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Supply Chain Interoperability Measurement

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DISSERTATION

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SUPPLY CHAIN INTEROPERABILITY MEASUREMENT

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Abstract

Academia recognizes that although supply chains have an inherent need to be validated for their performance, supply chain performance measurement systems are still inadequate and one of the major barriers to successful supply chain collaboration.

In this research, theory of Systems Architecture is used to make the first step towards an innovative supply chain performance measure defined as supply chain interoperability. Interoperability is considered a similarity metric with regard to a set of deterministic and stochastic characters (criteria) describing supply chain participants, a methodology that adapts and expands an interoperability measurement tool initially developed in and for a military context. A process that could be used to develop a set of initial supply chain interoperability characters to be included in the interoperability measurement is demonstrated based on interviews from managers of various functional roles at a single defense company in Greece.

The presented measurement methodology can assist in efficiently directing resources to best improve interoperability between and among the various elements of a supply chain.

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Table of Contents

List of Figures

List of Tables

SUPPLY CHAIN INTEROPERABILITY MEASUREMENT

I. Introduction

1.1 General discussion

Supply Chain Management literature identified the need for new measures for supply chain assessment (Gunasekaran et al., 2004) and inadequate supply chain performance measurement systems are recognized as a major barrier to successful supply chain collaboration (Fawcett, Magnan and McCarter, 2008). Yet, it has proved difficult to adopt a holistic measure to assess the collaborative concepts of Supply Chain Management and even more difficult to then improve supply chain performance based on such an assessment (Neely et al., 1997; Lambert and Pohlen, 2001; Hofman, 2004; Banomyong and Supatn, 2011). Lambert and Pohlen (2001) attributed the causes of this to managerial (absence of supply chain orientation and unwillingness to share information) or practical (complexity) factors. Burgess et al. (2006) found that process conceptual framing generally prevails in Supply Chain Management literature and believed that understanding the conceptual framing can assist *"in explaining the lack of consensus in definitions… in the expectations that organizations have of Supply Chain Management and… in revealing the constructs that sit behind Supply Chain Management."*

Towards this direction, the current research uses the theory of System of Systems (SoS) as a bridge between the Supply Chain Management process and system perspectives. SoS theory has not yet been adequately applied, despite its demonstrated power, to describe a supply chain's components (the firms). Here it is argued that a new lens is needed to change what Ackere (1993) recognized as the mentality of supply chain managers being *"regrettably ignorant of the fact that supply chains are designable."* Planning or building successful supply chains is the equivalent to architecting the interfaces between systems. Systems architecture and the use of architectural frameworks provide a variety of insightful views into any complex system. Such views can include organizational, behavioral/process, information/data, physical/interface, and technological/standards factors. However, Maier and Rechtin (2000) state that *"the greatest leverage in system architecting is at the interfaces… the greatest dangers are also at the interfaces."* A supply chain manager should act as a supply chain architect and be able to influence interfaces between the independent firms.

A measure focused on these interfaces would be valuable. This dissertation introduces interoperability as a candidate supply chain performance measure and provides insights on the selection of the appropriate characters (criteria) that should be included in the interoperability measurement. Considering interoperability as a supply chain property, an operation, called interoperability measurement, can be defined which objectively and empirically assigns a number to supply chain interoperability (Ford et al., 2010). This research analyses a method of quantitatively measuring supply chain interoperability through the adaptation and expansion of a method that was originally developed in and for a military context (Ford et al., 2009). The proposed method improves upon extant interoperability assessment techniques by refining current quantification methodologies to include both deterministic and stochastic characters, and by aggregating overall interoperability across the entire supply chain. Also, a semi-structured interview tool on the supply chain interoperability definitions and measurement is used to obtain perspectives of the practitioners.

1.2 Originality - Research contributions

This research makes the following contributions to the Supply Chain Management body of knowledge:

- Supply Chain Interoperability is defined as a novel supply chain measure.

- System of Systems theory and System Engineering heuristics are applied on Supply Chain Management.
- The feasibility of supply chain interoperability measurement (Chalyvidis, Ogden and Johnson, 2013) is studied to discover the complex set of supply chain interoperability constructs and the managers' perspective on interoperability measurement.
- Supply chain's participants are described through a series of mixed characters to facilitate supply chain interoperability measurement. While real valued discrete leveling methods have been reported, a mixed-characterization of participants is introduced that extends deterministic valued character states (either discrete or continuous) to include stochastic relationships.
- A cross functional methodology is presented on supply chain interoperability characters identification within an organization and along a supply chain. Feedback is collected from a specific company on the selection of such characters to be included in the interoperability measurement.

1.3 Organization of the dissertation

The remainder of this dissertation compasses six chapters. Chapter 2.0 addresses the overarching methodology applied throughout the course of the research. Chapter 3.0 is the academic paper titled, *"Using supply chain interoperability as a measure of supply chain performance"*. This paper was published in the 2013 Volume 14(3) of the *"Supply Chain Forum An International Journal''* and a similar paper was presented in the 22nd Annual North American Research Symposium in Phoenix, Arizona on March 2012 under the title *"Supply Chain Interoperability: A Framework and Measurement"*. Chapter 4.0 is the academic paper currently under review (submitted on October 2014) at the Journal of Business Logistics titled, *“A Method for Measuring Supply Chain Interoperability”*. Chapter 5.0 presents a draft manuscript titled *“Supply Chain Interoperability Characters Identification”*. Chapter 6.0 provides a summary of the research, including managerial implications as well as implications for the armed forces and ties together the major findings from Chapter 3.0 through Chapter 5.0. The bibliography and curriculum vita are included at the end of this dissertation.

II. Research Methodology

Here an overview of the research methodology applied throughout the research process is presented. The conducted research on supply chain interoperability measurement has been taken in three steps, resulting in a series of three academic papers. Each academic paper uses and modifies the research methodology as necessary to achieve its particular objective(s). More detail about the specific methodologies used for each of these articles is provided in each of the chapters 3.0 to 5.0.

This research takes the first step to fill the academic gap of inadequate supply chain performance measurement, performing a philosophical conceptualization on supply chain management and System of Systems Engineering (SoSE) in order to define a new measure. According to Meredith (1993) philosophical conceptualization, as a type of theory building, integrates a number of different works on the same topic, summarizes the common elements, contrasts the differences, and extends the work in some fashion. Following his expression, the research *"thoroughly immerses in the topic … in order to pull the commonalties and patterns into a unique, insightful perspective."* Initially a multi-discipline literature review is conducted on interoperability, supply chain and its performance measurement and system of systems theory. The research recognizes the parallels between Supply Chain Management and System of Systems Engineering (SoSE). These parallels are combined with systems heuristics to reveal the limitations of the existing supply chain measures. A system of systems perspective of supply chain is introduced and supply chain interoperability is defined and proposed as a performance measurement for the assessment of the efficiency and effectiveness of supply chains.

The second step considers supply chain interoperability a similarity metric with regard to a set of characteristics. A mathematical approach is used to adapt and expand an extant interoperability measurement to include firms' description using deterministic and stochastic types of characters.

In the third step, a semi-structured interview tool concerning the definition and measurement of supply chain interoperability is applied to obtain perspectives of the practitioners. Managers from various functional roles at a defense company in Greece were interviewed and a set of supply chain interoperability characters are identified. The characters are analyzed in terms of potential measurement methods and the literature is used to validate their potential importance in terms of supply chain performance. Semi-structured interviews were selected as the means of data collection because they are well suited for the exploration of the perceptions and opinions of respondents regarding complex issues (Barriball, 1994) and enable probing for more information and clarification of answers. This type of interviewing encourages the interviewee to share rich descriptions of phenomena while leaving the interpretation or analysis to the investigators (DiCicco-Bloom and Crabtree, 2006). Also the different professional experience and roles of the sample group precluded the use of a standardized interview. The same words/questions used in a structured interview, may have different meanings for each interviewee according his or her background. A semi-structured interview offers to the interviewer the flexibility to change wording in order to keep the understanding and meaning. Barribal (1994) and Turner (2010) noticed about the latter that, in the selected type of interview, validity and reliability depends not upon the repeated use of the same questions, but upon the equivalence of meaning. The research also follows Starkey and Madan (2001) for the need of academic management knowledge to be relevant to practitioners and for that purpose an assessment of supply chain interoperability, based on the identified characters, is demonstrated with an illustrative example.

III. Using Supply Chain Interoperability as a Measure of Supply Chain Performance

3.1 Introduction

The concepts of the supply chain and Supply Chain Management, first analyzed in the 80's (Oliver, 1982), are still considered a new and emerging scientific discipline. Being new, they come under Stock's (1997) writing, which argued that a young discipline can benefit from adopting and employing existing theories from other disciplines. The benefits of this practice include an avoidance of "wheel reinvention" and an acceleration of knowledge and understanding through the diffusion of innovation (Stock, 1997). This practice can also generate interesting and influential research (Fawcett and Waller, 2011). Furthermore, supply chains have an inherent need to be validated for their performance, but academia recognizes that supply chain performance measurement systems are still inadequate and one of the major barriers to successful supply chain collaboration. Here, theory of Systems Architecture is used to take the first step towards an innovative supply chain performance measure.

First Supply Chain Management and supply chain performance measurement are examined from the System of Systems (SoS) theory perspective. In order to demonstrate applicability, the parallels between Supply Chain Management and SoS theory are recognized. Systems heuristics combined with a multi-discipline literature review on interoperability and performance measurement reveal that the main limitation of the existing measures is their focus on measuring outputs of processes or interfaces rather than measuring the supply chain interfaces themselves. For example, the measurement of "on-time deliveries" reveals a supplier's performance, but contributes little on our understanding of the factors or characteristics owned by both suppliers and the buyer's organization, which lead to that performance.

Next, SoS theory concepts are applied to introduce supply chain interoperability as a candidate supply chain performance measure. Supply chain interoperability is proposed as a performance measurement for the assessment of the efficiency and effectiveness of supply chains. Our definition of supply chain interoperability contains at its core the notion of collaboration, which plays a vital role in improving performance as well as in protecting against unintended behaviors in supply chains. The last part of the paper suggests a method of supply chain interoperability measurement and provides a brief example of how this method can be used.

3.2 Literature Review

3.2.1 System of Systems and Supply Chain Management

The relationship between Supply Chain Management and other disciplines is broadly manifested. Nevertheless, to the best of our knowledge, SoS theory has not yet been adequately applied, despite its demonstrated power, to describe a supply chain's components (the firms) and to facilitate the definition of a supply chain performance measure, here called "supply chain interoperability."

Envisioning Supply Chain Management as a management philosophy characterized by strategic orientation (Mentzer et al., 2001) fits well in a Resource-Based framework (Mahoney and Pandian, 1992). Angerhofer and Angelides (2000) reviewed research and the development of Systems Dynamics Modeling in Supply Chain Management. Burgess, Singh and Koroglou (2006) and Sanders and Wagner (2011) classified Supply Chain Management articles into discipline categories including, among others, Strategy, Psychology/Sociology, Information/Communication and Operations management. Frankel et al. (2008) analyzed the contributions of the foundational Supply Chain Management disciplines of Purchasing, Operations Management, Logistics and Marketing. Williamson (2008) identified the common ground between Supply Chain Management and Transaction Cost Economics.

System thinking frequently appears in the Supply Chain Management literature. Defee et al. (2010) found that systems theory is used in over ten percent of Supply Chain Management related articles and in over twelve percent of logistics related research (see Table 3.1).

Table 3.1: Frequency of theoretical incidents in a sample of 294 Supply Chain Management and 389 Logistics articles from 2004 to 2009 (Defee et al., 2010).

Theory	**Logistics (%)**	**Supply Chain Management (%)**
Competitive	21.0	23.5
Microeconomic	11.9	21.9
Systems	12.5	10.7
Marketing	11.4	8.7
Theories of organizations	8.0	7.1
Other social psychological/sociological	2.8	6.1
Social exchange	2.3	5.6
Inventory	10.8	1.5
Institutional	6.3	1.5
Decision	4.5	3.1
Innovation	2.8	1.8
Psychological theories for individuals	1.1	1.8
Other	4.5	6.6

A supply chain is generally studied either as a system of coordinated firms, under the name “network of organizations” (Lambert and Cooper, 2000; Frankel et al., 2008), that strive to integrate supply and demand via coordination, or as a Complex Adaptive System (Choi, Dooley and Rungtusanatham, 2001; Pathak et al., 2007; Wycisk, 2008) emerging from the autonomous actions of the participating firms. Holmberg (2000) used system thinking on supply chain measurements. Mentzer et al. (2001) and Cooper, Lambert and Pagh (1997) argued that Supply Chain Management is a management philosophy primarily characterized by a systems approach of the whole supply chain. Burgess et al. (2006) found that process conceptual framing generally prevails in Supply Chain Management literature and believe that understanding the conceptual framing can assist *"in explaining the lack of consensus in definitions the expectations that organizations have of Supply Chain Management and… in revealing the constructs that sit behind Supply Chain Management."* Towards this direction of understanding Supply Chain Management, here it is argued that the theory of System of Systems (SoS) can provide a bridge between the Supply Chain Management process and system perspectives by introducing the notion of interoperability to supply chain performance management and by providing insights on the selection of the appropriate characters (criteria) that should be included in the interoperability measurement.

For the purposes of supply chain interoperability and its measurement the focus is on a higher level system, the System of Systems (SoS) or collaborative system (Maier, 1998) and its unique characteristics that clearly differentiate it from other systems. The characterization of SoS is not constrained by the size or complexity of the system being characterized. It refers to an interconnection of systems that are free to leave or stay connected and offer their services. Boardman and Saucer (2006) identified five differentiating characteristics that define and distinguish a SoS from a "simple" system, based on the nature of a systems' composition. Being a form of a SoS, supply chains have these characteristics, namely: Autonomy, Belonging, Connectivity, Diversity and Emergence. Each of these characteristics and their applicability to Supply Chain Management are discussed in greater detail in the following sections.

<u>Autonomy</u>

In a SoS, each component, or for our purpose organization, is an autonomous system, not simply a part of the whole network. These component systems exist autonomously to serve specific requirements. On the other hand, individual parts or subsystems exist only to perform a specific purpose in the greater system they belong to and have no autonomy. Boardman and Saucer (2006) used the example of an automobile brake. The brake does not serve a purpose of its own and cannot operate successfully if it is not connected to the vehicle, and thus lacks operational and managerial independence. In the case of a SoS, the component systems are separately acquired and integrated, but they maintain a continuing operational existence independent of the SoS. Similarly the components of a supply chain network are organizations and each of them was created and performs autonomously, under physical, economic and regulatory constraints, with the main objective to produce stakeholder value.

Belonging

When a firm decides to participate in a network under the integrative philosophy of supply chain management, it needs to collaborate, to make changes in the way it makes decisions and take actions, at times even operating its internal processes in what in isolation could be viewed as a suboptimal way, yet leading to overall benefits for the greater network. The firm is willing, on a cost/benefit basis, to pay these costs in order to achieve the “supra” purpose of optimality in the whole supply chain. Mentzer et al. (2001) discussed this phenomenon defining that firms possess a Supply Chain Orientation when they recognize the systemic and strategic results of managing the upstream and downstream flows in the supply chain across their suppliers and customers. By belonging to the supply chain with this orientation, the firms make likely this “supra” purpose that encompasses the separate purposes of the firms and improves the overall results.

Connectivity

When a system engineer is designing a system, he thinks of the constituent parts along with the interconnections between them. For an immense number of interconnections, system engineering golden rules dictate hiding connections and encapsulating them by using interfaces between the components to create a “black box” that facilitates interconnectivity management (Boardman and Saucer, 2006). Similarly leaders of organizations manage relationships and connections encapsulated within the firm’s functional departments in order to achieve the firm’s objectives. In SoS, connectivity refers to the legacy systems and also future new systems possibly added to the SoS. For the SoS’s connectivity two problems arise. First, similar to the autonomy and belonging characteristics previously discussed, the component systems determine the connectivity they wish to form between them. Secondly, in order to achieve connectivity between the systems components of the SoS, the encapsulated systems should be unraveled to give access to the hidden inner connectivity. Boardman and Saucer (2006) argued that *“this calls for a dynamic determination of connectivity, with interfaces and links forming and vanishing as the need arises. The ability of constituent systems to remain autonomous proves essential, for only then can they hope to make real time connections on behalf of the SoS to enable it achieve and sustain its capabilities.”* A parallel, referring to the supply chain, its connectivity characteristics and the necessary interfaces and links, can be recognized in the words of Williamson (2008) *“It is the black box of the firm and the black box of the market… with a vast buzzing, blooming profusion of transaction cost possibilities … prioritization, conceptualization and operationalization are needed.”* When focusing on a supply chain as a SoS, connectivity should be accomplished between the component firms and the possible, per supply chain dynamics, future members. Supply chain managers should establish connections using the integration of key business processes that run the length of the supply chain and cut across firms and functional departments within each firm (Croxton et al., 2001). These supply chain connections are often hindered by inconsistent vocabularies, terms, ontologies, and semantics utilized by various supply chain members (Ye et al., 2008).

Diversity

A supply chain is not typically built from scratch. Its components--firms--already exist. They have been operating alone or as components of other chains. They have international origins and incorporate many cultures, policies and routines. As such, they have certain differences and possess visible heterogeneity. In that context, diversity of capabilities and structure is an *a priori* characteristic of supply chains. What differentiates a SoS supply chain approach, is that diversity is diagnosed as a positive feature rather than an obstacle. This is considered, first of all, by introducing the law of requisite variety (Ashby, 1957). This law states that it is the variety of functions, which supply chains can demonstrate on an as needed basis, which guarantees that the supply chain has enough number of degrees of freedom to respond to the uncertainty of the environment. The reverse interpretation is also valid for the firms comprising the supply chain. The variety of behavior of a given controller, which can be measured by interoperability, limits what kind of system it can dominate (Nechanski, 2009). Secondly, diversity is considered positive because it subscribes Supply Chain Management to Williamson's (2008) pragmatic methodology of keeping it simple, with the introduction of interoperability between the firms as the means of achieving the synergistic effects demonstrated by successful supply chains and as a new Supply Chain Management paradigm.

Emergence

Holland (1998) discussed emergence and its hallmark, the sense of much coming from little. The study of emergence is “*closely tied to [the] ability to specify a large, complicated domain via a small set of 'laws'.*” Emergence is evident in both systems and SoS. The former possess deliberately designed-in emergence, while the latter exhibits unrestricted, unforeseen and emergent behaviors (Gorod, Sauser and Boardman, 2008). Unplanned emergent characteristics of systems are addressed by applying system engineering, while SoS architects seek to *“create a climate… and an agility to quickly detect and destroy unintended behaviors”* (Boardman and Saucer, 2006). The fact that the majority of Supply Chain Management literature emphasizes negative feedback for purposes of control is recognized by Choi et al. (2001), who discuss the importance of balancing control vs. emergence in the supply chains. There are plenty of instances of “much coming from little” in the supply chain domain. The “Bullwhip effect” (Lee, Padmanabhan and Whang, 1997) in traditional supply chains and the emergence of Vendor Managed Inventory control as a countermeasure (Disney and Towill, 2003) is one example. Emergence can be also recognized in the supply chain complexity triangle (Wilding, 1998) resulting from the interaction of deterministic chaos, parallel interactions and demand amplification, as the source of uncertainty in the supply chain causing, among other things, late deliveries, order cancellations and buffer inventories.

The five characteristics can be positively related (see Table 3.2) with the three theoretical perspectives of Supply Chain Management identified by Skjoett-Larsen (1999), namely Transaction Cost approach, Resource Based View and a Network perspective, representing *“an economic, a strategic and a sociological approach to the analysis”*. Transaction Cost Economics acknowledges bounded rationality and opportunism of individuals as the main behaviors governing firms. The inevitability of total knowledge and foresight combined with the normality of the mental capacity owned by the whole of the system players, plus the possibility of opportunistic behaviors, explain actions of firms and why they exist (Williamson, 2008). These assume autonomy and diversity of actors while opportunism acts as an emerging factor. The diversity of firms and their distinctive competencies are also fundamental components of Resource Based View theory, with heterogeneity to be considered a source of competitive advantage and Mahoney and Pandian (1992) reviewed the literature for connections between diversification, performance, motivation and direction of growth and firms' resources. Connectivity is present in Transaction Cost Economics in the discussion of the interactions between the environment, the individuals and the institutions. Interfaces can be detected in the transaction characteristics and asset specificity, uncertainty and frequency. The ultimate interface recognized by Transaction Cost Economics is the contract, acting as safeguard against opportunism and being required by specific transactions driven by the *"Mutuality of advantage from voluntary exchange"* (Buchanan, 2001). For example a transaction that requires specific investment, thus should be kept active for a minimum amount of time to be profitable and should be guaranteed under a contract or otherwise should be performed internally in the firm. Therefore in a way it possibly cannot be considered as supply chain oriented. Belonging and connectivity are also recognized in the analysis of contracts as frameworks ensuring the continuum of cooperation vs. contracts as legal rules (Williamson, 2008).

The five SoS characteristics of supply chains are best fitted in a Network Theory perspective and according to Skjoett-Larsen (1999) firms belong to the network because they depend on the other firms that control certain resources. Firms are characterized by autonomy of building or terminating relations. Their connectivity to the other firms depends not only on the exchange of goods but also on trust and the bilateral interoperability of administrative systems, processes and products. Finally emergence is evident in the network strategy that *"is able to influence its suppliers and customers but also its suppliers' suppliers and its customers' customer"* (Skjoett-Larsen, 1999).

Table 3.2: Relation between SoS and Transaction Cost Economics (TCE), Resource based View (RBV) and Network Theory (NT) approaches of Supply Chain Management.

	Autonomy	Belonging	Connectivity	Diversity	Emergence
TCE behavioral assumptions: "bounded rationality and opportunism"	**x**			**x**	**x**
TCE safeguards: "contract or other commitments"			**x**		
TCE "transaction cost"			**x**		
TCE asset characteristics: "specificity, uncertainty, frequency"			**x**	**x**	
TCE purpose of the firm: "Adaptation"		**x**			
RBV (heterogeneity of firms)	**x**			**x**	**x**
NT (Exchange processes)		**x**	**x**	**x**	**x**
NT (adaptation processes)		**x**	**x**	**x**	**x**
NT (power structure)	**x**				
NT (trust)		**x**	**x**		

3.2.2 Heuristics

Heuristics or design principles are *"soft rules correlated with success that can be inducted from observing system development"* (Maier, 1998) and some are examined here through the lens of a SoS supply chain perspective. The first heuristic originates from civil construction where buildings should be self-supporting and states (Maier, 1998) that: *"Systems will develop and evolve within an overall architecture much more rapidly if there are stable intermediate forms than if there are not."* A supply chain is a collaborative SoS. Supply chains are in constant evolution caused by the participating firms continuously appraising and modifying their objectives for collaboration or by sudden "reconfigurations" of the market, for example due to the introduction of a new product. Stability of the supply chain can be interpreted as participating firms and supply chains being technically, economically and politically self-supporting. Under technical stability the supply chain operates to fulfill customer demand. Economic stability assures that the SC generates revenues for its members. Political stability can be recognized as the willingness of the members to participate in the supply chain.

