoffs, followed by coalitions involving government and finally coalitions industry is member of. The Shapley value is higher for university and industry in South Korea than in West Africa; but, the reverse is true for government. The larger contribution of government in West Africa may explain the result; for example, the share of government is 13.32 in West Africa and 11.91 in South Korea (Cf. Table 3), but with collaboration, it rises to 41.44 in West Africa and 32.36 in South Korea (Cf. Table 4). In summary, university has more power in leading to and creating synergy than government, which in turn has more power than industry.

6.3 Nucleolus indicates solidarity for maintaining synergy

Although the nucleolus ranks players the same as the Shapley value, it is however generous towards university and industry to the detriment of government. Indeed, instead of attributing 22 to government in South Korea and 27 in West Africa, the nucleolus attributes it around 14 in the two areas. The losses of utility government undergoes regarding the nucleolus go entirely to university. The nucleolus may be interpreted as a fair allocation based on the coalitions players are involved in (Stolwijk, 2010, p. 68). “It is more a way the total payoff can be distributed in a fair way over all the players based on all the coalitions of which he is a member” (Stolwijk, 2010, p. 78). In other words, the nucleolus takes into account the payoffs of coalitions instead and makes them fairer as the Shapley value does for players’ payoffs. Clearly, with the nucleolus, coalition members agree to make supplementary concessions, a kind of solidarity, to share the total payoff among coalitions so that the ones that are disadvantaged could get more, in order to accept or continue playing the game. Thus, the nucleolus is an indicator of efforts coalitions make to maintain the synergy players lead to and create. In West Africa and South Korea, the coalitions government is involved in accept the reduction of their payoffs to the benefit of those government is not involved in; as a result, the nucleolus attributes government less than it expects, e.g. its Shapley value.

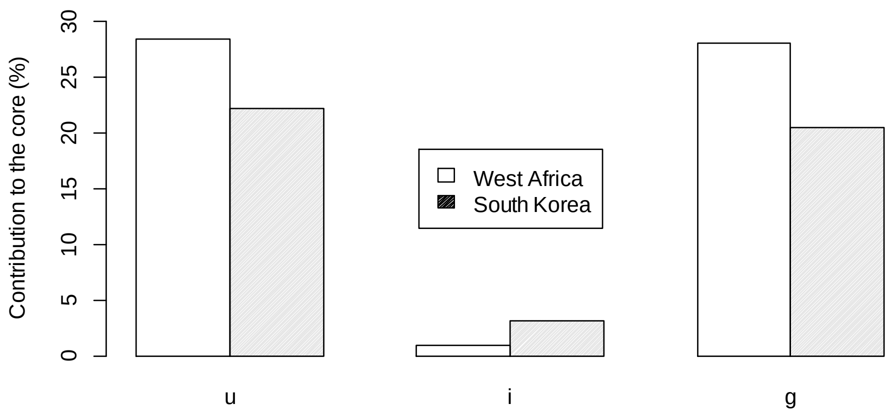

Figure 4. Contribution of Triple Helix players to the formation of West African and South Korea core (in percentage)

7. Conclusion

The Triple Helix of university-industry-government relations with number of publication as unit of analysis is a three-person cooperative game with transferable utility. The three players (university, industry and government) can bind coalitions to maximize their utilities. The payoff may be either publication count or corresponding percentage share. Hence, the synergy within a Triple Helix innovation system can be measured with game theory indicators like the core, the Shapley value or the nucleolus. The core expresses both individual and collective interests and the constraints exerted on them; it also indicates the extent of the synergy within the Triple Helix game. We used the Shapley value as the strength of players to lead to and create synergy and the nucleolus as the strength of coalitions to maintain that synergy.

We computed these indicators for the innovation systems of two geographical areas: the West African region and South Korea. The largest contribution to the extent of the core comes from university followed by government and then by industry. As a result, on a ternary diagram, the core is located close to the apex University and borders the Industry axis. The core of South Korea is wider than the one of West Africa because collaborations between the three actors occur largely in the former compared to the latter. Both the Shapley values and the nucleoli allocate a larger part of interests to university due to its high publication share in both areas. However, the nucleoli are too severe toward government and; conversely, more generous toward university and industry.

