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An integrated approach to evaluating sustainability in supply chains using evolutionary game theory

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ABSTRACT

Sustainability in supply chains is typically studied across one or more dimensions such as environmental, social, economic, culture and governance. Traditionally sustainability in supply chains has focused on environmental dimensions, while a few have attempted to focus on social and economic dimensions without really integrating them. There has been only a small effort to define sustainability by integrating all relevant dimensions (a holistic approach). This paper proposes to fill this gap. We identify sustainability of a supply chain with the equilibrium of the system over a long (but finite) period of time after integrating the various dimensions. Thus it necessitates looking at factors that can cause a shift in the equilibrium. Towards this, we propose to build a strong theoretical framework to integrate, explain, and predict sustainability for supply chains using cross-disciplinary effort. In our theoretical framework, evolutionary game theory serves as the pure conceptual theory-building tool, the metrics are qualitative in nature and the indicators are quantitative statistical measures. The use of evolutionary game theory concepts allows us to understand how sometimes trivial actions by members of the supply chain can trigger cascading effects that can move the system away from equilibrium. One of the salient aspects of our model is its complete scalability in terms of changes to the dimensions and metrics. As an example, we explain and predict social and economic sustainability (in tandem) for a public health insurance supply chain using evolutionary game theory.

1. Introduction

Operations research is applied in many areas of supply chain management including designing supply chains, coordinating decisions across members of the supply chain, optimization, logistics and sustainability. The focus of this paper is sustainability of supply chains. By its very definition, sustainability looks at the long-term effectiveness and continuation of the supply chain given the history of the supply chain and its future growth path. This allows the members of the supply chain to look beyond the present while making policy decisions. In this section, we highlight some of the literature on sustainability of supply chains to identify the gap that we hope to address through our model.

Brandenburg et al. [8] depict an aggregated research model to understand the notion of sustainable supply chain management solutions. As a part of this model, they define the various sustainability dimensions to include one or more of environment, social, and economic dimensions (often referred to as the triple bottom line approach). Some supply chains such as ecotourism may include an additional dimension referred to as either culture and society or governance, thus leading to the quadruple bottom line approach. The nature of the industry under study defines the actors, levels and process, and the dimensions to be considered. These serve towards modelling integrated sustainability to provide a sustainable supply chain management solution. Also in their literature surveys, Carter and Rogers [12], Seuring [30], and Brandenburg et al. [8] amongst others indicate that sustainability in supply chains has been usually defined along environmental dimensions in terms of "green" concepts. According to the breakup provided in their reviews, very meagre literature looks at integrated sustainability in service supply chains. While there exists some literature that looks at sustainability in terms of either economic or social dimensions, their analysis shows a lack of integration across the dimensions (social, economic, and environmental) when studying sustainability of supply chains. According to them, most of the small number of literature on holistic sustainable supply chain models are more focused on industrial sectors and rarely focus on the microscopic analysis. Gunasekaran and Spalanzani [19] review sustainable business development for manufacturing and services sector

Abbreviations: OOP, Out-of-pocket; PbHI, Public Health Insurance.

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and provide a framework based on seven building blocks. Further, in their work with Ageron et al. [1], they develop a conceptual model that looks at the factors influencing sustainable sourcing in a supply chain. They then study the impact of these factors on sustainability. In particular, they look at sustainable supply chain from a supplier selection perspective along with an empirical example. In both these papers, the need to develop a framework for performance measures and metrics for sustainable supply chains is identified as one of the future research directions. Carter and Rogers [12] provide a visual representation of the three dimensions (also called the triple bottom line developed by Elkington [16,17]) and indicate sustainability to lie in the intersection of the performance across all three dimensions. They further propose that firms that aim at integrated sustainability achieve the highest level of economic performance than firms that aim at only one or two of the dimensions.

Some other relevant literature includes Tang and Zhou [31] who review the operational research methodologies available to study the performance of supply chains along profit, planet, and people dimensions. However their review is aimed at identifying the metrics and gaps that are present in operational research and the arena of management decision-making, rather than an integrated look. De Brucker et al. [10] use multi-criteria analysis to arrive at sustainable project evaluation across multiple stakeholders. They look at the endogenous creation of an institutional equilibria that in turn results in collective benefit. However their work imposes boundary conditions that may restrict the equilibrium choices available. Devika et al. [15] look at designing a closed-loop supply chain network based on all three dimensions. However they aim at a Pareto-optimal solution rather than an equilibrium solution. Govindan et al. [18] explore which of the lean, resilient, and green supply chain practices impact the sustainability of the supply chain. Varsei et al. [34] develop a multidimensional assessment framework to study sustainability across the three dimensions. Kannegiesser and Günther [22] look at global supply chains with optimisation as the goal.