The second heuristic recognizes that a SoS development team does not fully control the development and the modes of operation of the system and provides guidance on what they should to try to control. This design principle, named "the policy triage" by Maier (1998), submits that: *"Let the dying die. Ignore those who will recover on their own. And treat only those who would die without help".* The above can be identified in the firm's efforts to manage a supply chain that led managers to struggle with the complex nature of the supply chain and the unavoidable lack of control and predictability. It is the same complexity that supports the proposed study and management of supply chains as Complex Adaptive Systems. Direct control of the entire supply chain seems impractical. If the supply chain managers believe that they can control the evolution of the supply chain, they will probably fail to incorporate management mechanisms for the robust collaboration of the participating firms.

The complexity and independence of the components of SoS also emphasize interface design. A design principle discussing the importance of the interfaces between the component systems is expressed by Maier (1998) as *"The greatest leverage and danger in system architecting is the interfaces."* A supply chain, even in its simplest form, includes firms characterized by operational and managerial independence. Since each firm is developed independently, the supply chain is an aggregate of the firms that emerge as a whole through the interaction between the component firms. Supply chain managers, considered here as the architects of supply chain, have to focus on the multi-level "interface" standards that ensure communication and exchange between the participating firms.

SoS thinking also dictates (Maier, 1998) that *"if a system requires voluntary collaboration, the mechanism and incentives for that collaboration must be designed-in."* At least two of these incentives can be recognized from an economic and a social perspective. The first has to do with the equilibrium between the cost and benefits of collaboration and the cost and benefits of independent function. The other is dictated by the joint utility of the collaboration when the well-being of each participating part depends on the eudaimonia (Greek word for well-being and happiness from ευ=good and δαίμον=demon) of the other participant components of the SoS. These incentives are clear in the Supply Chain Management literature. Cooper, Lambert and Pagh (1997) argued that the*"… driving force behind Supply Chain Management is the recognition that sub optimization occurs if each organization in the supply chain attempts to optimize its own results rather than integrate its goals and activities with other organizations to optimize the results of the chain."* Mentzer et al. (2001) defined Supply Chain Orientation as *"the recognition by an organization of the systemic, strategic implications of the tactical activities involved in managing the various flows in a supply chain.* Larson, Poist and Halldósson

(2007) found that the lack of a common Supply Chain Management perspective is a major barrier, among others, for Supply Chain Management implementation.

3.2.3 Performance Measurement and Interoperability

Business performance measurement has been defined in diverse areas of academic research but academia has yet to reach a consensus of the features, the roles and the processes of Business Performance Measurement Systems (Dumond 1994, Franco-Santos et al. 2007). Generally, performance measurement includes a set of processes and metrics that quantify how effective and how efficient the actions of an organization are and provides criteria for assessing future success and performance (Neely et al., 1997). The quantification of a firm's efficiency and effectiveness was historically based only on financial measures but the more recent academic research, following Eccles (1991) and Kaplan and Norton (1992), propose measurements with a multi-dimensional, balanced character. Modern performance measurement systems studied by De Toni and Tonchia (2001), who identified their conceptual dimensions and variables, concluded that the majority of performance models are of the "frustum" type that focus on low-level organization performance metrics. Also Tangen (2004) argued that although modern measurement frameworks are academically sound, they haven't facilitated the realization of the proposed measures at the operational level. Folan and Browne (2005a) proposed a performance management approach that would positively change organizational culture, systems and processes which is based on two frameworks; one devoted to the structure of the supply chain and a procedural framework for the selection of measures and logistical aspects. Griffis et al. (2004) reviewed the literature on the recommended qualities and frameworks of logistics and supply chain performance measures and identify that these, being broad and general, are applicable to all measurement systems and cannot guide firms to choose according their mission, their goals and their environment. Eccles (1991) called for business practitioners to design performance measurement systems starting from scratch by asking the question: *"Given our strategy, what are the most important measures of performance?"*, while he conceded the absence of both a valid answer and a predetermined process for changing measurement systems.

The question is still valid today and relates to the performance of the supply chain. Supply Chain Management has various strategic implications for companies. It dictates the level of collaboration between supply chain participants, the formulation of partnerships, the sharing of information and integrated logistics management and planning. The combination of the important amount of resources and the managerial effort that firms need to allocate to Supply Chain Management, with the firm's expectations of improved customer service and reduced cost from supply chain management, and also with the positive effects of performance measurement on actual performance (Pavlov and Bourne, 2011), all converge to the need to validate the performance of the supply chain. Supply chain performance measurement is a system that integrates the supply chain to maximize effectiveness and efficiency and includes a supply chain performance model with measures, procedures and also responsibilities, accountability and regulation of the system by the participating firms (Holmberg, 2000; Gunasekaran, Patel and McGaughey, 2004). The inherent complexity of supply chains adds further difficulties towards performance measurement. Beamon (1999) referred to the large number of performance measures that need to be maintained to characterize the system and Hofman (2004) developed a hierarchy of supply chain metrics to help managers *"cut through this maze of metrics"*. Existing supply chain performance measurement tools are admittedly complicated and difficult to use in real business settings (Banomyong and Supatn, 2011) and require the development of complex information systems (Papakiriakopoulos and Pramatari, 2010). Lambert and Pohlen (2001) argued that no meaningful performance measures exist that span the entire supply chain and attributed the causes of this as either managerial (absence of supply chain orientation and unwillingness to share information) or practical (due to complexity) factors.

Many researchers have studied the problem of supply chain performance measurement and have proposed various systems and frameworks to assess the performance of the supply chain both as a whole and as individual member firms to maximize the effects of their participation. Brewer and Speh (2000) proposed a balanced scorecard framework to assess supply chain performance. Also using a balanced scorecard approach, Bryceson and Slaughter (2010) developed a hybrid metrics system that facilitates internal supply chain coordination and cohesion. Bhagwat and Sharma (2007, 2009) used the Analytic Hierarchy Process to develop a model for supply chain performance evaluation and Bullinger, Kuhner and Van Hoof (2002) proposed a balanced measurement approach using Supply Chain Operations Reference Model (SCOR) metrics and network scorecards developed by the Supply Chain Council. Lockamy and McCormack (2004) used SCOR 4.0 to study the influence of supply chain practices on supply chain performance. Gunasekaran, Patel and Tirtiroglou (2001) and Gunasekaran et al. (2004) offered a framework for supply chain measurement and Charan, Shankar and Baisya (2008) offered a taxonomy of supply chain enabler variables that can be used to measure supply chain performance from a strategic perspective. Banomyong and Supatn (2011) developed the supply chain performance assessment tool and tested it in small and medium enterprises in Thailand. The tool assesses the cost, time and reliability performance for each of the supply chain processes proposed by Lambert, Cooper and Pagh (1998). Simatupang and Sridharan (2005) offered a means to identify the gaps in collaboration in the supply chain in three dimensions of information sharing, decision synchronization and incentive alignment and also studied the effects of collaboration practices on operational performance. The performance measurement of special types of enterprises is also addressed in the literature, like the extended enterprises (Bititci et al., 2005; Saiz, Rodriguez and Bas, 2005; Folan and Browne, 2005b) and virtual enterprises (Gunasekaran, Williams and McGaughey, 2005). Other methods are also proposed like Data Envelopment Analysis (Wong and Wong, 2007) and fuzzy set theory approach (Chan et al., 2003; Chan and Qi, 2003; Chan, 2003). The evolution of supply chain performance measurement is depicted in figure 3.1.

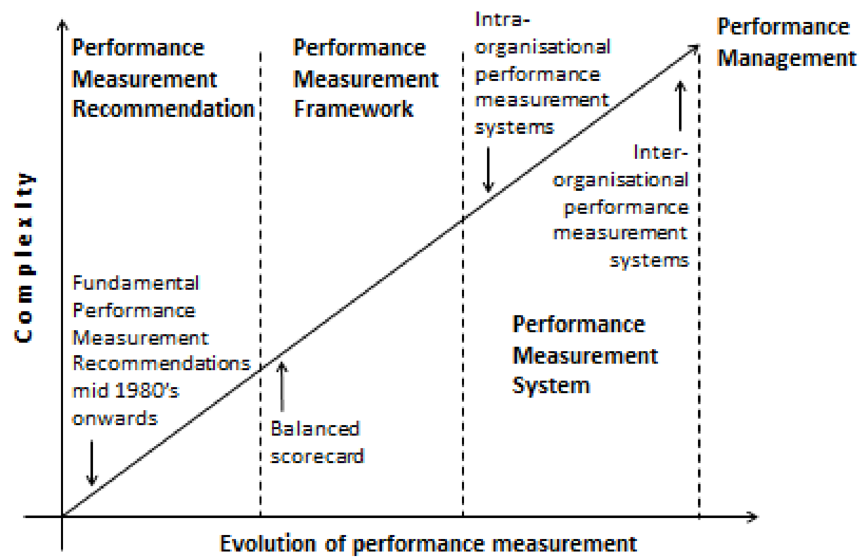


Figure 3.1: The evolutionary process of performance measurement (adopted from Folan and Browne, 2005a).

A common characteristic of the majority of the thus far reviewed papers proposing supply chain measurement methodologies, is that they build on previous research by addressing common weaknesses or by identifying new limitations. Holmberg (2000) used a systemic perspective to evaluate the connection between strategy and measurement, the biased focus on financial metrics and the incompatibility of measures. Lambert and Pohlen (2001) identified that many supply chain metrics are actually logistics metrics and Gunasekaran et al. (2001)

mentioned the lack of a balanced approach and the lack of distinction of metrics in different levels. Also Kennerly and Neely (2003) analyzed the need for evolution of measurement systems and the actions that firms should take to ensure change. Nevertheless, it is evident from Table 3.3, which presents the limitations of supply chain performance measurement systems that, despite the great number of extant frameworks and tools for supply chain performance measurement, so far none address all of the typical problems of supply chain performance assessment identified by previous research. Notwithstanding these prior research efforts in measuring supply chain performance, inadequate supply chain performance measurement systems are still recognized to be one of the major barriers to successful supply chain collaboration (Fawcett, Magnan and McCarter, 2008).

The purpose is not to propose a new framework to entirely fill this gap. A framework demonstrating this feature may not exist as claimed by Eccles (1991). Moreover, a candidate framework may be too complex to be considered an effective measure (Neely et al., 1997). On the contrary it is proposed a SoS perspective of the supply chain and interoperability as a measure of supply chain performance. Following the discussion on SoS characteristics, it is conjectured that supply chain interoperability captures the notion of collaboration that plays a vital role in emergence (i.e., it creates the climate to destroy unintended behaviors in the supply chain).

Table 3.3: Literature addressing typical problems of supply chain Performance Measurement Systems (PMS).

PMS problems addressed	Eccles (1991)	Kaplan, Norton (1992)	Beamon (1999)	Holmberg (2000)	Brewer and Speh 2000	Suwignjo et al (2000)	Norreklit 2000	Lambert, Pohlen (2001)	Gunasekaran et al(2001)	Stephens (2001)	Hudson et al 2001	De Toni, Tonchia (2001)	Zhao (2002)	Kennerley, Neely 2002	Bullinger et al (2002)	Ittner et al (2003)	Chan and Qi (2003)	Chan (2003)	Tian et al (2003)	Kennerley, Neely 2003	Chan et al (2003)	Stefan Tangen (2003)	Ren et al (2004)	Gunasekaran et al(2004)	Lockamy, McCormack 2004	Hofman (2004)	Gunasekaran et al(2005)	LI et al (2005)	Najmi et al (2005)	Folan, Browne (2005)	Folan, B rowne (2005b)	Saiz et al (2005)	Bititci et al (2005)	Simatupang and Sridharan (2005)	Busi and Bititci (2006)	Wong et al (2007)	Griffis et al (2007)	Gunasekaran and Kobu (2007)	Bbhagwat and Sharma (2007)	Charan et al (2008)	Martin and Patterson (2009)	Bbhagwat and Sharma (2009)	Papakiriakopoulos and Pramatari	Bryceson and Slaughter (2010)	Pavlov and Bourne (2011)	Banomyong and Supatn (2011)
Lack of connection between strategy and measurement	X		X	X	X	X	X	X	X	X	X	X	X	X		X	X		X		X	X		X	X			X	X	X		X	X		X		X		X		X	X	x		X	
Focus only on financial metrics	X	X	X	X	X		X	X	X	X	X	X	X	X	X	X	X	X	X		X	X		X	X					X	X	X	X		X	X			X		X	X	X		X	X
Too many isolated and incompatible measures				X		X			X	X			X	X			X					X		X	X	X				X					X	X		X	X	X		X				
Lack of System thinking and SC complexity-unholistic measurements			X	X	X			X		X					X		X	X			X		X		X		X			X	X	X	X	X	X								x			X
Historic nature of measures-Report past activity- don't forecast success					X						X			X	X	X						X										X														
Disconnection between measurement needs and measure choice																										X				X							X					X				
Meaures based on cause and effect relationships(eg. COOPERATION BENEFITS) vs logical relationships (eg.COOPERATION PROCESS)-Don't address synergies between SC	X			X		X	X									X							X										X												X	
Don't track effectiveness over time-lack of learning by experience																																														
Loss of SC context-Local optimization				X	X			X						X			X	X	X		X	X					X	X			X		X	X	X								X	X		
Lack of balanced approach (fail to address different types of performances, perspectives and organisational levels)	X		X	X	X			X	X	X					X		X		X		X	X	X										X		X				X							X
Low accessibility (information to the right person- time)																	X					X																								
Lack of adaptation of measurement system to the future needs-EVOLUTION			X			X					X									X									X	X		X					X									
No distinction between strategic, tactical and operational metrics									X															X						X			X				X		X							X
Lack of a PM development process	X										X												X						X	X	X				X								X			
Lack of qualitative (RELATIONSHIP) measurement																		X			X			X				X			X				X											
Lack of common definition-theoritical foundation												X																		X					X						x	X				X
Low quality of shared information	X														X													X															X			
Lack of alignment with organizational objectives		X														X																														

Min et al. (2005) offered a discussion of collaboration as an ultimate core capability of the firms that provides benefits like revenue enhancements, cost reduction and operational flexibility. Empirical data shows that collaboration has not been achieved as desired (Holmberg, 2000; Fawcett and Magnan, 2002; Wognum and Faber, 2002). Other authors (Barrat, 2001; Mentzer, Min and Zacharia, 2000) call for a means of assigning values to the various levels of collaboration among participating firms. Collaboration has been studied in the measurement literature, but current frameworks either discuss what to measure without any guidance of how actually to achieve the desired quantification (Tangen, 2005) or embed collaboration in other measures that partially cover all of its dimensions. Lockamy and McCormack (2004), in their exploratory study among nine supply chain practices that are more influential to supply chain performance, found collaboration to be the most important in three (namely in the Plan, Source and Make) of the SCOR decision areas (see Table 3.4).

Table 3.4: The nine most influential practices to supply chain performance measurement, ranked by relative SCOR significance (Lockamy and McCormak, 2004).

PRACTICE	PLAN	SOURCE	MAKE	DELIVER
Planning processes	Significant	Significant	Significant	Significant
Collaboration	Significant	Significant	Significant	Moderate
Teaming	Significant	Significant	None	None
Process measures	Moderate	Moderate	Moderate	Significant
Process credibility	None	None	None	Significant
Process integration	None	None	None	Significant
IT support	None	None	None	Significant
Process documentation	Moderate	Moderate	Moderate	Moderate
Process ownership	Moderate	Moderate	Moderate	Moderate

Busi and Bititci (2006) identified the lack of understanding of collaboration as the cause for its absence and proposed three types of measures to measure the performance of collaborative enterprises: the Extended process measures to quantify the performance of processes, the Collaborating measures to assess the degree that the enterprises are able to work as a single unit and the Collaboration Management measures to assess if the environment allows collaboration to flourish. Simatupang and Sridharan (2004) proposed the Collaboration Index (Figure 3.2) as a collaboration measurement tool that includes information sharing, decision synchronization and incentive alignment and empirically demonstrated that collaboration affects operational performance.

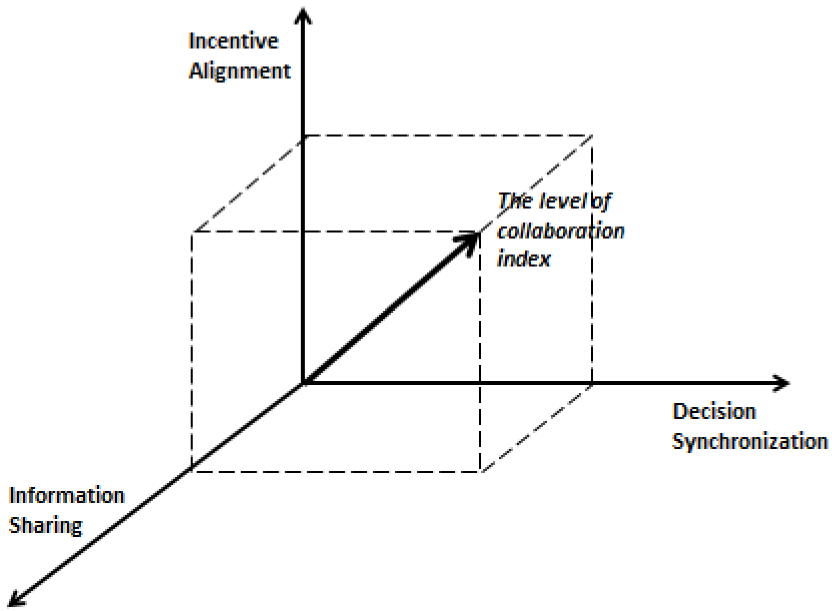


Figure 3.2: The Collaboration Index (adopted from Simatupang and Sridharan, 2005)

Collaboration is embedded in other works. The supply chain balanced scorecard framework proposed by Brewer and Speh (2000), includes collaboration under its innovation and learning perspective, using words of partnership and coordination measurement. They propose two metrics (the product category commitment ratio and the ratio of shared data sets relative to total data) that in our view partially address the need to include in supply chain measurement systems a holistic, multidimensional metric of cooperation and coordination in the supply chain.

Zhao (2002) proposed additional key performance indicators for inter- organizational partnerships (Table 3.5).

Table 3.5: Key performance indicators for inter-organizational partnerships (Zhao, 2002)

Critical Success Factor	**KPIs (Example)**
Commitment	Time and nature of contribution by partners
Communication	Frequency, mode and nature of communications between partners
Sharing	Frequency/amount and type of info/data exchanges between partners
Trust	Frequency of meeting one's expectation about another party's behavior and/or having confidence in another party
Profitability	Profit margins realized from collaborative projects
Productivity	Number /percentage of collaborative projects finished within time and budget
Market share	Percentage of market share obtained through partnerships
Corporate social responsibility	Speed and nature of responsiveness to environment introduced
Employee attitude	Employee turnover rate
Innovation and improvement	Number of new initiatives for improvement introduces
Customer satisfaction	Customer satisfaction rate

Similar to the work of Busi and Bititci (2006), Banomyong and Supan (2011) defined *"Total supply chain performance"* as including multiple performance measures related to supply chain members as well as the integration and coordination of members' performance. But despite the fact that they recognized the need for a holistic approach, they did not include a specific metric able to quantify total supply chain performance. Folan and Browne (2005a) admitted that supply chain performance measures that focus only upon logistics control systems cannot answer the question of how effectively firms are interacting in the supply chain. They propose not only procedural but also structural performance measures (Figure 3.3) and in a following work (Folan and Browne, 2005b) distinguished the supply chain performance measurement systems from what they propose as extended enterprise performance measurement systems. These incorporate the structural aspects of the supply chain and add non-logistics perspectives to the measurement effort.

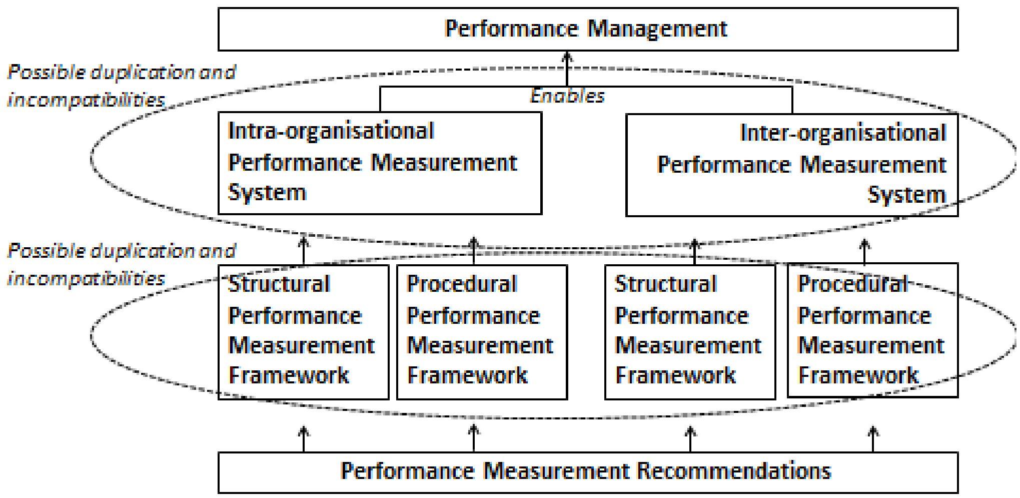


Figure 3.3: Supply Chain performance management (adopted from Folan and Browne, 2005a)

Holmerg (2000) discussed *"the structure that determines behavior"* comprised of tangible things like information technology and intangibles like business culture, policies and values, and stressed that a crucial factor to successfully restructure the supply chain measurement systems is to understand how positive behavior is determined by measurement. Among the other identified roles, a business performance measurement system should facilitate communication and enhance motivation through feedback on progress or diagnosed problems. This has special importance for supply chain managers, since their ability to coordinate supply chain activities depends on the successful communication of supply chain goals, performance and objectives both among supply chain partners (Stephens, 2001) and internally. The measures of individual actions and the set that assess the whole performance must be carefully chosen to serve supply chain objectives. Furthermore, the quality of the interfaces also affects the final result.

Sunwignjo, Bititci and Carrie (2000) noted that a problem which arises from that situation is the integration of those several measures expressed in heterogeneous units into a single unit. It is conjectured that this can be solved by using interoperability as a supply chain performance measure.

3.2.4 Supply Chain Management

The dissertation concurs with Kennerley and Neely (2002) about the need for a business performance measurement system that performs: i) quantification of the efficiency and effectiveness of actions, ii) assessment of the performance of an organization as a whole and iii) data acquisition and analysis. It is argued that the thus far proposed supply chain measures, being functionally- and organizationally-based, measure outputs of processes or interfaces rather than measuring the supply chain interfaces themselves. Planning or building successful supply chains is the equivalent of architecting the interfaces (Maier and Rechtin, 2009) between systems. A Supply chain manager, being an architect of the supply chain, is able to influence only interfaces between the independent firms. A measure focused on these interfaces would be valuable. Answering Gunasekaran et al. (2004) who identified the need for creative efforts to design new measures for the supply chain, interoperability is introduced as a candidate performance measure for supply chains. Interoperability could positively affect supply chain performance in a twofold manner; by improving collaboration between the firms and also by improving the supporting infrastructure of business performance measurement system thus facilitating the function of measurement.