This paper has two limits, the one related to the techniques (game theory) and the other to the unit of analysis. Firstly, the indicators used do not take into account how the payoffs of coalitions should be divided among members, so our study does not deal with it. Secondly, we used number of publications as unit of analysis; however, research output is not limited to publication only and research collaboration does not result in publication always. The reflection and the proposed indicators may apply to any other research output like patent or any field of interaction between university, industry and government, for example, funding, grants, etc.

Our main finding is related to the core as the expression of interests of players and constraints on these interests on the one hand, and on the other hand, the surface area of the core as the margin players have to negotiate payoffs sharing. Industry's contribution to the formation of the core is the thinnest, which reduces the extent of the synergy within the Triple Helix. Industry should interact more with university and government for knowledge producing and sharing in order to increase its margin while negotiating coalitions, and as a result, extend the core and increase the level of synergy within the system. We got this result perhaps because publications are the primary research output of university. Further studies may use as unit of analysis, for example, patents which are the primary research output of industry; findings could then be compared.

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Appendix 1. Turning a two-variable inequality into a one-variable inequality

A two-variable inequality of the analytic form of the core can be turned into a one-variable inequality; in the latter, the variable is the one not present in the former. For example, let us consider the following system representing the core of a Triple Helix game.

$$\begin{cases} x_u \geq \upsilon(\mathrm{u}) & (a) \\ x_i \geq \upsilon(\mathrm{i}) & (b) \\ x_g \geq \upsilon(\mathrm{g}) & (c) \\ x_u + x_i \geq \upsilon(\mathrm{ui}) & (d) \\ x_u + x_g \geq \upsilon(\mathrm{ug}) & (e) \\ x_i + x_g \geq \upsilon(\mathrm{ig}) & (f) \\ x_u + x_i + x_g = \upsilon(\mathrm{uig}) & (g) \end{cases} \qquad \textbf{(6)}$$

The equality (6g) $x_u + x_i + x_g = \upsilon(\mathrm{uig})$ leads to

$$(x_u + x_i) + x_g = \upsilon(\mathrm{uig}) \qquad \textbf{(7)}$$

and

$$(x_u + x_i) = \upsilon(uig) - x_g \qquad \textbf{(8)}$$

According to (6d), $x_u + x_i \geq \upsilon(\mathrm{ui})$. Replacing $x_u + x_i$ by $\upsilon(\mathrm{uig}) - x_g$ in (8) gives:

$$\upsilon(\mathrm{uig}) - x_g \geq \upsilon(\mathrm{ui}) \qquad \textbf{(9)}$$

which means that

$$-x_g \geq \upsilon(\mathrm{ui}) - \upsilon(uig) \qquad \textbf{(10)}$$

and

$$x_g \leq \upsilon(\mathrm{uig}) - \upsilon(ui) \qquad \textbf{(11)}$$

The same logical reasoning with inequalities (6e) and (6f) leads to the equivalences:

$$x_u + x_i \geq \upsilon(\mathrm{ui}) \iff x_g \leq \upsilon(\mathrm{uig}) - \upsilon(\mathrm{ui}) \qquad \textbf{(12)}$$

$$x_u + x_g \geq \upsilon(\mathrm{ug}) \iff x_i \leq \upsilon(\mathrm{uig}) - \upsilon(\mathrm{ug}) \qquad \textbf{(13)}$$

$$x_i + x_g \geq \upsilon(\mathrm{ig}) \iff x_u \leq \upsilon(\mathrm{uig}) - \upsilon(\mathrm{ig}) \qquad \textbf{(14)}$$

Appendix 2. Reading a ternary diagram and plotting the core of a Triple Helix game

Let us consider the ternary diagram in Figure 6. The top apex is labelled University, the left one Industry and the right one Government. The side of the triangle opposite to each apex constitutes the level 0 for its scaling; the one to its left is its axis. Any line parallel to a side and passing through the triangle intercepts the relevant axis at a point indicating the value of the variable at the apex. For example, the horizontal line that intercepts University axis at n has equation u = n. In order to read the coordinates of any point in such a system, one should draw three lines, each parallel to each side of the triangle and passing through this point, then read the scale where it intercepts the corresponding side.