As a continuation to the survey findings and to fill the research gap identified in the surveys by Seuring [30], Brandenburg et al. [8], Gunasekaran and Spalanzani [19], Ageron et al. [1] and others, we propose to define sustainability differently by posing the following questions while evaluating a supply chain. (1) What are the dimensions and metrics that concern and impact each stakeholder in the supply chain? (2) How does one study the effect of all these metrics as a cognizable whole on the entire supply chain at any point of time, instead of just looking at optimality? (3) If new factors come into play with the progress of time, are the objectives of the dimensions synthetically met across the supply chain? For this we turn towards a cross-disciplinary effort and look at a specific area of game theory [28]. In fact, Brandenburg et al. [8] specify game theory as an analytical modelling approach in sustainable supply chain management research.

The study of game theory looks at strategic interaction between one or more players, played in a cooperative or non-cooperative environment, as a single shot or repeated over finite or infinite time horizon, with pre-defined rewards for each player. Each player tries to select an action to play so as to maximise or minimise his or her payoff. Nash equilibrium is one of the most well-known solution concepts in game theory. General game theory solution concepts, by themselves, are insufficient to answer our questions completely on the holistic sustainability of supply chains. We turn towards evolutionary game theory [21] for the same. It had its beginnings in the seminal paper by two theoretical biologists, Maynard Smith and Price [23] who introduced a new solution concept, evolutionarily stable strategy, to define stability and equilibrium in a population over a period of time when the population is invaded by a small number of mutants. Later Taylor and Jonker [32] gave a dynamic approach (known as replicator dynamics) to the static evolutionary stability concept of Maynard Smith et al. Hence it is meaningful to view the long-term sustainability of supply chains from an evolutionary game theory perspective. It is important to look at the dynamic characterisation and detection of all evolutionarily stable strategies [5,6]. It is interesting to note that the concept of replicator dynamics has been used in some economic application studies such as portfolio selection [7]. There is very scarce literature on this inter-disciplinary topic. For example, in the insurance sector, Brown [9] looks at the co-evolution of the public/private insurance in the public and private hospital market in Australia. Further, Zhou and Dou [36] and Barari et al. [3] study greening supply chains by modelling as an evolutionary two-person game between the government and enterprise. Though Naini et al. [25] use evolutionary game theory to design a mixed performance management system, they focus only on the environmental dimension. Mota et al. [24] use generic multi-objective mathematical programming for economic, environmental and social design and planning of supply chains. However they do not focus on the actual evaluation of the supply chain for sustainability. The above papers restrict themselves in one or more of the following aspects: (1) They restrict themselves to two player games while there can be any number of players in reality; (2) They only address matrix games restricted to a simple payoff based on cost and reward, as opposed to payoff functions that consider various metrics; (3) They do not study the effects of mutations and learning; (4) They do not study dynamics that can exist within a population. To the best of our knowledge, there is no known literature that addresses the question of supply chain sustainability in a holistic manner using evolutionary game theory.

We propose to build a strong theoretical framework to explain and predict environmental, social, economic and cultural/governance (quadruple bottom line) sustainability in tandem for supply chains. In our theoretical framework, evolutionary games serves as the pure conceptual theory-building tool, the dimensions are qualitative in nature, and the metrics/indicators are quantitative statistical measures. We propose to go beyond the standard “green” definition of sustainability by looking at the equilibrium of the evolutionary game to be the sustainable point for the supply chain. Our theoretical framework provides a way to identify sustainability by depicting how the supply chains move into equilibrium over a long (but finite) period of time, as opposed to the traditional optimality conditions. Our model also reflects the fact that sometimes trivial choices by members of the supply chain can trigger cascading effects that can move the system away from equilibrium. We show that our model in no way restricts the dimensions or the metrics to be defined for each player or the methodology used to arrive at the measure. This theoretical framework offers the flexibility of expanding the model and makes it completely scalable. The scalability of our theoretical framework and its adaptation to any supply chain where we need to look at sustainability across multiple integrated metrics is a critical success factor for our model.

Towards this, we identify the members of the supply chain, the strategic stakeholders, the actions available to the members, the states that the supply chain can be in, the metrics for each member population, the nature of interactions, the payoff functions and equilibrium concepts. We also touch on various revision protocols that may come into play such as learning and invasion.

In Section 2, we detail how to model a supply chain using evolutionary game theory concepts to study sustainability by identifying its components. We then build an evolutionary game model for a generic supply chain. We also briefly touch upon revision policies and possible invaders. In Section 3, we provide a detailed example of building an evolutionary game model to evaluate the sustainability of a public health insurance (PbHI) supply chain. In