For the purpose of supply chain interoperability measurement each supply chain member can be modeled by a set of criteria, denominated here as "characters." According to Ford (2009) interoperability characters *"represent attributes, or characteristics describing its important* *features. These system characters can be of any type (morphological, physiological, interfacial, ecological, and distributional among others). Ideally, the set of characters chosen are natural (i.e., characters are not confounded with each other) and diagnostic (i.e., characters distinguish one system, or system type, from another).”* The Supply Chain Management discipline offers various frameworks to assist in the quest for suitable system characters. Additionally the System of Systems analysis could be incorporated into character selection.

Lambert and Cooper (2000) argued that for a complex network to be manageable, members should be distinguished into those providing value-adding activities (primary members) and those providing resources, knowledge and utilities for the primary members. They postulated that it is not appropriate to integrate and manage all business process links through the chain and identified four types of process links (managed, monitored, not managed and nonmember). For supply chain interoperability and its measurement purposes, different characters should be assigned to each of these links.

Also, for the needs of supply chain interoperability measurement, various supply chain constructs can be used as candidate natural characters to model firms participating in supply chains. Carter and Rogers (2008) introduced the concept of organizational sustainability and proposed a framework (figure 3.4) that demonstrates the relationships among environmental, social and economic performance of the firm. According to their framework, it is at the intersection of social, environmental and economic performance, where the sustainable Supply Chain Management field resides. Activities in that field result in long-term competitive advantage. Also their work mentioned other supporting factors of sustainability, like risk management (through contingency planning and more resilient and agile supply chains), strategy, culture and transparency of corporate practices.

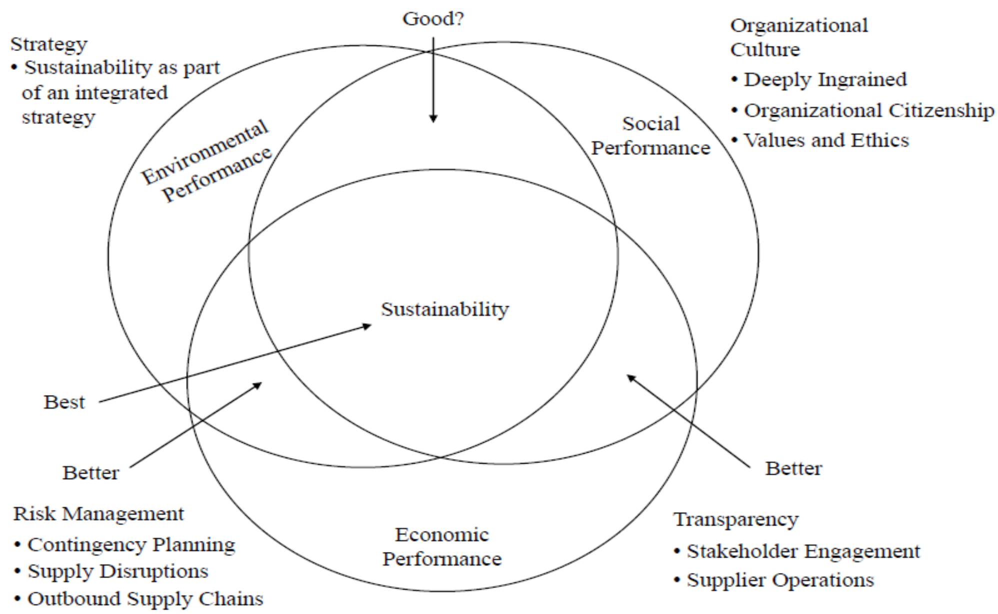


Figure 3.4: Sustainable Supply Chain Management (Carter and Rogers, 2008)

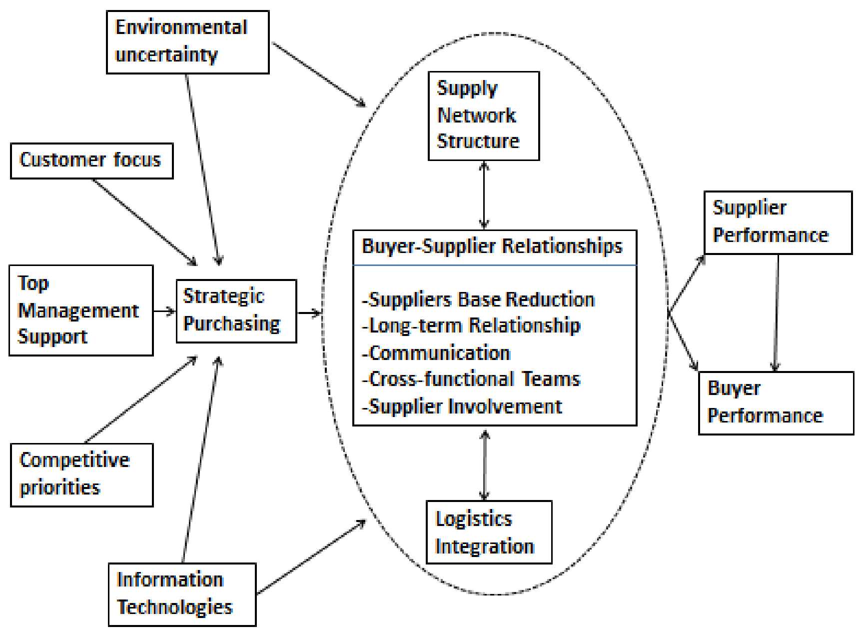


Figure 3.5: Supply Chain Management research framework (adopted from Chen and Paulraj, 2004)

Chen and Paulraj (2004) developed a framework (figure 3.5) that includes the driving forces of the relationships between the members of the supply chain based on the buyer-supplier relationship dyad. The constructs identified include environmental uncertainty, customer focus, top management support, competitive priorities, information technology, purchasing, logistics, the structure of the supply network, the relationships between buyer and supplier and their performance. Giannakis and Croom (2004) categorized the supply chain using three strategic dimensions. The “synthesis” dimension refers to the structural aspects of the chain and concerns decisions about the strategic position of the firm, the scope of vertical integration, the configuration of the supply base and the channels to customer’s choice. The “synergy” dimension is from the scope of inter-organizational relationships and helps on supplier selection, customer relationship management and inter-organizational behavior. The “synchronization” dimension involves logistics, operational research, operations management and system engineering concerns like scheduling and product flow and information management.

A key aspect of Supply Chain Management definitions concerns the integration of business processes. Enterprise integration refers to the improvement of the interrelations and interactions between the firms’ people, processes and technology. Vernadat (2007) recognized the need for a holistic approach to business integration that includes strategy, business processes and interoperable enterprise systems. He identified three integration purposes; communication, cooperation and coordination and stated that enterprise interoperability equates to loose integration. Also relevant to the seeking of appropriate supply chain interoperability characters, is the survey of Larson, Poist, and Halldósson (2007) that recognized various Supply Chain Management implementation barriers and facilitators (Table 3.6).

Table 3.6: Supply Chain Management (SCM) implementation barriers and facilitators (Larson et al., 2007)

FACILITATOR	**BARRIER**
Top management support	Functional silos
Customer relationship	Incompatible technology/systems
Organizational re-structuring	Lack of a common SCM perspective
Integrated Logistics Management	Conflict among supply chain members
Electronic data interchange (EDI)	Inadequate employee skills
Internet technology	Complexity of SCM
Employee training	Organizational structure
Enterprise resource planning (ERP)	Internal resistance
Hardware (computer equipment)	Cost of implementation
Supply chain software	Lack of electronic connectivity
Supplier involvement	Unwillingness to share information
Third –party logistics (3PL) providers	Customer resistance
Consultants	Supplier resistance
SCOR Model	
Fourth-party logistics(4PL) firms	

Fawcett and Magnan (2002) found that three levels of Supply Chain Management practice exist. At the first level, which characterized most of the companies, Supply Chain Management is the application of information technologies to increase the speed and quality of the exchanged information between the firms. The second level includes linked information systems, inter-organizational processes, common goals, shared risks and rewards, consistent performance measures. The third level recognizes Supply Chain Management as a philosophy and culture to guide decision making and relationships. They also mentioned that few companies have a formal map for their supply chain (Figure 3.6). This categorization is relevant to the discussion on the supply chain levels within which the interoperation takes place.

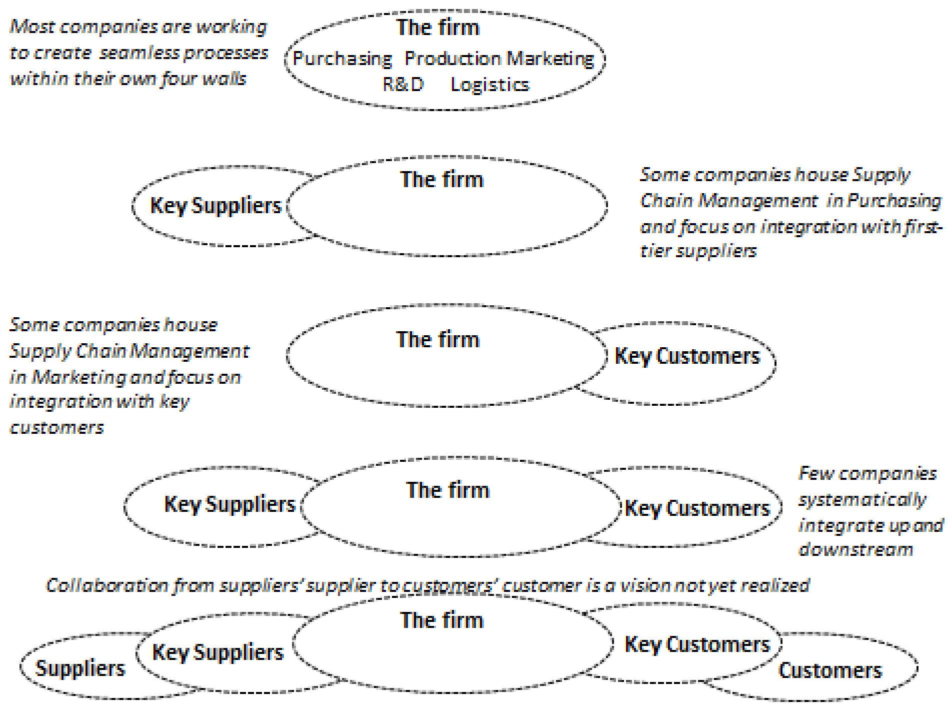


Figure 3.6: Different views of supply chain (adopted from Fawcett and Magnan, 2002)

Interestingly, there is wide agreement between the above seminal Supply Chain Management frameworks and various works on interoperability. Many of the recognized supply chain constructs have suitable systemic, per SoS discussion, attributes to be the central forces that drive interoperability. In accordance with Metrology, or the science of measurement, measurement is the objective representation of our empirical knowledge of the world by numbers (Finkelstein and Leaning, 1984). So to the extent that interoperability is considered as a property of a supply chain, then an operation, called interoperability measurement (Ford et al., 2010) can be defined which objectively and empirically assigns a number to supply chain interoperability.

3.2.5 Supply Chain Interoperability

There are various definitions for interoperability. IEEE defines interoperability as the *"Ability of a system or a product to work with other systems or products without special effort on* *the part of the customer"* (IEEE, 2013). Vernadat (2010) stated that interoperability is the ability for a system to communicate with another system and to use the functionality of the other system. Naudet, Guedria and Chen (2009) considered interoperability as a problem that occurs when incompatible systems are asked to relate. According to the Interoperability Development for Enterprise Application and Software (IDEAS, 2003), interoperability is the ability of interaction between enterprises. The literature review revealed a consensus of the academia on an interoperability framework recognizing that for interoperation between enterprises three (Chen, 2003; Chen, Doumeingts and Vernadat, 2008; Ralyte et al., 2008) or four (Panetto and Whitman, 2006; Kasunic and Anderson, 2004) layers of interoperability are needed. INTEROP NoE (Interoperability Research for Networked Enterprises Applications and Software - Network of Excellence, 2003-2007) developed a framework (figure 3.7) that defines interoperability in terms of interoperability barriers, the associated approaches to remove these barriers and the enterprise levels that the interoperation takes place at or between.

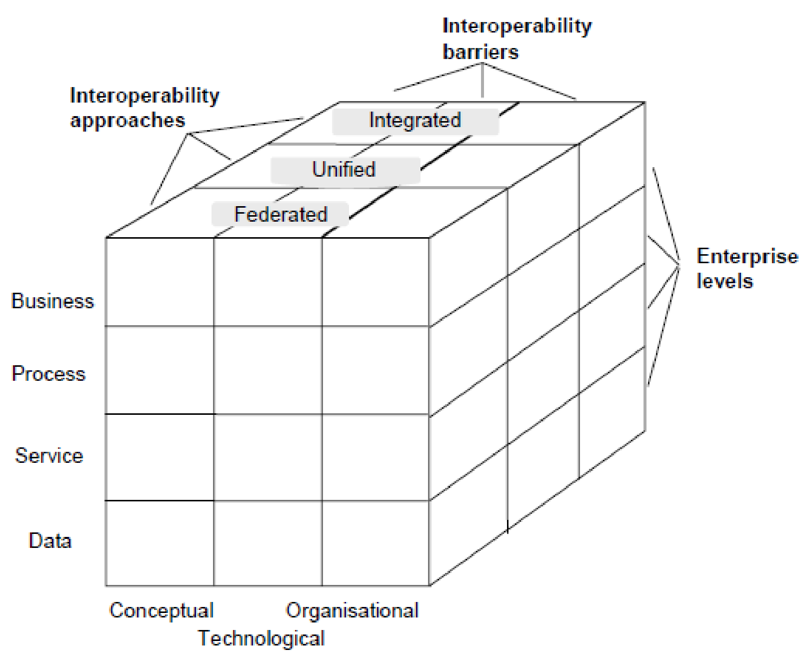


Figure 3.7: Interoperability framework (INTEROP NoE, 2003-2007)

Ford et al (2010) identified approximately two-dozen papers that have been published specifically on interoperability measurement and they classified the work of researchers who have proposed a new interoperability measurement method or an extension/improvement to an existing one. Blanc et al. (2007) defined heterogeneity (as non- interoperability) and presented various kinds of tools to identify and solve the heterogeneity in the supply chain and a method which manages the enterprise evolution towards interoperability. Also Chen, Vallespir and Daclin (2008) presented an enterprise interoperability measurement approach within INTEROP Noe frame.

The following definition of supply chain interoperability is proposed:

Supply chain interoperability is the ability of cooperating business entities to provide services to each other as well as to their users/customers by defining synchronization steps and messages to exchange information and goods, to coordinate their business processes, and align their business goals towards optimality of the chain, without losing individual sense of purpose and idiosyncratic capabilities.

3.3 A General Approach for Interoperability Measurement

A particular method of interoperability measurement was proposed by Ford et al. (2010). In order to introduce the idea of the measurement method, their pertinent definitions is included in this section, and then frame them in a supply chain context.

A set of systems $S = \{s_1, s_2, \ldots, s_m\}$ can be modeled by a set of characters $X = \{x_1, x_2, \ldots, x_n\}$ which represent traits, attributes, or characteristics that describe the important features of the systems set. Ideally, the set of characters chosen should not be confounded with another and have the ability to distinguish one system from another. Furthermore, the types of characters chosen should be related to the type of interoperability measurement that is to be undertaken.

Valid character states C for a set of characters X are $C = \{c_1, c_2, \ldots, c_k\}$. Character states are either qualitative (discrete) or quantitative (discrete or continuous), or a mixture of both. Generally, the set of character states is restricted to the binary numbers (absence/presence states) or the positive real numbers, although other states are certainly possible. Once systems, their interoperability characters, and the states of those characters have been identified, then a specific system can be modeled as a sequence of states of system characters.

Consider the simple three-element supply chain shown in Figure 3.8. The arrows represent possible directions of information or product flow between each element. Each element in this supply chain constitutes a separate system. The SCOR models five fundamental management processes: plan, source, make, deliver, and return provide a natural basis for a supply chain system's interoperability characters. SCOR processes are used here in order to facilitate understanding of the measurement approach. Diving at length into the details of the model would include the selection, per our previous SoS heuristics and SCM frameworks discussion, of suitable and tested supply chain constructs of a discrete or stochastic nature. Such a lengthy discussion is outside of the scope and space constraints of the current paper, but viewed as the next step in the process and is planned as part of ongoing and future research for publication.

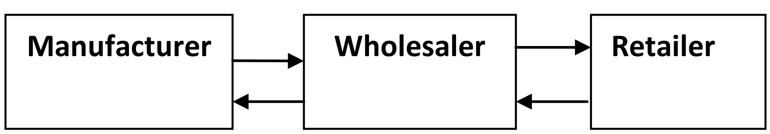


Figure 3.8. A simple supply chain.

A sample set of possible characters and states for three SCOR processes are depicted in Table 3.7. Arbitrarily a five point scale (0,1,2,3,4) can be used to define each state level and for relative comparisons.

Table 3.7. Supply chain interoperability characterization example.

	***P**lan. **D**emand.**F**orecasting.*		***P**lan. **I**nventory.**V**isibility.**S**haring.*		***S**ource. **R**elationship. **D**istance. **M**anaging.*	***D**eliver. **O**rder.**D**ata. **S**haring.*
Level	**M**edium (P_{DFM})	**F**requency (P_{DFF})	**M**edium (P_{IVSM})	**F**requency (P_{IVSF})	(S_{RDM})	(D_{ODS})
4	seamless	real-time	seamless	real-time	full integration & trust	always
3	electronic, with translation	daily	electronic, with translation	daily	long term sharing of tactical & strategic goals	frequently
2	electronic, with human intervention	weekly	electronic, with human intervention	weekly	moderate sharing of tactical & strategic goals	sometimes
1	paper	monthly	paper	monthly	tactical-level sharing, short term	rarely
0	none	never	none	never	no trust – arm's length	never

From the Figure 3.8 and Table 3.7 data, we can assign systems, interoperability characters, and character states as:

S = {Manufacturer (M), Wholesaler (W), Retailer (R)}

X = {Plan.demand.forecasting.medium (P_{DFM}), Plan.demand.forecasting.frequency (P_{DFF}), Plan.inventory.visibility.sharing.medium (P_{IVSM}), Plan.inventory.visibility.sharing.frequency (P_{IVSF}),

Source.relationship.distance.managing (S_{RDM}), Deliver.order.data.sharing (D_{ODS})}

C = {0, 1, 2, 3, 4}.

The final step is to objectively assign a number to measure the similarity among the constituent systems. A similarity function is the converse of a dissimilarity function such as Euclidean distance, in that it gives a larger result if its arguments are more similar and a smaller result if they are more dissimilar. An interoperability measurement represents the ability of two systems to interoperate; i.e., it represents the similarity between their capability to interoperate.

Ford et al. (2009) propose a similarity function consisting of a weighted, normalized measure of the similarity of systems instantiated with real-valued character states, based on the Minkowski similarity function. Their particular mathematic development requires extensive notation and thus is included in the Appendix 3.A. The interested reader is referred to their paper.

Consider two sample scenarios with supply chain interoperability levels as defined in table 3.7: Table 3.8.a represents a "lower interoperability" supply chain scenario (e.g. Wholesaler P_{DFM}=2, P_{IVSM}=2, P_{IVSF}=1, D_{ODS}=1). The second "higher interoperability" scenario, shown in Table 3.8.b., depicts a supply chain where for example the wholesaler makes significant effort to establish relationships with the maker and retailer, share information on inventory, and provide shipping lead time & expected delivery date data (Wholesaler P_{DFM}=3, P_{IVSM}=3, P_{IVSF}=3, D_{ODS}=4).

Table 3.8.a.
Lower interoperability scenario.

	Manufacturer	Wholesaler	Retailer
P_{DFM}	1	2	3
P_{DFF}	1	2	3
P_{IVSM}	1	2	3
P_{IVSF}	0	1	2
S_{RDM}	0	1	2
D_{ODS}	0	1	2

Table 3.8.b
Higher interoperability scenario.

	Manufacturer	Wholesaler	Retailer
P_{DFM}	1	3	3
P_{DFF}	2	2	3
P_{IVSM}	1	3	3
P_{IVSF}	1	3	2
S_{RDM}	0	2	2
D_{ODS}	1	4	2

Using Ford et al.'s (2009) equation (1 in the Appendix 3A) with $c_{max} = 4$, $r = 2$, *and* $n = 6$, the following supply chain interoperability measurements M result for each of the two respective scenarios:

$$M_{low\ int.} = \begin{bmatrix} & M & W & R \\ M & .13 & .21 & .24 \\ W & .21 & .38 & .38 \\ R & .24 & .38 & .63 \end{bmatrix} \qquad M_{sig.\ int.} = \begin{bmatrix} & M & W & R \\ M & .25 & .26 & .29 \\ W & .26 & .71 & .50 \\ R & .29 & .50 & .63 \end{bmatrix}$$

The lower interoperability scenario provides an example where the supply chain's interoperability is inversely proportional to distance from the retailer. This is a common scenario in many supply chains since often the information systems of those closer to the customer are more capable than those that are further upstream in the supply chain. Limited or nonexistent information sharing about inventory or forecasted demand leads to shortages and inefficient inventory levels, something that can be observed in simple exercises such as the Beer Game. Conversely, the higher interoperability scenario shows a much stronger interoperability relationship between the wholesaler and retailer. The manufacturer-wholesaler relationship is also improved but to a lesser extent because the manufacturer has not, by itself, significantly improved its information sharing capacity or business trust with external firms.

Note that due to space limitations; only three SCOR processes are illustrated in the example and only one or two interoperability characters for each process is proposed. This method of measuring supply chain interoperability can go much further—for example, the SCOR plan process can be further decomposed into inventory visibility and pricing & promotion characters. Characters can also be defined for the SCOR Make process, to assess production schedules and product packaging & sizing interoperability. Each SCOR process character can further be decomposed into directional measures that separately assess a firm's ability to share or receive products and information. Finally, it should be noted that it would be useful to have a single number that measures an entire supply chain's overall interoperability – we are currently investigating which of a variety of candidate matrix norms might best represent this value in a supply chain context.

We conjecture that supply chain interoperability is minimal between firms without a supply chain orientation or performing in the “market” area (figure 3.9) of the Transaction Cost Economics governance structure (Williamson, 2008) that denotes absence of dependency between firms and competition. Interoperability increases through the “hybrid” area that is a compromise mode and cannot be defined in hierarchy governance that denotes integration of firms.