It is very easy to plot the core of a three-player cooperative game on a ternary diagram once one knows how to read this kind of diagram. The tasks are restricted to i) plot six pairwise parallel lines that determine the lower and the [2] upper values of players interests, and ii) determine the surface of the triangle common to the three areas delimited by the pairwise parallel lines. For example, let us plot the core of which analytic form follows:

$$\begin{cases} \mathbf{43 \leq x_u \leq 75} \\ \mathbf{16 \leq x_i \leq 22} \\ \mathbf{15 \leq x_g \leq 47} \\ \mathbf{x_u + x_i + x_g = 100} \end{cases} \qquad (15)$$

i) Firstly, we should plot the lines corresponding to $x_u = 43$ and $x_u = 75$, e.g. two horizontal lines, the one intercepting the University axis at n = 43 and the other at n = 75; the surface of the triangle delimited by these two lines is the solution to the inequality $43 \leq x_u \leq 75$;

ii) Secondly, we should plot the lines corresponding to $x_i = 16$ and $x_i = 22$, e.g. two lines parallel to the side of the triangle opposite to the Industry apex, the one intercepting the Industry axis at n = 16, and the other at n = 22; the surface of the triangle delimited by these two lines is the solution to the inequality $16 \leq x_i \leq 22$;

iii) thirdly, we should plot the lines corresponding to $x_g = 15$ and $x_g = 47$, e.g. two lines parallel to the side of the triangle opposite to the Government apex, the one intercepting the Government axis at n = 15 and the other at n = 47; the surface of the triangle delimited by these two lines is the solution to the inequality $15 \leq x_g \leq 47$.

The whole triangle (surface and boundary included) is the solution to the equation $\boldsymbol{x_u + x_i + x_g = 100}$. The core of the game is the surface of the triangle common to the three surfaces obtained above, e.g. the coloured part of the surface of the triangle (Figure 6).

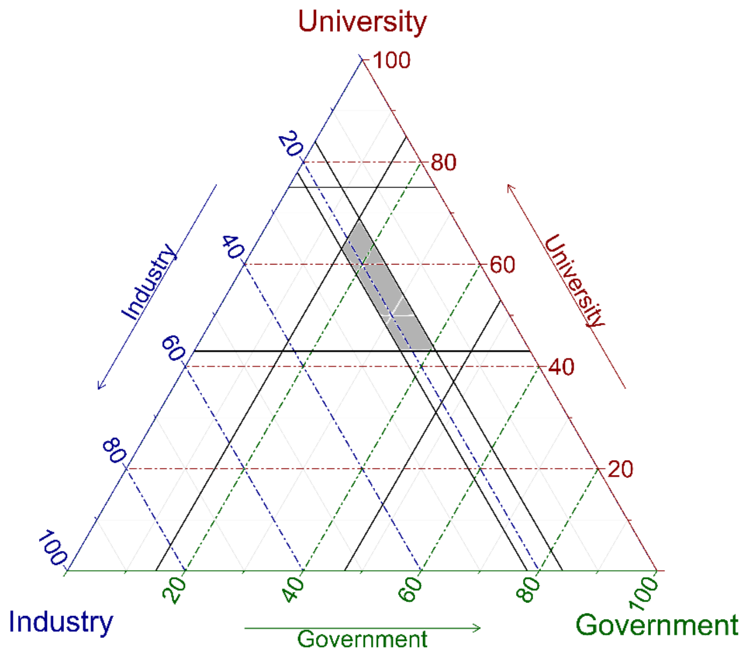

Figure 6. Reading a ternary diagram and plotting the core of a Triple Helix game

Note: The dashed lines represent the grid of the diagram and the solid ones delimit contributions of players to the formation of the core.