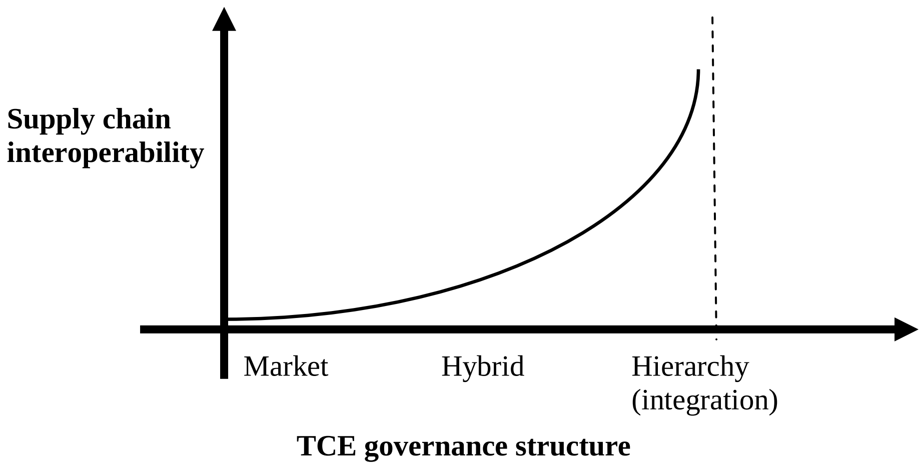


Figure 3.9: Supply Chain Interoperability degrees and Transaction Cost Economics government structures

3.4 Summary

A literature review reveals that despite the great number of frameworks and tools for supply chain performance measurement, none addresses all of the typical problems for supply chain performance assessment. Additionally it may be impossible to overcome the barrier of inadequate supply chain performance measurement systems. A new lens is needed to change what Ackere (1993) recognized as the mentality of supply chain managers being *“regrettably ignorant of the fact that supply chains are designable.”* A new perspective could help shape *"supply chain design principles"* (Geary et al., 2006), facilitate interface management and balance control vs. emergence in supply chains (Choi et al., 2001).

Toward that direction, the System of Systems approach and the application of System Engineering heuristics on supply chain performance measurement is a significant contribution to the Supply Chain Management discipline. Supply chains are analyzed as systems of systems and the parallels with the theoretical perspectives of Transaction Cost Economics, Resource Based View and network systems are identified. This offers an alternative to fill the gap with the introduction of a new supply chain performance measure, defined as supply chain interoperability. Various calls for a means of assigning values to the various levels of collaboration among participating firms (Barrat, 2004; Mentzer, 2000) are answered. The literature review and framework analysis on interoperability, the definition of supply chain interoperability and the systems of systems perspective of supply chains presented, are original in the Supply Chain Management literature. Supply chain managers take on the role of the architects of the supply chain and should focus on the multilevel interfaces that ensure cooperation and exchange between the participating firms.

Based on the previous discussion, supply chain interoperability measurement would be a valuable tool for practitioners willing to assess interoperability and for researchers to evaluate a suitable framework and interoperability quantification method in various industries. The goal of such a measurement would be to study the changes that can be made to improve supply chain interoperability. However it may not be possible, financially profitable or even desirable for all supply chain members to interoperate perfectly. Naturally, the relationship between supply chain interoperability and performance should be validated in the future.

Finally, it is proposed a generalizable and customizeable approach that could be useful in measuring supply chain interoperability. The overall goal of measuring supply chain interoperability is to better understand how changes can be made to improve supply chain interoperability.

The next step in this process would be to further develop and refine the characters (criteria) that should be included in the interoperability measurement model. For that purpose, the constructs of some of the so far developed supply chain management frameworks are strong candidate characters, since their relevance with enterprise performance has been already tested.

Also there is a need to improve upon extant interoperability assessment techniques by refining current quantification methodologies to include both deterministic and stochastic characters, and by aggregating overall interoperability across the entire supply chain. The creation and definition in the supply chain context, of the interoperability upper bound would be also useful. The possible difference between the upper bound and the current interoperability measurement would define an interoperability gap, which represents the trade space in which changes can occur on interoperability characters, to improve supply chain performance. Perhaps a qualitative research effort based on semi-structured interviews would be suitable to explore meanings and perceptions to gain a better understanding of the topic, and to obtain thoughts and perspectives of practitioners that are unfamiliar to the authors and have not been considered in the literature. Following the further refinement of the interoperability measurement, empirical data should be utilized to test, validate, and further refine the measurement.

Appendix 3.A

(adopted from Ford et al.(2009,2010)

DEFINITION: *Given a set of systems S, then* $X : S \rightarrow C$ *is a function which maps systems in S to a set of character states C and X is called the characterization of S.*

DEFINITION (System Instantiation): *Given a specific* $s \in S$ *and a set* $x \subseteq X$ *of system characters descriptive of s, then* $\sigma = x(s)$ *is a sequence of system character states, called the instantiation of s, which models s.*

DEFINITION (Instantiation Alignment): *Given a set* $x' \subseteq X$ *of system characters descriptive of* s' *and a set* $x'' \subseteq X$ *of system characters descriptive of* s''*, then two system instantiations* σ' *and* σ'' *are aligned if* $\sigma' = X(s')$ *and* $\sigma'' = X(s'')$.

DEFINITION (Interoperability Function): *An interoperability function I is a similarity function* $Sim(\sigma', \sigma'')$ *which 1) takes a pair of system instantiations as its arguments, 2) has a range of [0,1] (i.e., 0 indicates non-interoperable systems while 1 indicates perfectly interoperable systems), 3) rewards for shared characters and optionally penalizes for unshared characters (i.e.,* α, β *), and 4) gives a greater reward (i.e.,* θ *) to system pairs whose shared characters' states have a "better" value.*

DEFINITION (Sim_{Bin}): *Given a pair of systems* s', s'' *instantiated as* $\sigma', \sigma'' \in \{0,1\}^n$ *where* $\{0,1\}^n$ *represents binary n-space and where* $\wedge$ *is the boolean AND operator, then* $I = Sim_{Bin} = Sim(\sigma', \sigma'')$ *is an interoperability function which gives a weighted, normalized measure of the similarity of systems instantiated with absence/presence character states where* $f = \sum_{i=1}^{n} (\sigma' \wedge \sigma'')$ *and*

$\theta = 1/n, \ \alpha = \beta = 0$.

DEFINITION (Sim_{Real}): *Given a pair of systems* s', s'' *instantiated as* $\sigma', \sigma'' \in R^n \cap [0, c_{max}]$ *,* *then* $I = Sim_{Real} = Sim(\sigma', \sigma'')$ *is an interoperability function as specified in Equation (2) which gives a weighted, normalized measure of the similarity of systems instantiated with real-valued character states. The function f is the modified Minkowski similarity function in Equation (2),* θ *is the average character state value (Equation (3)) of a pair of system instantiations, n is the number of characters used to instantiate* σ', σ'' *,* $c_{\max}$ *is the maximum character state value, r is the Minkowski parameter (usually set to* $r = 2$ *), and* $\alpha = \beta = 0$.

$$I = Sim_{Real} = \left[\frac{\sum_{i=1}^{n} \sigma'(i) + \sum_{i=1}^{n} \sigma''(i)}{2nc_{\max}} \right] \left[1 - \left(\frac{1}{\sqrt[r]{n}} \right) \left(\sum_{i=1}^{n} b_i \left(\frac{\sigma'(i) - \sigma''(i)}{c_{\max}} \right)^r \right)^{1/r} \right] \tag{1}$$

$$Modified\ Minkowski\ Similarity = \left[1 - \left(\frac{1}{\sqrt[r]{n}} \right) \left(\sum_{i=1}^{n} b_i \left(\frac{\sigma'(i) - \sigma''(i)}{c_{\max}} \right)^r \right)^{1/r} \right]$$

$$b_i = \begin{cases} 0 & \sigma'(i) = 0 \ or\ \sigma''(i) = 0 \\ 1 & else \end{cases} \tag{2}$$

$$Average\ Character\ State\ Value = \theta = \frac{\sum_{i=1}^{n} \sigma'(i) + \sum_{i=1}^{n} \sigma''(i)}{2nc_{\max}} \tag{3}$$

AXIOM (System Similarity and Interoperability): *If a pair of systems is instantiated only with system interoperability characters, then a measure of the similarity of the instantiations is a measure of their associated systems' interoperability.*

IV. A Method for Measuring Supply Chain Interoperability

4.1 Abstract

The ability of systems or organizations to provide services to, and accept services from, other systems or organizations is the fundamental tenet of interoperability. This paper introduces Supply Chain Interoperability and proposes it as a metric to facilitate supply chain management performance analysis. Interoperability can be considered a similarity metric with regard to a set of characteristics. Our methodology adapts and expands an interoperability measurement tool initially developed in and for a military context. Through an illustrative example, the assessment of interoperability is demonstrated across a supply chain, where participants are described using deterministic and stochastic characters. The measurement methodology can assist in efficiently directing resources to best improve interoperability between and among the various elements of a supply chain.

4.2 Introduction

Supply Chain Management has been characterized as including collaborative concepts such as channel-wide evaluation of costs, mutual information sharing, multiple levels of coordination, joint planning, and the sharing of risks and rewards (Cooper and Ellram, 1993). The literature and Supply Chain Management (SCM) practitioners have adopted and extensively use words such as cooperation, coordination, integration and collaboration. Yet, it has proved difficult to adopt a holistic measure to assess these concepts and even more difficult to then improve supply chain performance based on such an assessment (Neely et al., 1997; Lambert and Pohlen, 2001; Hofman, 2004; Banomyong and Supatn, 2011). Inadequate supply chain performance measurement systems are recognized as a major barrier to successful supply chain collaboration (Fawcett, Magnan and McCarter, 2008).

Here is argued that planning or building successful supply chains is the equivalent to architecting the interfaces between systems. Systems architecture and the use of architectural frameworks provide a variety of insightful views into any complex system. Such views can include organizational, behavioral/process, information/data, physical/interface, and technological/standards factors. However, Maier and Rechtin (2000) state that *"the greatest leverage in system architecting is at the interfaces… the greatest dangers are also at the interfaces."* A supply chain manager should act as a supply chain architect (Chalyvidis et al., 2012), and be able to influence interfaces between the independent firms.

A measure focused on these interfaces would be valuable. Gunasekaran et al. (2004) identified the need for new measures for supply chain assessment. This research paper introduces interoperability as a candidate supply chain performance measure. Interoperability could positively affect supply chain performance in a twofold manner. First, it could help improve collaboration between a supply chain's members; and secondly, it could improve the discipline's methods, processes and tools for business performance measurement.

Each supply chain member can be modeled by a set of characters or attributes, representing characteristics describing important features for the chain. The supply chain management discipline offers various frameworks to assist in the quest for suitable system characters. Additionally, the systems engineering community has an extensive System of Systems (SoS) literature (Boardman and Saucer, 2006), which could be incorporated into criteria selection. Interestingly, there is wide agreement between several supply chain management frameworks and various works on interoperability. Many of the recognized supply chain constructs have proposed suitable systemic attributes to be the central forces that drive interoperability.

In accordance with metrology, measurement is the objective representation of our empirical knowledge of the world by numbers (Finkelstein and Leaning, 1984). So to the extent that interoperability is considered as a supply chain property, then an operation, called *interoperability measurement* can be defined which objectively and empirically assigns a number to supply chain interoperability (Ford, Ogden and Johnson, 2010). This paper proposes a method of quantitatively measuring supply chain interoperability through the adaptation and expansion of a method that was originally developed in and for a military context (Ford et al., 2009). The proposed method improves upon extant interoperability assessment techniques by refining current quantification methodologies to include both deterministic and stochastic characters, and by aggregating overall interoperability across the entire supply chain.

To present these concepts, the paper is organized as follows: we first review the literature on interoperability and its measurement, and provide a definition for supply chain interoperability. We then present a method of measuring interoperability between systems, based on the similarity of their characters. Then a generic supply chain is examined, the selection of suitable supply chain characters is discussed and a supply chain interoperability assessment example follows. We conclude by summarizing the proposed method, discussing its managerial implications and suggesting opportunities for future research.

4.3 Literature Review on Interoperability

4.3.1 Defining Interoperability

Several definitions exist for interoperability. IEEE defines interoperability as the *"Ability of a system or a product to work with other systems or products without special effort on the part of the customer"* (IEEE, 2013). Vernadat (2010) stated that interoperability is the "*ability for a system to communicate with another system and to use the functionality of the other system.*"

Naudet et al. (2010) consider interoperability as a problem that occurs when incompatible systems are asked to relate. They suggest that interoperability is not only related to communications technology, but that there are structural and behavioral aspects as well.

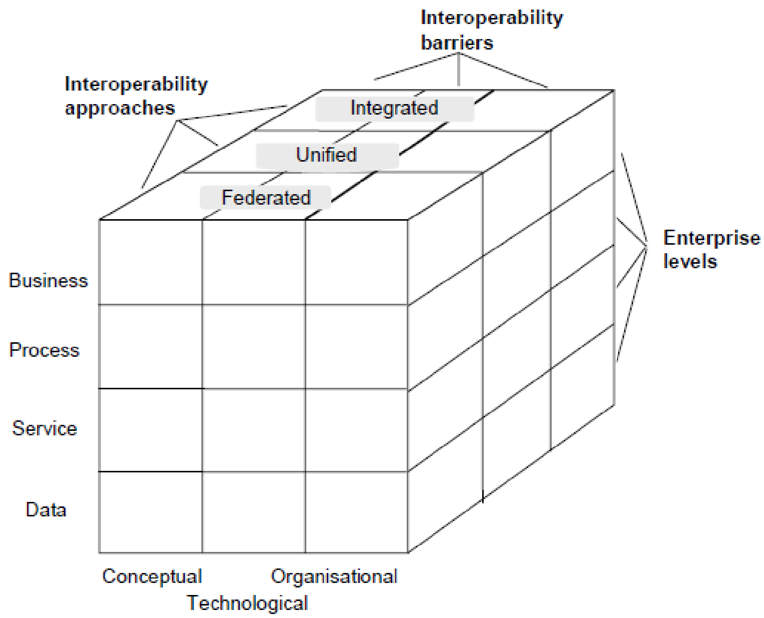


Figure 4.1: An Interoperability Framework (INTEROP NoE, 2013)

According to the Interoperability Development for Enterprise Application and Software (IDEAS, 2003), interoperability is simply the "*ability of interaction between enterprises*." Research has examined interoperability frameworks, with the recognition that multiple layers (three or four views) may be required for interoperation between enterprises (Chen and Doumeingts, 2003; Chen, Doumeingts and Vernadat, 2008; Ralyte et al., 2008; Whitman and Panetto, 2006; Kasunic and Anderson, 2004). During 2003-2007, the international Interoperability Research for Networked Enterprises Applications and Software project (INTEROP NoE, 2013) developed a framework (Figure 4.1) that defined interoperability in terms of interoperability barriers, the associated approaches to remove these barriers and the enterprise levels where interoperation takes place.

Gasser and Palfrey (2007, 2012) conclude that interoperability has several meanings according to the context and is not *"good for everyone all the time."* Ford et al., (2009) found over 60 different types of interoperability mentioned in the literature, and note that the most common types are technical, organizational and operational. Chalyvidis, Ogden and Johnson (2013) suggest that supply chain interoperability should consider the multidimensional nature of the technical communications, the functions and behavior of participants along with organizational and cultural aspects of the chain and define it as follows:

> *Supply chain interoperability is the ability of cooperating business entities to provide services to, and/or receive services from each other, as well as to their users/customers by coordinating their business processes and information solutions toward alignment with the optimality of the chain, without losing individual sense of purpose and idiosyncratic capabilities.*

4.3.2 Interoperability vs. Similar Terms in Supply Chain Management

Integration and interoperability are used in various disciplines, but both concepts require a systemic approach to their solutions. They often are used to refer to collections of physical or software systems or aspects across an enterprise. Integration is broadly used in the supply chain management literature (Mentzer et al., 2001; Chen and Paulraj, 2004; Carter and Rogers, 2008; Cooper, Lambert and Pagh, 1997). The integration of business processes is a key aspect of both Enterprise Architecture and SCM and refers to alignment towards optimal management of assets and processes (Vernadat, 2010). Integrated logistics management has recognized incompatibility of systems as a significant SCM barrier (Larson, Poist and Halldorsson, 2007). Vernadat (2007) recognized the need for a holistic approach to business integration that includes strategy, business processes and interoperable enterprise systems. He identifies three integration principles: communication, cooperation and coordination and stated that "*enterprise interoperability equates to loose integration.*" Chen et al. (2008) further distinguishes interoperability vs. integration, giving to the first the meaning of *"coexistence under autonomy"* and referring to the latter as *"coordination, coherence and uniformization"*. They state that *"two integrated systems are inevitably interoperable; but two interoperable systems are not necessarily integrated."* On the basis of autonomy, Whitman and Panetto (2006) notes that integration involves some degree of functional dependence, with integrated systems losing functionality if the flow of interconnections is interrupted. They further acknowledge that *"Interoperability lies in the middle of the Integration Continuum between compatibility and full integration, taking into account cultural requirements."*

According to ISO 14258 (Industrial automation systems - Concepts and rules for enterprise models), *"two systems are considered as integrated if there is a detailed standard format for all constituent components."* Other perspectives use integration to signify the coordination of information systems within an enterprise (Mouzakitis, Sourouni and Askounis, 2010). Cooper and Ellram (1993) distinguish three kinds of coordination in supply chains: across members, across management levels, and across functions.

The draft standard IEC TC65/290/DC on "Industrial-process measurement, control and automation" characterizes the concept of interoperability as one level of compatibility (shown in Table 4.1). Table 4.2 (also from the standard) depicts the different interaction types to achieve interoperability. Inter-functional and inter-corporate coordination in the supply chain are key issues for customer satisfaction, profitability and competitive advantage (Mentzer et al., 2001).

Table 4.1: Compatibility levels (IEC TC65/290/DC, 2002)

Compatibility level / System feature	Incompatible	Coexistent	Interconnectable	Interworkable	Interoperable	Interchangeable
Dynamic Behavior						x
Application Functionality					x	x
Parameter Semantics					x	x
Data Types				x	x	x
Data Access			x	x	x	x
Communication Interface			x	x	x	x
Communication Protocol		x	x	x	x	x

Table 4.2: Interoperability implications of different interactions (IEC TC65/290/DC, 2002)

	Communication	Coordination	Cooperation	Collaboration	Channel
Management of External Relationships				●	●
Employees and Culture			◗	●	●
Business Processes		◗	●	●	●
Information Systems	●	●	●	●	●

Min et al. (2005) offers that collaboration is an ultimate core capability of firms that provides benefits like revenue enhancements, cost reduction and operational flexibility. Empirical data shows that collaboration has not been achieved as desired (Holmberg, 2000; Fawcett and Magnan, 2002; Wognum and Faber, 2002). Other authors (Barratt, 2004; Mentzer et al., 2000) call for a means of assigning values to the various levels of collaboration among participating firms. Lockamy and McCormack (2004), in their exploratory study of nine influential supply chain practices, found collaboration to be the most important. Tangen (2004, 2005) argues that current measurement frameworks only discuss what to measure, without any guidance of how to actually achieve the desired quantification. Holmberg (2000) notes that understanding how positive behavior is determined by measurement is a crucial factor to successfully restructure supply chain measurement systems. Among the other identified roles, a business performance measurement system should facilitate communication and enhance motivation through feedback on progress or diagnosed problems. This discussion has special importance for supply chain managers, since their ability to coordinate supply chain activities depends on their successful communication of goals, performance and objectives among their supply chain partners (Stephens, 2001).

4.3.3 System Interoperability Measurement

Ford et al. (2009) identified a recent surge in interoperability research. They recognize two kinds of assessment methods: *leveling* methods are largely based upon the maturity model concept, such as the Capability Maturity Model (CMM) for software, and represent thresholds of increasing interoperability capability. *Non-leveling* interoperability assessment methods are specialized to a particular system or interoperability type and generally pre-date the leveling methods. They argue that extant methods cannot offer a complete and general method of measuring the interoperability of a set of heterogeneous systems and propose an interoperability measurement based on the similarity of system characteristics. Table 4.3 summarizes some popular interoperability measurement methods and can be summarized as a mix of technical and organizational interoperability frameworks, using both leveling and non-leveling deterministic measures.

Table 4.3: Interoperability measurement methods (adapted from Ford et al., 2009) (Note: Type is L-Leveling, NL-non leveling)

Method	**Type**	**Contribution**
Spectrum of Interoperability Model (SOIM)	L	Interoperability can be measured in levels
Quantification of Interoperability Model (QOIM)	NL	Interoperability can be correlated to measures of effectiveness.
Military Comm & Info Systems Interoperability (MCISI)	NL	Distanced between systems modeled as points in space indicates their interoperability
Levels of Information System Interoperability (LISI)	L	Systems possess interoperability-related attributes
NATO C3 Technical Architecture Reference Model for Interoperability	L	Similar to LISI, focused on levels of data interoperability
Levels of Coalition Interoperability (LCI)	L	Provides relationship between organizational and technical interoperability
Organizational Interoperability Maturity Model (OIM)	L	Organizations interoperate, but have other interoperability attributes than technical
Non-technical Interoperability in Multinational Forces (NTI)	L	Introduced social, personnel and process as non-technical attributes
System of Systems Interoperability (SoSI)	--	Framework for examining interoperability beyond system context (external SoS)
Interoperability score (i-score)	NL	Interoperability is process-specific and has a theoretical upper bound
Generalized Interoperability Measurement	L/NL	Introduced directionality, confrontation/ collaboration, similarity measurement

4.4 Method of Mixed-Character Interoperability Measurement

Here a supply chain interoperability measurement method is propose that combines previous measurements (Chalyvidis, Ogden and Johnson 2013, Ford et al. 2009, 2010) and extends the body of work to include both deterministic and stochastic characters.

4.4.1 Interoperability Measurement Formulation

A set of N systems $S = \{s_1, s_2, \ldots, s_N\}$ can be modeled by a set of n characters $\{X_1, X_2, \ldots, X_n\}$ which represent the important features, traits, attributes, or characteristics of the systems. Ideally, the set of characters chosen should not be confounded with another and have the ability to distinguish one system from another. Furthermore, the types of characters chosen should be related to the type of interoperability measurement that is to be undertaken. Specific values (or states) can be assigned to the characters. These values can be either discrete or continuous real values defined in $[0,\kappa_i], \kappa_i \in \mathbb{R}, \kappa_i > 0$, Boolean values (true/false, 0/1), and can be deterministic or follow a specific distribution. For supply chain analysis, the systems could be the set of manufacturers, suppliers and distributors. Once systems, their interoperability characters, and the states of those characters have been identified, then a specific supply chain can be modeled. The foundation of interoperability measurement is a similarity measurement calculated using a similarity function which takes two aligned system instantiations S as its arguments. A similarity function is the converse of a dissimilarity function (e.g. Euclidean distance) in that it gives a larger result if its arguments are more similar and a smaller result if they are more dissimilar.

Ford et al. (2009) propose a similarity function consisting of a weighted, normalized measure of the similarity of systems using real-valued character states, based on the Minkowski distance. Their following definitions are used here:

Definition 1 (System Characterization):Given a set of N systems S, then X: S → C is a function which maps systems to a set of n character states C with specific order $X=(X_1,X_2,\ldots,X_n)$ is called the characterization of S.

Definition 2 (Interoperability Function): *An interoperability function I of two systems s', s'', is also a similarity function I=Sim(s', s'')=||X' - X''|| which 1) takes, as its arguments, the values* $\left(x_1',x_2',...,x_n'\right)$ *and* $\left(x_1'',x_2'',...,x_n''\right)$ *of a pair of characterizations:* $X'=\left(X_1',X_2',...,X_n'\right)$ *and* $X''=\left(X_1'',X_2'',...,X_n''\right)$ *of systems s', s'', 2) has a range of [0,1] (i.e. zero indicates non-interoperable systems while one indicates perfectly interoperable systems), 3) gives a greater reward to system pairs whose shared characters states have a "better" and/or "closer" value.*

Axiom 1 (System Similarity and Interoperability): If a pair of systems is characterized only with system interoperability characters, then a measure of their similarity of characters is a measure of their associated systems' interoperability.

The Minkowski distance is a generalization of the Euclidean distance, defined for two vectors $Z=\left(z_1,z_2,z_3,...,z_n\right)$ and $W=\left(w_1,w_2,w_3,...,w_n\right)$ where $z_i,w_i\in\mathbb{R}, i=1,2,...,n$:

$$\text{Minkowski Distance }(Z,W)=\left[\sum_{i=1}^{n}\left|z_i-w_i\right|^r\right]^{\frac{1}{r}} \qquad (1)$$

Whenever the coordinates of vectors Z, W transformed (normalized) to $\tilde{Z},\tilde{W}$ in the closed interval [0,1], Minkowski distance can be converted to a similarity function by

$$\begin{aligned}\text{Minkowski Similarity }(\tilde{Z},\tilde{W})&=1-\left(\frac{1}{\sqrt[r]{n}}\right)\cdot\left[\sum_{i=1}^{n}\left|\tilde{z}_i-\tilde{w}_i\right|^r\right]^{\frac{1}{r}}=\\&=1-\left(\frac{1}{n}\right)^{\frac{1}{r}}\cdot\left[\sum_{i=1}^{n}\left|\tilde{z}_i-\tilde{w}_i\right|^r\right]^{\frac{1}{r}}=1-\left[\frac{1}{n}\cdot\sum_{i=1}^{n}\left|\tilde{z}_i-\tilde{w}_i\right|^r\right]^{\frac{1}{r}}\Rightarrow\end{aligned} \qquad (2)$$

$$\Rightarrow \text{Minkowski Similarity } (\tilde{Z},\tilde{W}) = 1 - \left[\frac{\sum_{i=1}^{n} \left| \tilde{z}_i - \tilde{w}_i \right|^r}{n} \right]^{\frac{1}{r}} \quad (3)$$

The Minkowski similarity directly does not reward for system pairs whose characters have "better value." For interoperability measurement a weighting must be applied (Ford et al. 2009) such as the average character state value, so interoperability measurement *I= (average character state)(Minkowski Similarity).*

For our purposes consider a characterization $X=(X_1,X_2,\ldots,X_n)$ where X_i $i=1,2,\ldots,n$ can be either:

Case 1: X_i *takes values on* $A_i = \{0 = x_{i,0}, x_{i,1}, x_{i,2}, \ldots, x_{i,n_i} \mid x_{i,j} \in \mathbb{R}, x_{i,0} < x_{i,1} < x_{i,2} < \ldots < x_{i,n_i}\}$,

($n_i \in \mathbb{N}^*$ *and* x_{i,n_i} indicates the maximum state value for the i^{th} character),

Case 2: X_i *takes values* $x_i \in [0,\kappa_i]$, $\kappa_i \in \mathbb{R}, \kappa_i > 0$

This characterization can be used in an Interoperability function I, after normalized in [0,1].

For case 1: $\tilde{x}_{i,j} = \dfrac{x_{i,j}}{x_{i,n_i}},\ j = 0,1,2,\ldots,n_i$,

$\tilde{X}_i$ *takes values* $\tilde{x}_{i,j} \in \tilde{A}_i = \{0 = \tilde{x}_{i,0}, \tilde{x}_{i,1}, \tilde{x}_{i,2}, \ldots, \tilde{x}_{i,n_i} = 1\}$

For case 2: $\tilde{x}_i = \dfrac{x_i}{\kappa_i}$, $\tilde{X}_i$ *takes values* $\tilde{x}_i \in [0,1]$

The characterization is now transformed to:

$\tilde{X} = (\tilde{X}_1, \tilde{X}_2, \tilde{X}_3, \ldots, \tilde{X}_n)$

The interoperability function of the two systems s', s'' with characterization $\tilde{X}' = (\tilde{X}_1', \tilde{X}_2', \tilde{X}_3', ..., \tilde{X}_n')$ and $\tilde{X}'' = (\tilde{X}_1'', \tilde{X}_2'', \tilde{X}_3'', ..., \tilde{X}_n'')$ respectively, can be calculated by multiplying the normalized average of the characters by the Minkowski Similarity:

$$I = \left[\frac{\sum_{i=1}^{n} \left(\tilde{x}_i' + \tilde{x}_i'' \right)}{2 \cdot n} \right] \cdot \left[1 - \left[\frac{\sum_{i=1}^{n} \left| \tilde{x}_i' - \tilde{x}_i'' \right|^r}{n} \right]^{\frac{1}{r}} \right] \quad (4)$$

The above similarity measure can now be extended for stochastic characters adapting the Wasserstein metric from Gibbs and Su (2002). The distance for an individual character $\tilde{X}_i$ between two systems can be generalized as following:

$$D(\tilde{X}_i', \tilde{X}_i'') = \begin{cases} \left| \tilde{x}_i' - \tilde{x}_i'' \right| & \text{, deterministic} \\ \sum_{j=0}^{n_i - 1} \left| F_{\tilde{X}_i'}(\tilde{x}_{i,j}) - F_{\tilde{X}_i''}(\tilde{x}_{i,j}) \right| \cdot \frac{1}{\left(\tilde{x}_{i,j+1} - \tilde{x}_{i,j} \right)} & \text{, stochastic (discrete)} \\ \int_0^1 \left| F_{\tilde{X}_i'}(x) - F_{\tilde{X}_i''}(x) \right| dx & \text{, stochastic (continuous)} \end{cases} \quad (5)$$

where $F_{\tilde{X}_i'}(x)$ and $F_{\tilde{X}_i''}(x)$ are the cumulative distributions *of* $\tilde{X}_i'$ and $\tilde{X}_i''$ respectively. Consider D is the area between the two cumulative distributions $F_{\tilde{X}_i'}(x)$ *and* $F_{\tilde{X}_i''}(x)$ plotting them in the same graph. Note that for the deterministic case, all probability mass is on a value $\tilde{x} \in [0,1]$, $P(\tilde{X}_i = \tilde{x}) = 1$.

Interoperability between two systems s' and s'' with characterization $\tilde{X}' = \left(\tilde{X}_1', \tilde{X}_2', ..., \tilde{X}_n' \right)$ and $\tilde{X}'' = \left(\tilde{X}_1'', \tilde{X}_2'', ..., \tilde{X}_n'' \right)$ can now be measured by:

$$I = \left[\frac{\sum_{i=1}^{n} E\left(\tilde{X}_i' + \tilde{X}_i''\right)}{2 \cdot n} \right] \cdot \left[1 - \left[\frac{\sum_{i=1}^{n} \left(D(\tilde{X}_i', \tilde{X}_i'') \right)^r}{n} \right]^{\frac{1}{r}} \right] \tag{6}$$

where,

$$E\left(\tilde{X}_i\right) = \begin{cases} \tilde{x}_i \\ \sum_{j=0}^{n_i} \tilde{x}_{i,j} \cdot f_{\tilde{X}_i}(\tilde{x}_{i,j}) \\ \int_0^1 x \cdot f_{\tilde{X}_i}(x) dx \end{cases} \tag{7}$$

Consider E being the expected value and f the probability density function (pdf) of the character. In this paper we do not address the interoperability of a system with itself, and therefore define $I(s', s') = 0$.

4.5 Supply Chain Interoperability Measurement

Many researchers (Cooper et al., 1997; Mentzer et al., 2001; Croxton et al., 2001; Chen and Paulraj, 2004; Min and Mentzer, 2004; Giannakis and Croom, 2004) have offered frameworks to analyze the structure of the supply chain and have also identified candidate natural characters of the participating firms. Interestingly, there is wide agreement among the referenced supply chain management frameworks and their characters that drive interoperability. The research framework developed by Chen and Paulraj (2004) provides a natural basis for a supply chain system’s interoperability characters. The framework depicted in Figure 4.2 identifies ten unique elements of the supply chain, namely:

- Environmental Uncertainty
- Customer Focus

- Top Management Support
- Competitive Priorities
- Information Technology
- Supply Network Structure
- Buyer-Supplier Relationships
- Logistics Integration
- Supplier Performance
- Buyer Performance

In order to quantify the character states, supply chain managers can use the instrument questionnaire used by Chen and Paulraj, part of which (Information Technology) is depicted for demonstration purposes, in Figure 4.3.

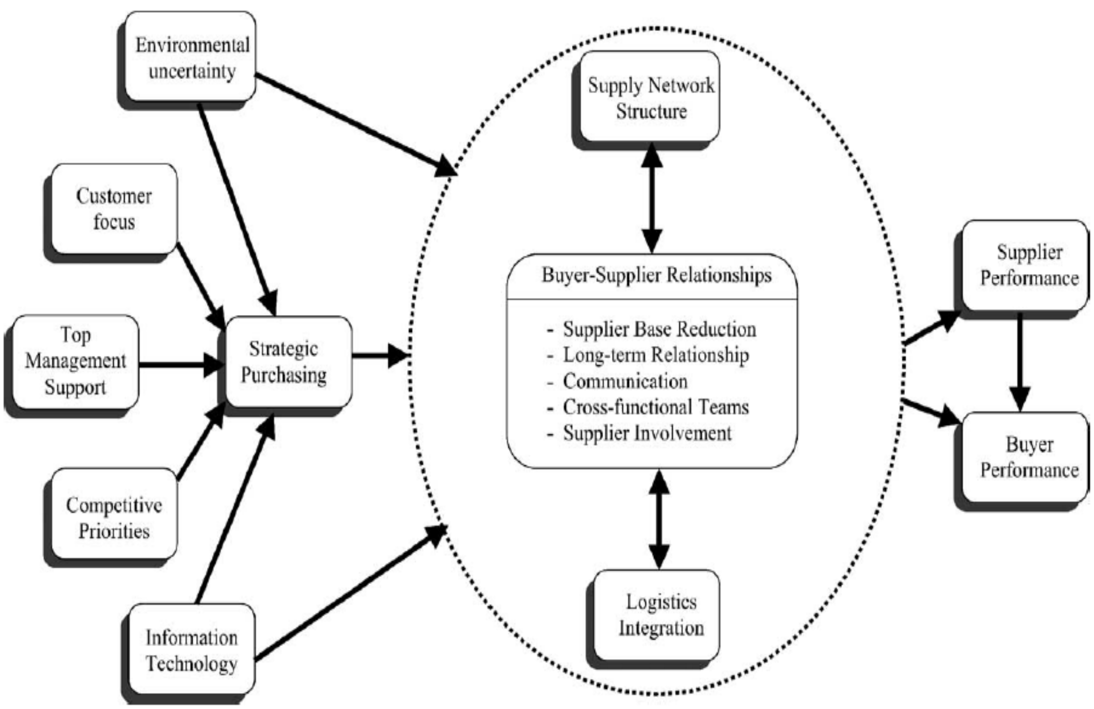


Figure 4.2: Framework of of Supply Chain Management (Chen and Paulraj, 2004)

Information Technology	✓ There are direct computer-to-computer links with key suppliers. ✓ Interorganizational coordination is achieved using electronic links. ✓ We use information technology-enabled transaction processing. ✓ We have electronic mailing capabilities with key suppliers ✓ We use electronic transfer of purchase orders, invoices and/or funds. ✓ We use advanced information systems to track and/or expedite shipments

Figure 4.3: Sample questions for the quantification of Information Technology of a firm (Chen and Paulraj, 2004).

4.5.1 An Illustrative Example of Supply Chain Interoperability Measurement

Consider the simple three-element supply chain shown in Figure 4. The arrows represent possible directions of information or product flow between each element. Each element in this

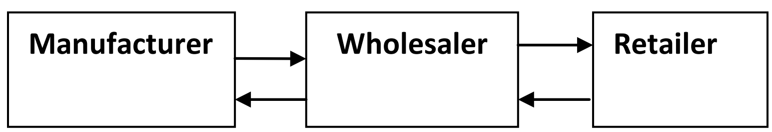


Figure 4.4: Example Supply Chain

supply chain constitutes a separate system. In order to measure interoperability in this supply chain, we use the three example interoperability characters shown in Table 4.4, namely Environmental Uncertainty (EU) (a stochastic character that follows a triangular distribution for each company), Information Technology (IT) (a deterministic leveling character with a single value from 0 to 4 for each company) and the Buyer-Supplier Relationship (BSR) (a stochastic character with values from 0 to 4 with certain probability for each company).

From the data of Figure 4.4 and Table 4.4, one can identify the systems *S = {Manufacturer (M), Wholesaler (W), Retailer (R)}* and the interoperability characters and character states as:

*X = {*Information Technology *(P_{IT})*, Buyer-Supplier Relationship (P_{BSR}), Environmental Uncertainty *(P_{EU})}*

Table 4.4: Supply chain interoperability characterization example

Environmental Uncertainty (EU), X_1 stochastic, continuous
X_1~Triangular (min, max, mode)

Information Technology (IT), X_2 deterministic, discrete		
Medium	**Frequency**	**Level X_2**
seamless	real-time	4
electronic, with translation	daily	3
electronic, with human intervention	weekly	2
paper	monthly	1
none	never	0

Buyer-Supplier Relationship (BSR), X_3 stochastic, discrete	
% Probability for:	**Level X_3**
full integration & trust	4
long term sharing of tactical & strategic goals	3
moderate sharing of tactical & strategic goals	2
tactical-level sharing, short term	1
no trust – "arm's length" relation	0

Next we examine two sample scenarios. Table 4.5.a represents a low-integration supply chain. The second scenario, shown in Table 4.5.b, depicts a more highly integrated supply chain where the members possess similar character values. For illustrative purposes and brevity, detailed interoperability computations are shown only between the Wholesaler and the Retailer in the low-integration scenario.

Table 4.5.a: Low integration

	Manufacturer	**Wholesaler**	**Retailer**
P_{IT}	2	1	3
P_{BSR}	(0.4, 0.3, 0.2, 0.1, 0)	(0.05, 0.35, 0.5, 0.1, 0)	(0, 0.2, 0.3, 0.3, 0.2)
P_{EU}	Triangular (0.1,0.4, 0.25)	Triangular(0.7,0.9, 0.8)	Triangular (0.5,1, 0.75)

Table 4.5.b: Significant integration

	Manufacturer	**Wholesaler**	**Retailer**
P_{IT}	4	3	4
P_{BSR}	(0, 0, 0.1, 0.35, 0.55)	(0, 0, 0, 0.4, 0.6)	(0, 0, 0.1, 0.3, 0.6)
P_{EU}	Triangular (0.9,1, 0.95)	Triangular (0.7,0.8, 0.75)	Triangular (0.8,1, 0.9)

Concerning the deterministic character of Information Technology (P_{IT}) states:

P_{IT} characterizes how, and to what extent, an inter-organizational relationship uses shared IT technology in a scale from 0 (absence of IT) to 4 (state of the art applied). In the low integration scenario, the Wholesaler is ranked 1, so $\tilde{X}_1' = \tilde{X}_1^W = \frac{1}{4}$ and the Retailer is ranked 3 so $\tilde{X}_1'' = \tilde{X}_1^R = \frac{3}{4}$. Consider this ranking as the distribution function $F(\tilde{X}_1)$. Then,

$D\left(\tilde{X}_1', \tilde{X}''\right) = \left|\tilde{X}_1^R - \tilde{X}_1^W\right| = 3/4 - 1/4 = 0.5$ that corresponds to the area between

$F\left(\tilde{X}_1^R\right)$ and $F\left(\tilde{X}_1^W\right)$, shown in Figure 4.5, where:

$F^W(x) = \begin{cases} 0 & , if \ x < 0.25 \\ 1 & , if \ x \geq 0.25 \end{cases}$ and $F^R(x) = \begin{cases} 0 & , if \ x < 0.75 \\ 1 & , if \ x \geq 0.75 \end{cases}$.

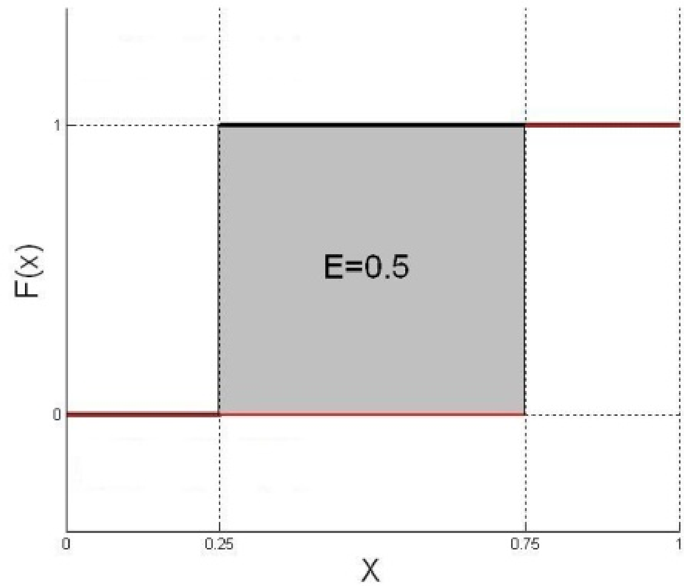


Figure 4.5: Difference in Cumulative Distributions, $F^{W}\left(\tilde{X}_1\right)$ and $F^{R}\left(\tilde{X}_1\right)$

Concerning stochastic-discrete character states of Buyer-Supplier Relationship (P_{BSR}):

Assume that from historical data for the wholesaler, it uses level 0 transactions in 5% of its relationships, level 1 transactions in 35%, level 2 in 50%, level 3 in 10%, and is fully integrated with 0% of its customers or suppliers. We are then able to define the Buyer-Supplier Relationship character $\tilde{X}_2^{'} = \tilde{X}_2^{W} = \left(0, \frac{1}{4}, \frac{2}{4}, \frac{3}{4}, \frac{4}{4}\right) = (0,\ 0.25,\ 0.5,\ 0.75,\ 1)$ where,

$\tilde{X}_2^{W} = 0$ corresponds to an "arms-length relationship" in 5%: $P(\tilde{X}_2^{W} = 0) = f(\tilde{X}_2^{W} = 0) = 0.05$,

$\tilde{X}_2^{W} = 0.25$ corresponds to "tactical-level sharing, short term" in 35% and so

$P(\tilde{X}_2^{W} = 0.25) = f(\tilde{X}_2^{W} = 0.25) = 0.35$,

$\tilde{X}_2^{W} = 0.5$ corresponds to "moderate sharing of tactical and strategic goals" in 50% and

$P(\tilde{X}_2^{W} = 0.5) = f(\tilde{X}_2^{W} = 0.5) = 0.50$,

$\tilde{X}_2^W = 0.75$ corresponds to "long term sharing of tactical and strategic goals" in 10% and

$P(\tilde{X}_2^W = 0.75) = f(\tilde{X}_2^W = 0.75) = 0.10$,

$\tilde{X}_2^W = 1$ corresponds to "full integration and trust" in 0% and $P(\tilde{X}_2^W = 1) = f(\tilde{X}_2^W = 1) = 0$. The $\tilde{X}_2^W$ probability density and cumulative distribution are shown in Figure 4.6.

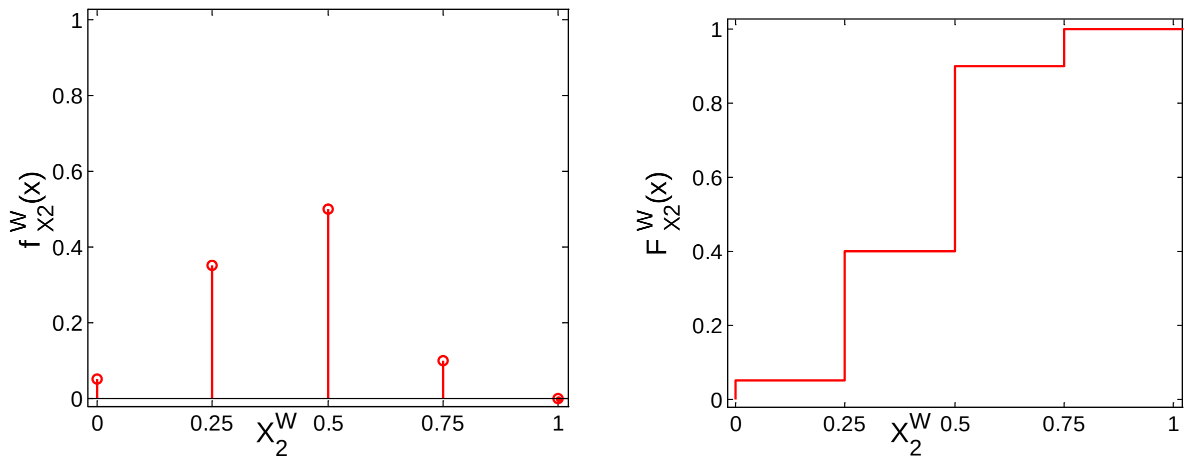


Figure 4.6: Distributions of $f^W\left(\tilde{X}_2\right)$ and $F^W\left(\tilde{X}_2\right)$

Similarly, for the Retailer, we assume the following, $\tilde{X}_2'' = \tilde{X}_2^R = (0,\ 0.25,\ 0.5,\ 0.75,\ 1)$ shown in Figure 4.7.

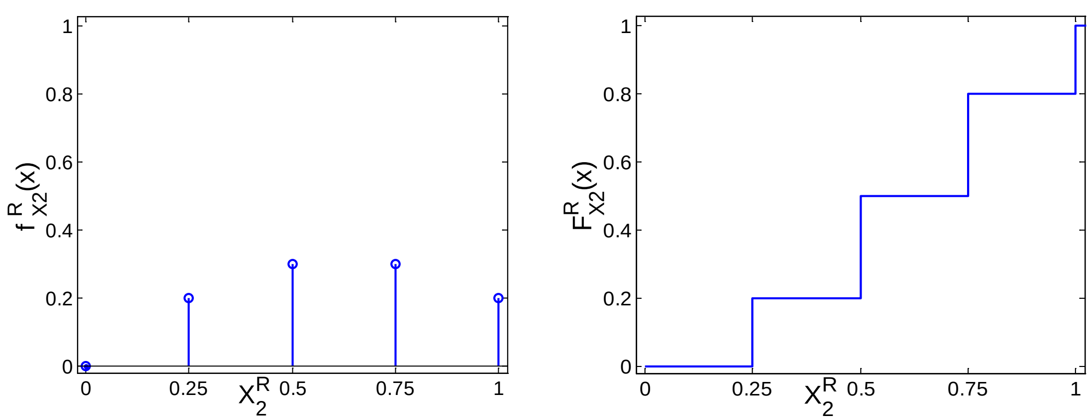


Figure 4.7: Distributions of $f^R\left(\tilde{X}_2\right)$ and $F^R\left(\tilde{X}_2\right)$

We next compute $D\left(\tilde{X}_i', \tilde{X}_i''\right) = \sum_{j=0}^{n_i-1}\left|F_{\tilde{X}_i'}(\tilde{x}_{i,j}) - F_{\tilde{X}_i''}(\tilde{x}_{i,j})\right| \cdot \frac{1}{\left(\tilde{x}_{i,j+1} - \tilde{x}_{i,j}\right)} = 0.2125$, which

corresponds to the area between $F\left(\tilde{X}_2^R\right)$ and $F\left(\tilde{X}_2^W\right)$, shown in Figure 4.8.

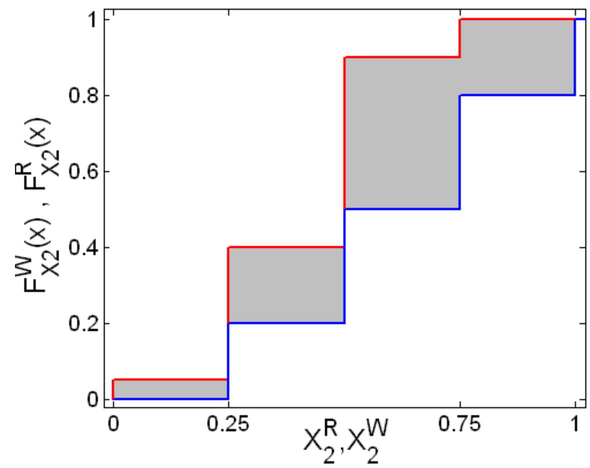


Figure 4.8: Difference in Cumulative Distributions, $F^W\left(\tilde{X}_2\right)$ and $F^R\left(\tilde{X}_2\right)$

Concerning stochastic-continuous character states of Environmental Uncertainty (P_{EU}):

Environmental uncertainty in the example framework is considered in the forms of supply, demand and technology. Supply uncertainty arises from quality, timeliness and the inspection requirement issues related to suppliers. Demand uncertainty is about fluctuations and variations in customer demand. Technological uncertainty addresses technological changes evident within the industry.

Environmental uncertainty is a dimensionless [0,1] number where 0 represents no uncertainty and a 1 represents extreme uncertainty. For the Wholesaler, the Environmental Uncertainty character is assumed without loss of generality to follow a symmetric triangular distribution over [0.7, 0.9, 0.8]. The distributions for $\tilde{X}_3^W$ are shown in Figure 4.9.

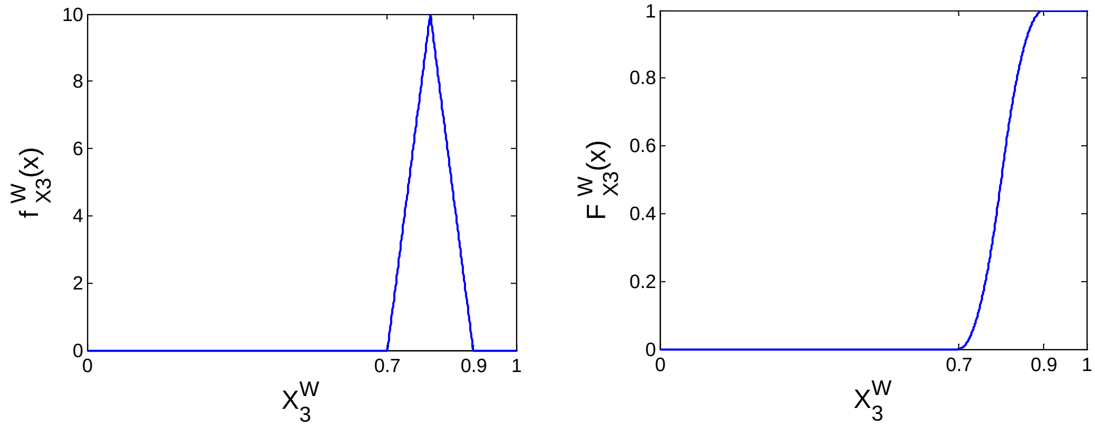


Figure 4.9: Distributions for $f^W\left(\tilde{X}_3\right)$ and $F^W\left(\tilde{X}_3\right)$

Similarly, for the Retailer's Environmental Uncertainty, $\tilde{X}_3^R$, we assume, for this example, a symmetric triangular distribution over [0.5, 1.0, 0.75] as shown in figure 4.10.

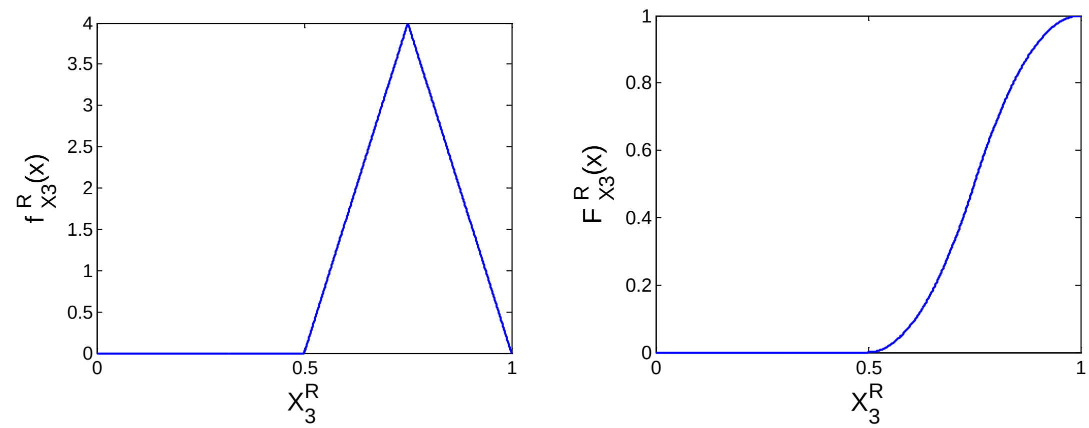


Figure 4.10: Distributions for $f^R\left(\tilde{X}_3\right)$ and $F^R\left(\tilde{X}_3\right)$

Now we calculate $D\left(\tilde{X}_i', \tilde{X}_i''\right) = \int_0^1 \left| F_{\tilde{X}_i'}(x) - F_{\tilde{X}_i''}(x) \right| dx = 0.0648$, which corresponds to the area between the distribution functions of $\tilde{X}_3^W$ and $\tilde{X}_3^R$ as shown in figure 4.11.

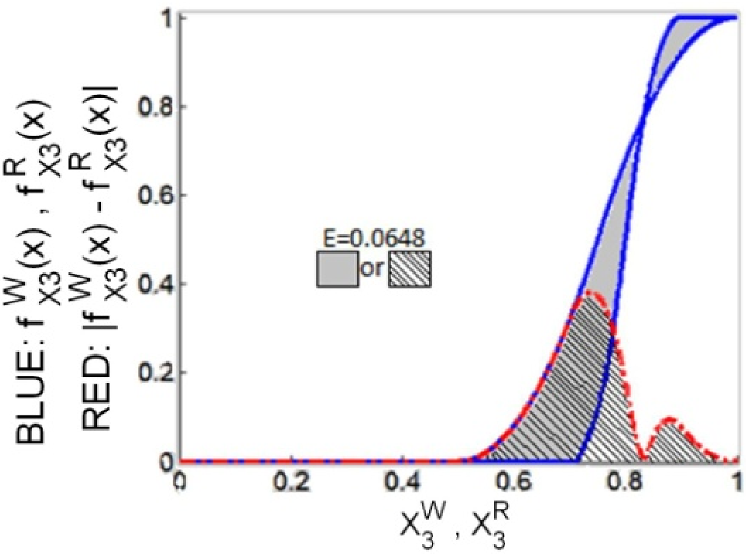


Figure 4.11: Difference in Cumulative Distributions $F^{W}\left(\tilde{X}_3\right)$ and $F^{R}\left(\tilde{X}_3\right)$

The interoperability between the Wholesaler and the Retailer is $I(s_R, s_M)=0.43$, on a scale between 0 and 1.

Using the interoperability function (set r=2) the following supply chain interoperability measurement matrix, M_{low} *and* M_{high}, results for each of the two respective scenarios (low and high/significant integration). Note, for managerial purposes, that the "weak" links of the supply chain can be easily identified by comparing interoperability measurements.

$$M_{low} = \begin{array}{c|ccc|} & M & W & R \\ M & 0 & 0.2907 & 0.3413 \\ W & 0.2907 & 0 & 0.4310 \\ R & 0.3413 & 0.4310 & 0 \end{array} \qquad M_{high} = \begin{array}{c|ccc|} & M & W & R \\ M & 0 & 0.7135 & 0.9120 \\ W & 0.7135 & 0 & 0.7230 \\ R & 0.9120 & 0.7230 & 0 \end{array}$$

The low integration scenario provides an example where the supply chain's interoperability is inversely proportional to distance from the retailer. This is a common scenario in many supply chains since the information systems of those participants closer to the customer are more capable than those that are further upstream in the supply chain. Limited or nonexistent information sharing about inventory or forecasted demand leads to shortages and inefficient inventory levels. Conversely, the significant integration scenario shows a much stronger interoperability relationship between the Wholesaler and Retailer. The Manufacturer-Wholesaler relationship is also improved but to a lesser extent because the Manufacturer has not, by itself, significantly improved its information sharing capacity or business trust with external firms.

Due to space limitations, we illustrated only three supply chain characters. This method of measuring supply chain interoperability can go much further- for example Min and Mentzer (2004) developed a supply chain measurement framework that identified seven first-order factors incorporating up to thirty indicators. Using the SCOR model, many additional pertinent characters can be identified, within the areas of Plan, Source, Make, Deliver, and Return. For example, the SCOR *plan* process can be decomposed into inventory visibility, pricing & promotion, production schedules assessment and product packaging. Each SCOR process character can further be decomposed into directional measures that separately assess a firm's ability to provide or receive products, information/data and/or services.

Finally, it would be useful to have a single number that measures an entire supply chain's overall interoperability. Rank or priorities can be used, which can be converted to weights. Consider the following Rank Matrix of participant interactions:

$$R = \begin{bmatrix} & Manuf. & Wholesale & Retailer \\ Manuf. & 0 & 2 & 1 \\ Wholesale & 3 & 0 & 4 \\ Retailer & 3 & 2 & 0 \end{bmatrix}$$

The supply chain manager or decision maker may value and rank objectives differently throughout the chain. The diagonal values are zero to reflect non-applicability of "self-interoperability." For example, the Rank Matrix above reflects a priority (rank = 1) on the Manufacturer to Retailer interface, and the least priority (rank = 4) to the Wholesaler to Retailer relationship. This method also accommodates directionality of interoperability values, identified by Ford et al. (2009), thus the matrix need not be symmetric.

To maintain a unity scale, the Rank Matrix is transformed to weights. A variety of weighting methods can be used (Buede, 2000). We chose the rank reciprocal approach. Each weight element is calculated from the reciprocal of the corresponding rank element, scaled by the sum of the reciprocals across the entire Rank Matrix.

$$W_{\text{RRScaled}} = \left[w_{i,j} \right] = \left(\frac{\frac{1}{r_{i,j}}}{\sum_{k=1}^{N} \sum_{l=1}^{N} \frac{1}{r_{k,l}}} \right), \forall i = 1..N, \forall j = 1..N, i \neq j$$

Applying the Weighting Matrix to the Interoperability Matrix, *M*, for the low integration scenario results in the overall weighted assessment of the supply chain. While in this case the Interoperability Matrix was symmetric, the Weighting Matrix (based on ranks) is not. Thus, all off-diagonal elements must be used in this calculation. The operator $\oplus$ is defined as the summation of the weighted element products. For the characters of interest, this provides an overall measurement of interoperability.

$$\begin{aligned} I_{Weighted} &= W_{\text{RRScaled}} \oplus M_{\text{low}} \\ &= \frac{1}{N(N-1)} \begin{bmatrix} 0 & 0.1714 & 0.3429 \\ 0.1143 & 0 & 0.0857 \\ .1143 & 0.1714 & 0 \end{bmatrix} \oplus \begin{bmatrix} 0 & 0.2907 & 0.3413 \\ 0.2907 & 0 & 0.4310 \\ 0.3413 & 0.4310 & 0 \end{bmatrix} = 0.3499 \end{aligned}$$

It is intent that this aggregated measure be used in a relative sense, to compare options, process improvements, or infrastructure/IT enhancements. Also it is noted that the characters' relative numeric values and their value patterns over time are of more use to managers than their precise values are. Used collectively, the character measurements can clarify the extent to which the entire supply chain is consistently interoperable. Furthermore, they can identify specific opportunities for inter-organizational management attention or investment as part of an effort to effectively and efficiently manage value co-creation across the supply chain.

4.6 Summary, Implications and Future research

A novel supply chain interoperability measure is proposed. Extant methods have captured a variety of frameworks (both qualitative and quantitative) within the logistics, management, operations research and systems engineering communities. This research paper describes the supply chain's participants through a series of characters then applies a similarity measure. While real valued discrete leveling methods have been reported, this paper introduces a mixed-characterization of participants. This extends deterministic valued character states (both discrete and continuous) to include stochastic relationships. Basing the stochastic descriptions on empirical data can capture the likelihood of interoperability-related challenges. Lastly, a weighting scheme can be applied to the interoperability measurement matrix for an overall supply chain assessment.

Various calls are answered for a means of assigning values to the various levels of collaboration among participating firms (Barratt, 2004; Mentzer et al., 2000). The definition of supply chain interoperability is original in the supply chain management literature.

For managers, the paper offers a strategic and holistic method to evaluate their respective firm's progress toward successful supply chain management implementation. Results may be used for the reengineering of the company or a supply chain audit across participating firms. The overall goal of measuring supply chain interoperability is to better understand how changes can be made to improve supply chain interoperability. In such an effort the careful selection of the supply chain constructs used for the characterization of the companies is crucial. The literature offers a plethora of suitable frameworks. For example Min and Mentzer (2004) developed a framework and confirmed that certain constructs of SCM and Supply Chain Orientation (SCO) lead to improved business performance of individual firms within the supply chain. However it may not be possible, financially profitable or even desirable for all supply chain members to interoperate perfectly.

Supply chain interoperability measurement should be reflected and related to the "value" of interoperability for the company. The work of Lebreton (2007) on the operational and strategic impacts of enterprise interoperability might be considered. Naturally, the relationship between supply chain interoperability and performance should be validated. Lastly, with a SCM assessment method created, there exists a need to study the upper bound of supply chain interoperability in terms of performance and cost-benefit.

The next step in this process would be to further develop and refine the characters that should be included in the supply chain interoperability measurement model. The directionality of supply chain interoperability discussed here, could be further refined to include directionality of characters, as well as the concepts of confrontational interoperability and competitive interoperability. The creation and definition, in the supply chain context, of the interoperability upper bound would be also useful. The possible difference between the upper bound and the current interoperability measurement would define an interoperability gap, which represents the trade space in which changes can occur on interoperability characters, to improve supply chain performance. Following the further refinement of the interoperability measurement method, empirical data should be utilized to test, validate, and further refine the measurement approach.

V. Supply Chain Interoperability Characters Identification

5.1 Introduction

In order to focus improvements across a supply chain, performance measurement must be considered. Academia recognizes that inadequate supply chain performance measurement systems are still a major barrier. These measurement systems seem overly complicated and difficult to use in practice (Banomyong and Supatn, 2011) or require the development of complex information systems (Papakiriakopoulos and Pramatari, 2010). Lambert and Pohlen (2001) argued that no meaningful performance measures exist that span the entire supply chain and attributed the causes of this to managerial (absence of supply chain orientation and unwillingness to share information) or practical (complexity) factors. Systems architecture and the use of architectural frameworks should help, by providing a variety of insightful views into any complex system. Such views can focus on organization, behavior/ process, information/ data, physical/ interface, or technology/ standards. Maier and Rechtin (2000) state that *"the greatest leverage in system architecting is at the interface… the greatest dangers are also at the interface."* The main limitation of existing supply chain measures is their focus on the companies and not necessarily the characteristics of the interface itself. Chalyvidis, Ogden and Johnson (2013) argued that planning or building successful supply chains is the equivalent to architecting a system-of-systems (SoS) and strengthening the interfaces across the SoS. In their perspective, the supply chain manager is considered an “architect” of the supply chain who is able to predominantly influence interfaces between independent firms. They proposed supply chain interoperability as a performance indicator for the assessment of the efficiency and effectiveness of supply chains, under the following definition:

> *Supply chain interoperability is the ability of cooperating business entities to provide services to each other, as well as to their users and customers, by defining synchronization of goods, services and information to coordinate their business processes, and align their business goals towards optimality of the chain, without losing individual sense of purpose and idiosyncratic capabilities.*

Supply Chain Interoperability should consider the multidimensional nature of the technical communications, the shared functions and behavior of participants, and the organizational and cultural aspects across the chain. The above definition implies different levels of supply chain interoperability between companies. As Gasser and Palfrey (2007) concluded, interoperability has several meanings according to the content and is not *"good for everyone all the time."* Thus supply chain management has a need for interoperability measurement across the context of company interactions.

Measurement is the objective representation of our empirical knowledge of the world by numbers (Finkelstein and Leaning, 1984). By considering interoperability as a property of a supply chain, an operation called *interoperability measurement* can be defined, which objectively and empirically quantifies supply chain interoperability. According to Ford, Ogden and Johnson, (2010) each supply chain member or member relationship can be modeled by a set of characters or attributes, representing characteristics describing important features for the chain.

The supply chain management discipline offers various frameworks and constructs to assist in the identification of suitable interoperability characters (Cooper et al 1997; Mentzer et al 2001, 2004; Croxton et al 2001; Chen and Paulraj 2004; Giannakis and Croom 2004). Additionally, the systems engineering community has examined system of systems (SoS) characteristics (Boardman and Saucer, 2006) which could also be incorporated into the characters selection procedure. Interestingly, there is wide agreement between several supply chain management frameworks and various works on system interoperability (Chen, 2003; Chen, Doumeingts and Vernadat, 2008; Ralyte et al., 2008; Panetto and Whitman, 2006; Kasunic and Anderson, 2004).

The following two research questions are addressed.

1) How can firms use supply chain interoperability measurement?

2) How can supply chain interoperability characters be developed for use in the measurement?

The research uses a cross-functional, qualitative methodology to demonstrate the feasibility of supply chain interoperability measurement introduced by Chalyvidis, Ogden and Johnson (2014), investigates a complex set of potential supply chain interoperability constructs, and captures the managers' perspectives on interoperability measurement.

The scope of the research is limited to supply chain interoperability within a particular large defense industry firm. The focus was narrowed for two reasons. First, the paper does not intend to propose an all-inclusive character set for all supply chains. Feedback is collected from a specific company on the proposed method recommending a selection of characters (criteria) that should be included in the interoperability measurement. Secondly, Griffis et al. (2004) reviewed the literature on the recommended qualities and frameworks of logistics and supply chain performance measures. They identified that these qualities, being broad and general, are applicable to all measurement systems and firms must choose according their mission, their goals and their environment. So by narrowing on the defense industry sector, we can offer value to the relevant practitioners.

This research affirms the thoughts of Bell et al. (2006) that unless managers can easily relate research findings to the specific situation at hand, it becomes difficult for them to apply available knowledge. Academic management knowledge becomes relevant to practitioners when it informs and supports their decision-making (Starkey and Madan, 2001). Here the research findings are practically applicable by

(1) Capturing topics relevant to practitioners,

(2) Addressing outcomes that are pertinent to practitioners,

(3) Incorporating what guide managers to intervene,

(4) Providing counter-intuitive insights,

(5) Being available to practitioners when required.

The remainder of the paper is organized as follows. Section 5.2 describes the interview methodology that was utilized with a large Defense supplier located in Greece. Section 5.3 identifies the 17 types of characters that managers considered important to a supply chain assessment. An illustrative example is provided in Section 5.4 using a few different types of characters and their relevant similarity metrics. The derivation of these mixed-character interoperability measurement methods is provided in Chapter 4. The conclusions and recommended next steps are discussed in Section 5.5.

5.2 Methodology

Ideally, the development of a supply chain interoperability measurement tool in a specific industry sector should sample all supply chains in the sector and identify all suitable characters (Chalyvidis, Ogden and Johnson, 2013). In order to identify a set of initial supply chain interoperability characters, managers from various functional roles at a single Defense company in Greece were interviewed. A semi-structured interview tool on the above supply chain interoperability definition and measurement was used to obtain perspectives of these practitioners and to reveal supply chain interoperability characters. This interview method introduces more “richness” of data than a questionnaire survey or a structured interview (DiCicco-Bloom and Crabtree, 2006).

While some research is designed to test *a priori* hypotheses using a structured interviewing format in which the questions are standardized, our research sought to explore meaning and perceptions to gain a better understanding (DiCicco-Bloom and Crabtree, 2006). The used type of inductive research generally requires some form of qualitative interviewing which encourages the interviewee to share rich descriptions of phenomena while leaving the interpretation or analysis to the investigators. The purpose of the qualitative research interview is to contribute to a body of knowledge that is conceptual and theoretical and is based on the experiences and perspectives of the interviewees (Flick et al., 2004).

Semi-structured interviews were selected as the means of data collection because they are well suited for the exploration of the perceptions and opinions of respondents regarding complex issues (Barriball, 1994) and enable probing for more information and clarification of answers. Also the varied professional and educational background of the sample group precluded the use of a standardized interview schedule. Effort was made for the meaning and sequence of all the questions to be exactly the same for each respondent to be sure that any differences in the answers are due to differences among the respondents rather than in the questions asked (Gordon, 1975, cited in Barriball, 1994). So validity and reliability achieved by keeping the same meaning in each question rather than the repeated use of the same words (Denzin, 1989 cited in Barriball, 1994 and Turner, 2010).

The interviews were organized around a set of predetermined questions. Initially the development of the questions was based on the interoperability measurement proposed by Chalyvidis, Ogden and Johnson (2013). The authors used this set of questions to initiate the interviews. Qualitative data analysis occurred concurrently with data collection. The emerging understanding about research questions was used to inform both the sampling and augment the questions being asked. The set of interview questions was continuously updated to include any unconsidered aspects of interoperability raised during previous interviews. When other questions emerged, as anticipated from the dialogue between the interviewee and the interviewer, they were included in subsequent interviews to ensure a consistent approach across the research thus to establish qualitative reliability (Gibbs, 2007). A list of the questions used is provided in Appendix 5.A. Follow-up interviews were held where needed to discuss new questions raised by other interviewees and to maintain consistency. In addition, follow-up interviews with the heads of departments were held to provide them the opportunity to comment on and help validate the findings. The interviews began with a brief informative discussion on the various frameworks and supply chain constructs developed in the literature, and a presentation on supply chain interoperability measurement.

The company includes a workforce of over 2000 employees, with very specialized capabilities and knowledge in defense and aerospace manufacturing. It has significant research and development (R&D) activities for new products, both independently and in collaboration with national and international establishments.

Over 80 employees with post-graduate academic degrees, holding various positions in all the departments of the company, were interviewed. A majority of employees had been employed by the company for more than ten years (Table 5.1, and Figures 5.1 and 5.2) and has participated in research interviews in the past. Interviewees were considered being “upper management” if they were the head of an office.

Table 5.1: Interviewees by Department

Directorate	Department	Number Interviewed
General Finance	Supply Chain	10
	Accounting	5
	Cost Management	8
	Organization and Planning	5
	Information Technology (IT)	5
General Plan Operations	Maintenance	3
	Engines Maintenance	3
	Electronics Maintenance	3
	Installation Maintenance	3
	Construction	3
	R&D	2
General Marketing	Marketing Sales	5
	Marketing Sales - Abroad	4
	Training Marketing Support	2
	Investments	1
	Contracting and Projects	2
	Environment	3
General Support	Human Resources (HR)	5
	Training	5
	Public Relations	2
	Quality	2
	Innovation	2
Total		83

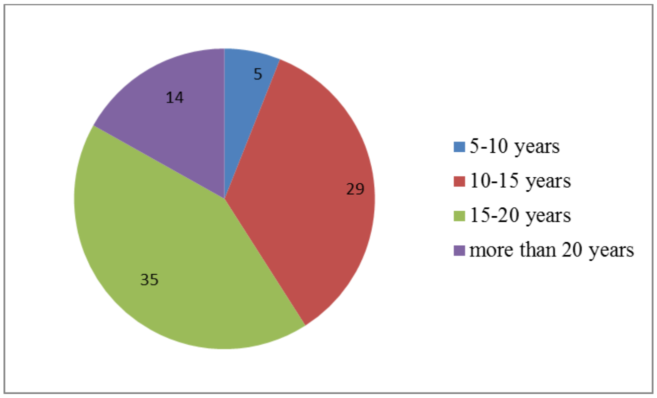


Figure 5.1: Demographics- Number of years in the company

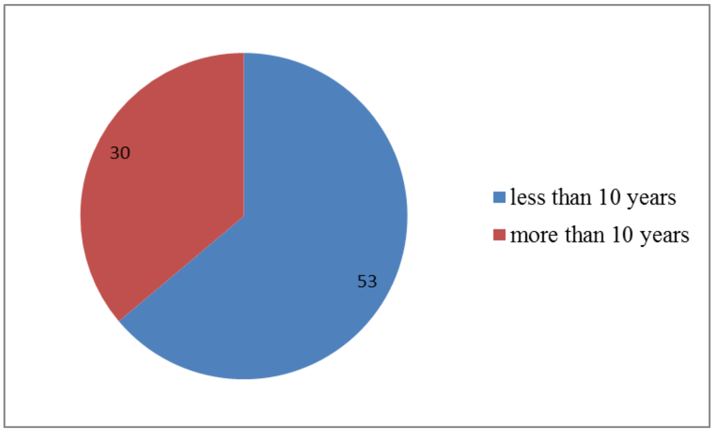


Figure 5.2: Demographics- Number of years of experience in the current department

The company agreed to let researchers conduct the interviews, with initial contact made through the human resources (HR) department. All interviews were conducted in-person, which began with the Supply Chain Department under the General Finance Directorate. Then, in order to facilitate the emergence of new questions/themes, subsequent interviewees were from departments closely related to the logistics of the company and the other departments were gradually accessed following data analysis requirements. This iterative process of data collection, followed by analysis eventually led to a saturation point, when no new themes emerged. Recurring words, concepts, and ideas were integrated into groups and characters as discussed in the next section.

5.3 Supply Chain Interoperability Characters

One of the main goals of this research was to investigate the varying perspectives of significant characters that should be included in the interoperability measurement of a specific supply chain. Interviewees identified these important characters from their specific Department's perspective and/or their experience. The seventeen characters identified are defined and discussed in the next sections. A mapping of the characters identified in each company department is presented in Table 5.2 and a characters overview in Table 5.3.

As it is considered useful a research to addressee outcomes relevant to practitioners and support their decision-making (Starkey and Madan, 2001), the character analysis also utilizes literature to validate the potential importance of the identified characters. Characters are discussed in terms of supply chain and firm performance and in relation with their positive or negative consequences on various aspects of business. Additionally and without losing generality, potential scales and measures of the recognized characters are listed (Table 5.3).

Note the overarching groups include Systems, Environment, Manpower, Production, Machinery, Customer, PEST, Materials, Reputation, Process and Finance. Interestingly characters identified by people of the Supply Chain Department are consistent with some supply chain constructs in the supply chain literature, such as the customer focus and IT systems in the framework of Chen and Paulraj (2004) and organizational culture in the work of Carter and Rogers (2008).

Table 5.2: Supply chain interoperability characters identified by each company department

Company department		IT systems and infrastructure	Business process structure	Environmental impact	Human resources ability	Subcontractors on site	Government regulations impact	Effectiveness of communication	Supply chain business culture	Human Resources practices	Innovation	Quality	Equipment	Customer service	Macro-environmental factors	Reputation	Process effectiveness	Effective finance
Directorate General Marketing Sales	Marketing-Sales							X	X					X		X		X
	Marketing-Sales abroad							X	X					X		X		X
	Training-Marketing Support				X													
	Investments							X			X		X					
	Contracting and Projects					X		X						X		X		X
	Environment			X									X			X	X	
Directorate General Plants (Operations)	Systems Maintenance				X					X	X		X	X			X	
	Engines Maintenance				X					X	X		X	X				
	Electronics Maintenance				X					X	X			X				
	Constructions				X					X	X			X			X	
	R&D				X					X	X						X	
	Installations					X				X	X		X					
Directorate General Support	HR				X		X		X	X					X	X		
	Training-Marketing Support				X													
	Public Relations			X					X							X		
	Quality								X	X	X	X						
	Innovation								X		X							
Directorate General Finance	Accounting																	X
	Cost Management														X			X
	Organisation and planning		X															
	Supply chain					X		X	X	X	X	X		X	X			
	IT	X	X		X			X										

IT SYSTEMS AND INFRASTRUCTURE

Based on the comments from the interviewees, IT Systems refers to the systems implemented specifically for the purpose of managing some element of the supply chain, or to support supply chain management efforts. Throughout the interviews, respondents emphasized the importance of the investments in IT to be well targeted to achieve specific business objectives. Managers consider that the implementation of IT systems leads the company to make important changes in the business processes and increases training. Also, they recognize that IT system adoption (such as a new Enterprise Resource Planning (ERP) system) may cause changes which introduce a company to a cycle of modernizing the methods of doing business and improving its relationships with upstream and downstream partners through the improvement of inventory turnover, lead times, stock outs, and other logistics or customer service metrics. Furthermore, IT investments are evidence of change in a particular company. Blankey (2008) reported that these technologies have been identified by prior research as a critical element in firms' efforts to cut costs, reduce waste, and increase efficiency both internally and along their supply chains while often leading to improvements in communication, decision making, and coordination between supply chain member firms. His literature review revealed that investments in IT have been found to lead to greater systems integration, tighter supply chain integration, better information sharing capabilities, and increased domain knowledge. This character can be considered using a deterministic leveling scale from 0 to 4.

BUSINESS PROCESS STRUCTURE

An enterprise can be better integrated and improved through its business processes. Some interviewees expressed the utility of business process structure as an interoperability character by phrases like: "I expect that agreement on business process structure would facilitate efforts of cooperation". One "Functional" perspective (Maier and Rechtin, 2009) (i.e. what the system does) is applicable here and expressed like " I assume it would be easy to define what values for the customer from the company's point of view by examine the outputs of its business processes". In order to coordinate processes between firms, there are multiple factors challenging the performance of the chain. Different process technologies between a supplier (manufacturer processes) and the retailer (service processes and distribution), different working routines (shifts, holidays, shutdowns), different priorities between the firms and inadequacies in manufacturing planning are considered here. A deterministic character of the agreement on planning and executing material and information flow between firms can be used for this character.

ENVIRONMENTAL IMPACT

Interviewees discussed environmental matters recognizing a twofold importance: 1) as a risk in the form of the pollution liability of the firm and 2) as a factor of performance. Pollution liability has recently become a matter of increasing importance for firms. Companies are induced by various regulations, commonly used in Europe and US to control environmental pollution. The common regulations (emission standards, technology standards, economic instruments), that make polluters liable for the costs of the environmental damage they have already caused, were strengthened to provide the appropriate incentives to reduce the risk of environmental damage. Polluters tend to acquire limited financial liability to avoid paying large damages by becoming insolvent. A proposed solution is to extend environmental liability to lenders such as banks to create incentives to condition their loans on the efforts firms make to reduce the risk of environmental liabilities. This causes further distortions since it is impossible or expensive for banks to properly monitor environmental risks being run by firms, causing inefficiently low levels of environmental care being taken by polluters and also distortions to the capital structure of firms (Ulpf and Vallentiny, 2004). The same authors noted that "If only firms are held liable for environmental damages, and they have limited liability, then firms may take on too much bank debt to protect shareholders against environmental risks. On the other hand if banks are also held liable, then firms may take on too little bank debt if either banks impose significant charges to cover monitoring costs or banks use credit rationing in response to the asymmetry of information". They found that for the chemical industry, imposing environmental liabilities on firms would cause bank borrowing to rise by 15–20%.

There are concerns on the relationship between Environmental Management Practices (EMPs) and company performance. Chen, Tang and Feldmann (2014), studying companies in Sweden, China and India, found that green management efforts do not have a positive correlation with financial performance. This controversial finding could discourage innovative green management efforts and practices (Hall and Matos 2010, Wolf 2011). Many companies include various environmental issues in their strategy to correspond to the stakeholders' needs and competitive pressures (Hofer et al., 2012). Others (Yang et al., 2011) described that EMPs alone are negatively related to market and financial performances. Lee et al. (2009) argued that tighter environmental restrictions make Green Supply Chain Management (GSCM) activities, whether upstream with the suppliers or downstream with the customers, a challenge to manufacturers. Srivastava (2007) describes GSCM as the combination of environmental thinking and Supply Chain Management encompassing product design, material sourcing and selection, manufacturing processes, delivery of the final product to the consumer, and end-of-life management of the product. Tseng and Chiu (2010) argued that practicing GSCM requires identification of appropriate measures in order to complete a robust study and to advance the body of knowledge in a field, both academically and practically and identified several GSCM criteria.

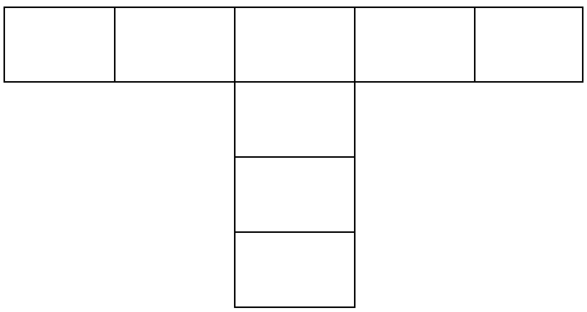
In the specific industrial sector of this research--characterized by high entry barriers and costs associated to the production processes--green practices have impacts in costs and resource requirements. The company is required to adopt instruments to check environmental aspects and to manage the interactions with the environment. Managers regularly require specific information to enable proper decision-making. A deterministic binary character of the presence or absence of Environmental Management Practices is considered suitable to capture both the two issues.

HUMAN RESOURCES ABILITY

According to one interviewee, the company "…put a premium on the quality of (our) personnel…" so there is constant need to check the skills and certification of personnel. Another interviewee stated, "supply chain interoperability would be useful to manage that (manpower) quality".

Kenny (2012) referred to many examples of effective Chief Executive Officers (CEOs) having to choose effective business-unit managers. Mangan and Christopher (2005) argued that supply chain managers not only need to be equipped with the skills and knowledge to manage logistics but also they must be relationship managers and reviewed the literature about the "critical role played by people, knowledge and talent in the context of supply chain success". They noted that in order for a process-focused management to become a reality, awareness of interfaces in the supply chain and of how actions taken in one area might affect the performance of the whole is needed. They noted a T-shaped skills profile for the supply chain manager, who brings specific logistics management skills to the job (Figure 5.3-the vertical bar) and also has a wide understanding of related areas such as business process engineering, asset management and activity-based costing (the horizontal bar). These skills also facilitate the internal functional alignment that Hoek et al. (2008) identified as critical for Supply Chain Management and the provision of customer service. Keller and Ozment (2009) reviewed the literature on the recruitment, development, supervising, and retention of logistics personnel. Among others they referred to the work of Murphy and Poist (1993) who mention training employees in multiple topics while stressing the basic requirements of the job. They also discussed Keller et al. (2006)

who empirically confirmed the components necessary for managers to create highly customer-focused logistics workforces, namely providing employees with opportunities to develop basic and advanced knowledge; efficient and effective information and a positive work environment. Also Ulrich (1995) offered an extensive list of measures on various domains of human resources activities including staffing, training, performance systems, safety/health, labor relationships, internal communication and diversity.



Managers need
in-depth expertise in one discipline
and
enough breadth to recognize
connection with others

Figure 5.3: Skill profile of Supply chain managers (adapted from Mangan and Christopher, 2005), requiring significant cross-functional skills

A stochastic character of the percentage of personnel that received training over the last number of years is used for interoperability assessment. Keller and Ozment's (2009) review on the skills and carrier preparation of logistics personnel can be utilized to further specify the subject of training to be considered in the measurement.

<u>SUBCONTRACTORS ON SITE</u>

The use of subcontractors and outsourcing is recognized as offering various economic, technological and strategic advantages for the firm. Wilding and Juriado (2004) discussed reasons why firms outsource. Hoffer et al (2009) recognized a change in the relationship between Third Party Logistics providers and the firms using their services, towards "partnerships" and studied the factors influencing the firms' partnering behavior. Other research focuses on outsourcing risks (Padovani and Young 2006, Liu and Nagourney 2010, Olson and Wu 2011).

Our interviewees identified this by saying "… subcontractors' manpower in our facilities hides risks". The particular character is considered stochastic and continuous following a triangular distribution of the average staff cost to contractor staff cost and characterizing how heavily the company depends on subcontractors.

GOVERNMENTAL REGULATIONS IMPACT

Interviewees supported the notion that governmental regulations could affect supply chain interoperability. Interviewees pointed out that in an international environment different government regulations should be paid special attention by the firms and could have financial impacts for the chain (e.g. in the case process changes are needed or in labor regulations). This stochastic discrete character is proposed to be measured by the percentage of regulations that are different and the financial impact they are anticipated to have on the firm. It is assumed that different regulations may or may not have financial impacts and that in any case firm should allocate resources dealing with the differences. The relevant levels are recognized as follows:

- Level 4 (% of regulations with no differences and positive financial impact)
- Level 3 (% of regulations showing no differences and having no financial impact)
- Level 2 (% of regulations with differences and no financial impact)
- Level 1 (%of regulations with differences-minor financial impact),
- Level 0 (% of regulations with differences-major financial impact)

EFFECTIVENESS OF COMMUNICATIONS

As expressed by an interviewee from Marketing-Sales department "We need to communicate effectively… in order to understand our partners… and to share our capabilities…" The effectiveness of communications is measured here by a deterministic character based in the work of Knoppen et al. (2007) on Behavioral Inter-organizational adaptation. For our purpose, we use their notion of direction of learning thus “learning from” versus “learning with” where “the former refers to individual companies that learn and act versus the latter that involves joint activities either during learning or during subsequent acting”. Both “learning from” and “learning with” are subdivided according to the span of learning to “incidental” versus “incremental” learning. Incidental learning can be reliable (i.e., leading to stability in shared beliefs) and valid (i.e., leading to increased understanding, predicting and controlling of the environment) and “reliability and validity are likely to be increased when both partners consciously try to enrich the experience of the incident, through joint reflection”. In cases where that reliability and validity is reduced, the bond between the partners is weakened. On the other hand “incremental learning is likely to be reliable due to its repetitive nature” and “… its validity may only be threatened because of epistemic boundaries that hinder the flow of knowledge between different ‘‘communities’’ within the same dyad”. For purposes of the research model the deterministic scale used for this character is 0 for Incidental "Learning from", 1 for Incremental "Learning from", 2 for Incidental "Learning with" and 3 for Incremental "Learning with".

HUMAN RESOURCES PRACTICES

The impact of human resources on companies is of the main interest in the Human Resources Management (HRM) literature. Birdi et al. (2008) concluded that evidence exists to show that investment in Human Resources (HR) practices impacts business results, both financially as well as in terms of their market value. Wall and Wood (2005) argued that circumstantially there is promising evidence about a causal link between HRM practices and performance while the measures of HRM are generally of unknown reliability. Datta et al. (2005) reported investments in human resources management may be more beneficial in some contexts (industries) than in others. They argued that “the human element becomes more integral to the production process as capital intensity decreases… a system of human resources practices used broadly to endow all employees in a workforce with greater skill and commitment should offer greater advantages in labor-intensive than in capital-intensive industries”.

Here the effectiveness of Human resources is measured by the labor productivity defined as a ratio of the total output divided by labor inputs. This measure indicates the extent to which a firm’s labor force is efficiently creating output. While a number of other measures (e.g., turnover, absenteeism, profits) have been used to ascertain the effectiveness of HR systems, according to Data et al. (2005) productivity is the most frequently used workforce performance indicator variable in Human Resources Management.

SUPPLY CHAIN BUSINESS CULTURE

Mentzer et al. (2001) defined Supply Chain Orientation as “the recognition by an organization of the systemic, strategic implications of the tactical activities involved in managing the various flows in a supply chain. Larson, Poist and Halldósson (2007) found that the lack of a common Supply Chain Management perspective is a major barrier for Supply Chain Management implementation. Here, supply chain business culture is measured by a deterministic character of the firm’s adoption of the following supply chain management activities recognized by Mentzer et al. (2001). These activities are:

- Integrated Behavior
- Mutually Sharing Information
- Mutually Sharing Risks and Rewards
- Cooperation
- Focus on customer service

- Integration of Processes
- Build and Maintain Long-Term Relationships

INNOVATION

Damanpour et al. (2009) argued that “the study of innovation hardly needs justification... innovation is a primary source of economic growth, industrial change, competitive advantage, and public service.” As such, the company has assigned a specific department in innovation elements. Also innovation has been recognized as an interoperability character by interviewees in other departments. Kenny (2012) discussed the development of innovative financial approaches as one of the head office roles with the others being keeping external stakeholders adequately informed, ensuring the company is ready for unforeseen crises, ensuring that the company is seen as a reputable corporate citizen and ensuring that the corporate culture is communicated throughout the firm. Also Lindgreen and Wynstra (2005) and Lindgreen et al. (2012) studied the value that businesses create and recognized two major research streams emerging in the literature: the value of goods and services and the value of buyer-seller relationships. The emphasis of the second research stream is on “relationship value” including key relationship aspects such as the reputation of the supplier and its innovation capability. Damanpour et al. (2009) studied the consequences of adopting three types of innovation (service, technological process, and administrative process) in service organizations contradicting manufacturing organizations’ innovation efforts which are mainly focused on technology. They argued that the impact of innovation on organizational performance depends on the compositions of innovation types over time. They found that, specifically in service industry, a divergence from the industry norm in adopting innovation types could possibly be beneficial to organizational performance.

In this research on supply chain interoperability measurement a deterministic character is used of how well the firms practice innovation types (technological, administrative and product/service) based on what is the most applicable to the particular supply chain. For the particular company in the defense sector, which characterized mostly by state of the art technology, the character is considered 0 in the case that the firm does not innovate, 1 in case that technological innovation is present, 2 for technological and products innovation and 4when the three types of innovation being practiced.

QUALITY

Interviewees from the quality and procurement departments pointed out that they are seeking suppliers with commitment to quality. They expressed that cooperation and common decisions with suppliers for the materials and parts used are a key aspect of this commitment. Kanan and Tan (2005) advocated that “it is short sighted to view Total Quality Management and Supply Chain Management (and Just in Time) as being unrelated” since they represent alternate approaches to improving the effectiveness and efficiency of an organization’s operations function. They found that working closely with supply chain partners and designing products with manufacturing needs in mind are consistent with efforts to streamline material and that product design can reduce part production needs, further simplifying material flows. Robinson and Malhotra (2005) reviewed the literature considering the aspect of quality management within a supply chain perspective and provided a definition for Supply Chain Quality Management as “the formal coordination and integration of business processes involving all partner organizations in the supply channel to measure, analyze and continually improve products, services, and processes in order to create value and achieve satisfaction of intermediate and final customers in the marketplace.” For the operationalization of this character a deterministic measure that denotes the adoption/not adoption of quality management standards is proposed.

EQUIPMENT

Factors that are related to a company’s equipment are its age, type, quality, complexity of operation, and degree of usage. Interviewees discussed the company’s relevant standard procedures and policies towards equipment management decisions that include factors such as maintenance policies, replacement decisions, inventory management and control, standby repair and maintenance facilities, and procurement systems. Furthermore interviewees from both Marketing and Operations departments mentioned that in the past investing in proper equipment was of strategic importance for the firm since the award of an important contract was based, among other factors, upon the availability of equipment with specific technology. It is worthy to mention and further discussed in the next chapter, that according the interviewees the customer insisted for certain treatments performed with specific equipment for reasons pertaining better final results but also for the new equipment being environmental friendly. Here a deterministic character measures the suitability of the available equipment. An assumption is made that "the more modern equipment the better" and three level are used namely 0 (old equipment), 1 (adequate equipment), 2(state of the art equipment).

CUSTOMER SERVICE

Interviewees identified and prioritized the customer needs in three terms; of the process and delivery quality, the supported equipment (fleet) availability and the product support. They supported that the nature of the company’s main activities as a subcontractor in aviation manufacturing and maintenance industry, dictates to seek these needs through the involvement with their partners and through long term relationships, within an effective relational approach.

Lado et al. (2011) argues that “while it is generally agreed that firm profits result from how well customer needs and wants are satisfied, the path from customer focus and firm profitability is not often straightforward” and empirically investigated a positive relationship between customer service and financial performance of supply chain partners. For the operationalization of this character measurement, customer service was considered as “a process … results in a value added to the product or service exchanged. This value added in the exchange process might be short-term, as in a single transaction, or longer term, as in a contractual relationship” (La Londe et al. 1998, Johnson et al. 2007.The exact value added from the specific firm to its customers was considered difficult to be measured. Interviewees agreed to use a stochastic character that includes the measure of the percentage of negative and positive customer satisfaction as it was perceived by customers on the three dimensions of the delivery quality, the supported equipment (fleet) availability and the product support.

MACRO-ENVIRONMENTAL FACTORS

Interviewees pointed out that the economic crisis in Greece (year 2012) had caused several disturbances both upstream and downstream in the supply chain. The importance of this character is generally recognized in the literature. Manuj and Mentzer (2008) stated that the macro-environmental factors (Political, Economic, Social and Technological) should be considered since they introduce uncertainty into the supply chain and Rao and Goldsby (2009) described the general environmental risk variables that could include political instability, shifts in government policy, macroeconomic uncertainties, social uncertainties, and natural uncertainties and argued that “managers seem to be recognizing the importance of studying political risks involved in conducting business with overseas supply chain partners”. The perception of the managers about the macro-environmental factors in a given place and time frame and how these factors are perceived to impact firms of the supply chain, can be used as a measure here. The character is considered stochastic discrete with 3 levels of the percentage of positive, negative or no impact of these factors.

REPUTATION

Kenny (2012) analyzing best practices of leading companies recognized "ensuring that the company is seen as a reputable, responsible corporate citizen" as one of the head office roles. Resnick (2004) referred to corporate reputation management as a key asset for companies and identified the objectives that CEOs believe their companies' corporate reputations help them to achieve. They also identified nine dimensions that drive the reputational strength in a specific industry sector. In agreement with the literature, interviewees mentioned that having a corporate reputation management program would help the company in its partnerships become more interoperable. This character is considered of deterministic nature with a value of 0 or 1 indicating presence or absence of a reputation management system in the firm.

PROCESS EFFECTIVENESS

Based on the responses of the interviewees, for the assessment of process effectiveness we have adopted the school of thought of Process Performance Measurement Systems (Kueng, 2000, Kueng and Krahn, 1999) supporting the stepwise improvement of business processes. These information systems provide a visualization of process performance, taking into account aspects of performance of various stakeholders (Societal, employees', customers' and financial aspects). The system collects current performance values and compares it against target values communicating the results. The character is considered as stochastic discrete from level 0 representing absence of process performance assessment and levels 1 to 4 disseminating process performance from the above mentioned stakeholders' perspective.

EFFECTIVE FINANCE

Kaplan and Norton (1992, 2001) commented that financial measures in firms, report on the outcomes of past actions while the exclusive reliance on financial indicators could promote behaviors towards short term performance. They introduced balanced scorecard supplementing it with measures that also drive future financial performance. Interviewees recognized the importance of measuring company success also in financial terms noticing that financial performance also implies operational performance. In order to assess the effectiveness of finance of the firm, its financial performance can be compared to the competitors over a period of years. The character is deterministic with a 0 level denoting financial performance that was inferior to industry average, 1 for performance on the average and 2 for the performance exceeding the specific industry average.

5.3.1 Discussion on the identified supply chain interoperability characters

Ford et al. (2010) argued that a foundational concept in any interoperability measurement of any system is the interoperability characters describing what systems do to each other. They identified numerous types of system characters that can be used to describe a system and noticed that generally any type of character is an interoperability character in specific circumstances. According to their analysis, an interoperability character represents a pair of actions, such as “provide” and “accept,” which constitute an interoperation. These pairs describe how systems provide and accept matter, energy, or information from each other.

Here several supply chain interoperability characters are recognized. Some of these characters are attributes of the firms in the chain and do not contain the dyad of action/reaction mentioned by Ford et al. (2010). The purpose is to identify characters for the measurement of supply chain interoperability as a supply chain performance measure. It have been recognized that the inherent complexity of supply chains adds further difficulties towards performance measurement. The literature referred to the large number of performance measures that need to be maintained to characterize the supply chain system (Beamon, 1999), the existing supply chain performance measurement tools that are complicated and difficult to use in real business settings (Banomyong and Supatn, 2011) and the requirement of complex information systems (Papakiriakopoulos and Pramatari, 2010). Lambert and Pohlen (2001) argued that no meaningful performance measures exist that span the entire supply chain and attributed the causes of this as either managerial (absence of supply chain orientation and unwillingness to share information) or practical (due to complexity) factors. Chalyvidis et al. (2013) argued that the theory of System of Systems (SoS) can provide a bridge between the Supply Chain Management process and system theory, by providing insights on the selection of the appropriate characters that should be included in the interoperability measurement. They discussed in detail each of the five differentiating characteristics (Autonomy, Belonging, Connectivity, Diversity and Emergence) that define and distinguish a SoS from a “simple” system, based on the nature of a systems’ composition (Boardman and Saucer, 2006) and analyzed their applicability to Supply Chain Management. Consequently here is argued that the characters identified for supply chain interoperability measurement purposes either describe a dyad of action/reaction between the firms or describe firm’s attributes differentiating the supply chain as a System of Systems.

Table 5.3: Summary of identified supply chain interoperability characters

DEFINITION	PROPOSED MEASUREMENT	ACTUAL QUESTION	S
s implemented specifically some element of the supply o support supply chain agement efforts	Availability and reliability of the IT infrastructure supporting supply chain management. Existence of: direct IT to IT links with the suppliers/ customers- electronic shipments tracking/ transactions processing/ coordination/funds transfer	To what extent, an inter-organizational relationship uses IT technology ?	0 (absence needed), 2 (interventic intervention) a
y of business processes s the supply chain	Agreement on planning and executing material and information flow between firms	How the companies work towards a "smooth" flow of data and goods?	0 (difference technologies, priority plann planning and c in these asp
of firms' efforts, throughout ain, to reduce the risk of l liabilities (air and water). er firms or the partnership	Environmental Management Practices (EMP).	Are there instruments to check environmental aspects and to keep management of the interactions with the environment?	0 (for no EMP
lity supporting supply chain s in terms of training or specialization	Employes abilities	Is ongoing training a priority for the firm?	Level 0 (% of p training/certific level 1(% of pe x years)
		or alternatevely: What is the specialization distribution in the company?	Assesement of distribution. Tri mode assesen specilization fo company)
subcontractors -SMEs	Average Staff Cost TO average contractor cost	How heavily the company depends on subcontractors ?	triangular (a mode) f

Table 5.3: Summary of identified supply chain interoperability characters (continued)

serting the impact of different regulations between firms	Measures how much the differences in regulations of each firm, impacts supply chain activities in terms of changes in business processes or the relevant financial impact.	Is there any impact from the different regulations on supply chain activities?	4 (% of regulatio differences or poss impact), 3(% of regu no differences or nc of regulations with c financial impac regulations with diff small financial impa 0(% of regulations w and a major finar anticipat
y to communicate, and negotiate, ve supply chain partnerships and meet partnership goals	Measure the effectiveness of communication	How the company seeks partners inputs to determine their requirements?	0(Incidental "Lea 1(Incrimental "Lea 2(Incidental "Lea 3(Incrimental "Lea
ent to which a firm's labor force is efficiently creating output.	Measure the effectiveness of Human resources	The total output (e.g. firm sales) divided by labor inputs (number of employes).	0 (Output was infer average), 1 (output o 2 (output exceed averag
gnment of motivations, attitudes, , ethics and and expectations in r to achieve the supply chain partnership goals	Measure the supply chain orientation of the firm.	Are the Supply Chain Management activities being performed by the firm?	0 (The firm does no chain managemen (The firms adopts management a
nistrative innovation reflects the ation's new approaches to service g and budjeting , 'improvements' management, re-engineering) and anagement processes' (e.g. hing new teams). Technological n refers to the capacity to absorb gical knowledge. Service/product on (e.g. new services/products to new users).	Measure the composition of innovation in the firm	How innovation is practiced by the firm?	0 (the firm do not in firm demonstrates innovation), 2 (tv innovations), 4 (th innovati
Use of Quality standards	Quality of the product/supplies moving through the system.	How advanced is the implementation of the quality program in comparison with other organizations?	0 (no standards standarc

Table 5.3: Summary of identified supply chain interoperability characters (continued)

equipment	Measure how suitable is the machinery on site with the assumption "the more modern the better".	Is the available equipment suitable?	0 (old equi
service	Measure customer service in terms of process and delivery quality, availability and product support.	What is the perceived customer satisfaction for the customer service provided?	0 satisfac
litical Economical ical health across chain.	Measure the perception of the managers about the macro-environmental factors in a given place and time frame	How macro-environment is perceived to impact firms of the supply chain?	0 (% impac
w of companies in local community the supply chain. rtnerships with firms	Existence of a Corporate reputation management program	Has the company established a corporate management program?	0 (No prog m
roduct-service mes, prototyping, to make product signs across the eral use of best- es.	Measure how effective are the internal processes to meet and exceed customer needs	How are the company's processes performing from a stakeholder-driven approach?	0 (abs manag with po aspec positi aspec positive proce
ance, stability and s the supply chain.	How effective is the company in finance	What is the financial performance of the firm compared to competitors over the last x years?	0 (Fi inferi (perfo (perfo

5.3.2. An Illustrative Example on Supply Chain Interoperability

For illustrative purposes, consider the three-element supply chain shown in Figure 5.4.

Figure 5.12: Example Supply Chain

The arrows represent possible directions of information or product flow between each element. Each element in this supply chain constitutes a separate system. In order to measure interoperability in this supply chain, we consider the three example interoperability

Table 5.4: Supply chain interoperability characterization example.

Human resources	Information Technology (IT), X_2	Process effectiveness (PE), X_3

ability (HR), $\boldsymbol{X_1}$ stochastic, continuous	deterministic, discrete			stochastic, discrete	
	Medium	**Frequency**	**Level** $\mathbf{X_2}$	**% :**	**Level** $\mathbf{X_3}$
X_1~Triangular (a,b,c)	seamless	real-time	4	of processes with positive societal aspects	4
	electronic, with translation	daily	3	of processes with positive customer aspect	3
	electronic, with human intervention	weekly	2	of processes with positive employee performance aspect	2
	paper	monthly	1	of processes with positive financial performance aspect	1
	none	never	0	absence of business process management	0

characters shown in Table 5.4 namely the Human resources ability (HR) (a stochastic character that follows a triangular distribution for each company), the Information Technology (IT) (a deterministic leveling character with a single value from 0 to 4 for each company) and the Process Effectiveness (PE) (a stochastic character with values from 0 to 4 with certain probability for each company).

From the data of Figure 5.4 and Table 5.4, one can identify the systems, interoperability characters, and character states as:

S = {Supplier (S) Manufacturer (M), Customer (C)}

X = { X_1 Information Technology (P_{IT}) , X_2 *Process Effectiveness* (P_{PE}) ,X_3 Human Resources Ability (P_{HR}) *}*

Next two sample scenarios are considered. Table 5.5.a represents a low-integration supply chain. The second scenario, shown in Table 5.5.b, depicts a more highly integrated supply chain where the members possess similar character values.

Table 5.5.a: Low integration.

	Supplier	**Manufacturer**	**Customer**
X_1	2	1	3
X_2	(0.4, 0.3, 0.2, 0.1, 0)	(0.05, 0.35, 0.5, 0.1, 0)	(0, 0.2, 0.3, 0.3, 0.2)
X_3	Triangular (0.1,0.4, 0.25)	Triangular (0.7,0.9, 0.8)	Triangular (0.5,1, 0.75)

Table 5.5.b: Significant integration.

	Supplier	**Manufacturer**	**Customer**
X_1	4	3	4
X_2	(0, 0, 0.1, 0.35, 0.55)	(0, 0, 0, 0.4, 0.6)	(0, 0, 0.1, 0.3, 0.6)
X_3	Triangular (0.9,1, 0.95)	Triangular (0.7,0.8, 0.75)	Triangular (0.8,1, 0.9)

Using the interoperability function (section 4.4.1) the following supply chain interoperability measurement matrix, M_{low} *and* M_{high}, results for each of the two respective scenarios (low and high/significant integration). Note, for managerial purposes, that the "weak" links of the supply chain can be easily identified by comparing interoperability measurements.

$$M_{low} = \begin{array}{c} \\ S \\ M \\ C \end{array} \begin{array}{ccc} S & M & C \\ \hline 0 & 0.2907 & 0.3413 \\ 0.2907 & 0 & 0.4310 \\ 0.3413 & 0.4310 & 0 \end{array} \qquad M_{high} = \begin{array}{c} \\ S \\ M \\ C \end{array} \begin{array}{ccc} S & M & C \\ \hline 0 & 0.7135 & 0.9120 \\ 0.7135 & 0 & 0.7230 \\ 0.9120 & 0.7230 & 0 \end{array}$$

Finally, we note that it would be useful to have a single number that measures an entire supply chain's overall interoperability. We propose using rank or priorities, which can be converted to weights. Consider the rank matrix of participant interactions:

$$R = \begin{bmatrix} & Suppl. & Manufact & Customer \\ Suppl. & 0 & 2 & 1 \\ Manufact. & 3 & 0 & 4 \\ Customer & 3 & 2 & 0 \end{bmatrix}$$

Similar to Value Focused Thinking or the Analytical Hierarchy Process, the supply chain manager or decision maker may value and rank objectives differently throughout the chain. The diagonal values are zero to reflect non-applicability of "self-interoperability." For example, the Rank Matrix above reflects a priority (rank = 1) on the Supplier to Customer interface, and the least priority (rank = 4) to the Manufacturer to Customer relation. This method also accommodates directionality of interoperability values, identified by Ford et al. (2009), thus the matrix need not be symmetric.

To maintain a unity scale, the Rank Matrix is transformed to weights. A variety of weighting methods can be used (Beude, 2000, pp 367); we chose the rank reciprocal approach. Each weight element is calculated from the reciprocal of the corresponding rank element, scaled by the sum of the reciprocals across the entire rank matrix.

$$W_{\text{RRScaled}} = \left[w_{i,j} \right] = \left(\frac{\frac{1}{r_{i,j}}}{\sum_{k=1}^{N} \sum_{l=1}^{N} \frac{1}{r_{k,l}}} \right), \forall i = 1..N, \forall j = 1..N, i \neq j$$

Applying the Weighting Matrix to the Interoperability Matrix, *M,* for the low integration scenario results in the overall weighted assessment of the supply chain. While in this case the Interoperability Matrix was symmetric, the Weighting Matrix (based on ranks) is not. Thus, all off-diagonal elements must be used in this calculation. The operator $\oplus$ is defined as the summation of the weighted element products. For the characters of interest, this provides an overall measurement of interoperability. This aggregated measured might be used in a relative sense, to compare options, process improvements, infrastructure/IT enhancements, etc.

$$I_{Weighted} = W_{\text{RRScaled}} \oplus M_{\text{low}}$$

$$= \frac{1}{N(N-1)} \begin{bmatrix} 0 & 0.1714 & 0.3429 \\ 0.1143 & 0 & 0.0857 \\ .1143 & 0.1714 & 0 \end{bmatrix} \oplus \begin{bmatrix} 0 & 0.2907 & 0.3413 \\ 0.2907 & 0 & 0.4310 \\ 0.3413 & 0.4310 & 0 \end{bmatrix} = 0.3499$$

In order to enhance understanding a further scenario is considered here where one aspect of one of the firms changes over time. Arbitrarily it is assumed that the stochastic character Human resources ability (X_1) of the supplier is improved after training initiatives in that company over five time periods. Consequently the corresponding interoperability matrix entries as long as the overall aggregate number $I_{weighted}$ are also shifted up as shown below:

Period 1: X_1 follows triangular (0.3-0.4-0.35) =

$$M_{low} = \begin{array}{c} \\ S \\ M \\ C \end{array} \begin{array}{ccc} S & M & C \\ \hline 0 & 0.3247 & 0.3750 \\ 0.3247 & 0 & 0.4310 \\ 0.3750 & 0.4310 & 0 \end{array} \qquad I_{Weighted} = W_{\text{RRScaled}} \oplus M_{\text{low}} = 0.3750$$

Period 2: X_1 follows (0.3-0.6-0.5) =

$$M_{low} = \begin{array}{c} \\ S \\ M \\ C \end{array} \begin{array}{ccc} S & M & C \\ \hline 0 & 0.3587 & 0.4067 \\ 0.3587 & 0 & 0.4310 \\ 0.4067 & 0.4310 & 0 \end{array} \qquad I_{Weighted} = W_{\text{RRScaled}} \oplus M_{\text{low}} = 0.3992$$

Period 3: X_1 follows (0.5-0.7-0.6)=

$$M_{low} = \begin{array}{c} \\ S \\ M \\ C \end{array} \begin{array}{ccc} S & M & C \\ \hline 0 & 0.4069 & 0.4476 \\ 0.4069 & 0 & 0.4310 \\ 0.4476 & 0.4310 & 0 \end{array} \qquad I_{Weighted} = W_{\text{RRScaled}} \oplus M_{\text{low}} = 0.4317$$

Period 4: X_1 follows (0.7-0.9-0.8) =

$$M_{low} = \begin{array}{c} \\ S \\ M \\ C \end{array} \begin{array}{c} \begin{array}{ccc} S & M & C \end{array} \\ \left|\begin{array}{ccc} 0 & 0.4526 & 0.4791 \\ 0.4526 & 0 & 0.4310 \\ 0.4791 & 0.4310 & 0 \end{array}\right| \end{array} \quad I_{Weighted} = W_{\text{RRScaled}} \oplus M_{\text{low}} = 0.4592$$

Period 5: X_1 follows (0.9-1-0.95) =

$$M_{low} = \begin{array}{c} \\ S \\ M \\ C \end{array} \begin{array}{c} \begin{array}{ccc} S & M & C \end{array} \\ \left|\begin{array}{ccc} 0 & 0.2785 & 0.3260 \\ 0.2785 & 0 & 0.4310 \\ 0.3260 & 0.4310 & 0 \end{array}\right| \end{array} \quad I_{Weighted} = W_{\text{RRScaled}} \oplus M_{\text{low}} = 0.3394$$

It is interesting to notice that in period 5 of the previous scenario, even though the character X is further improved for the supplier, the supply chain interoperability of the supplier with the other two firms and also the $I_{weighted}$ are reduced. The reduction of interoperability in this case is due to the fact that the supplier has overcome the other two companies in terms of the character X_1 to the extent that the similarity between the companies is reduced even though the average value of the character improves.

5.4 Conclusions and further steps towards supply chain interoperability measurement

The overall goal of measuring supply chain interoperability (Chalyvidis, Ogden and Johnson, 2013) is to better understand how changes can be made to firms to improve supply chain interoperability. In such an effort, the careful selection of the supply chain constructs used for the characterization of the companies is crucial. Here we explore the managers' perspective concerning the feasibility of using a measurement tool for supply chain interoperability, we assess the perceptions and explore the patterns of decision making that are closely connected with interoperability.

A novel supply chain interoperability measure is proposed. Extent methods have captured a variety of frameworks (both qualitative and quantitative) within the logistics, management, operations research and systems engineering communities. Our research describes the supply chain's participants through a series of characters, then applies a similarity measure. While real valued discrete leveling methods have been reported, this paper introduces a mixed-characterization of participants. This extends deterministic valued character states (either discrete or continuous), to include stochastic relationships. Basing the stochastic descriptions on empirical data can capture the likelihood of interoperability-related challenges. Lastly, a weighting scheme can be applied to the interoperability measurement matrix for an overall supply chain assessment.

For managers, the paper offers a strategic and holistic method to evaluate their respective firm's progress toward successful supply chain management implementation. Results may be used for a supply chain audit across participating firms. Also the research would help interoperability to be established as a performance metric of *"the structure that determines behavior"* (Holmerg, 2000). Managers would be equipped with a new tool assessing both tangible things like IT technology and intangible like business culture, policies and values.

The interaction between supply chain interoperability and performance has not been investigated. The literature offers a plethora of suitable supply chain frameworks linked with performance. For example Min et al. (2004) developed a framework and confirmed that certain constructs of Supply Chain Management and Supply Chain Orientation lead to improved business performance of individual firms within the supply chain. However it may not be possible, financially profitable or even desirable for all supply chain members to interoperate perfectly. Also supply chain interoperability measurement should be reflected and related to the "value" of interoperability for the company. The work of Lebretton (2007) on the operational and strategic impacts of enterprise interoperability might be considered. Naturally, the relationship between supply chain interoperability and performance should be validated. Lastly, with an SCM assessment method created, there exists a need to study the upper bound of supply chain interoperability in terms of performance and cost-benefit.

Another limitation of this work concerns the study of supply chain interoperability in the limited domain of defense industry and especially in only one company. Further research would be recommended to include greater depth and width of the supply chain. Also it is not considered that we have been able to drill down to the score of overall interoperability since some characters cancel out others. Delphi rounds to reduce the recognized characters could be used to define uncorrelated characters to be taken into measurement and further test the measure. Nevertheless the quantification of supply chain interoperability involves judgment and bias from optimistic or organizationally committed individuals possibly rating higher their own company than their more pessimistic counterparts in another company. The paper offers the linkages necessary to further test and enhance the quality of supply chain interoperability characters.

The next step would be to further develop and refine the characters that should be included in the supply chain interoperability measurement model. The directionality of supply chain interoperability discussed here, could be further refined to include directionality of characters, as well as the concepts of confrontational interoperability and competitive interoperability. Also the possible difference between the upper bound and the current interoperability measurement would define an interoperability gap, which represents the trade space in which changes can occur on interoperability characters, to improve supply chain performance. Following the further refinement of the interoperability measurement, empirical data should be utilized to test, validate, and further refine the measurement.

Appendix 5.A Semi-structure interview questions

The interviews started with a brief explanation of the supply chain interoperability tool (chapters 3.0, 4.0) and the purpose to identify suitable characters to be included in the measurement. Interviewees were assured for the confidentiality of the interview; they were informed with an estimation of the finishing time and the contact details of the interviewer for future contact if needed. Also they were explained the semi-structured format of the interview and they were asked for any questions before starting. The following questions were used as a general framework of the discussion:

1) What aspects of your company's supply chain should be included as supply chain interoperability characters? How these are going to be quantified?

2) Specifically for your company's supply chain, what factors facilitate cooperation towards optimality of the chain and coordination of business processes? How do you consider measuring these factors?

3) How your departments' processes facilitate a better flow of data and goods in the chain?

4) Do you consider that the optimality of the supply chain of your company can be influenced by direct IT links or electronic data transfers (for example of purchase orders, invoices, funds)?

5) According your experience are environmental aspects facilitating or causing difficulties in your firm's interactions with other members of the supply chain?

6) How are human resources issues affecting the company's interaction with other firms?

7) How the imposed regulations affect establishing relationships or doing business with other firms?

8) How innovation practices influence the synchronization of goods, services and information between firms?

9) How quality is considered to affect the interaction with other firms?

10) How the firm's cultural aspects could affect its supply chain?

11) How the Political, Economic, Social and Technological environment has affected firm's cooperation with others?

12) Do you consider that the reputation of one company affects its current and future relation with other partners?

13) Do you consider that the financial results of the firm affect its present and future relation with other partners?

VI. Conclusion

6.1 Major Research Findings

In the sections that follow, the primary findings captured in Chapters 3.0-5.0 are discussed. The findings are presented in summary format. The individual chapters should be referenced for additional detail or supporting information.

6.1.1 Findings on "Using Supply Chain Interoperability as a Measure of Supply Chain Performance."

A literature review reveals that despite the great number of frameworks and tools for supply chain performance measurement, none addresses all of the typical problems for supply chain performance assessment.

A System of Systems (SoS) approach and the application of System Engineering heuristics on supply chain performance measurement contribute significantly in the Supply Chain Management discipline. Supply chains are analyzed as Systems of Systems and the parallels with the theoretical perspectives of Transaction Cost Economics, Resource Based View and network systems are identified. This offers an alternative to fill the gap on Supply Chain Measurement, with the introduction of a new supply chain performance measure, defined as supply chain interoperability.

A generalizable and customizable approach is proposed that could be useful in measuring supply chain interoperability.

6.1.2 Findings on "A Method for Measuring Supply Chain Interoperability."

A novel supply chain interoperability measure is proposed. Extant methods have captured a variety of frameworks (both qualitative and quantitative) within the Logistics, Management, Operations Research and Systems Engineering communities. Here the supply chain's participants are described through a series of characters and then a similarity measure is applied.

While real valued discrete leveling methods have been reported, here a mixed characterization of participants is introduced. This extends deterministic valued character states (both discrete and continuous) to include stochastic relationships. A demonstrative example is also presented.

6.1.3 Findings from "Supply Chain Interoperability Characters Identification."

Here a methodology that could be used to identify supply chain interoperability characters is presented and potential characters are refined through a semi structured interview tool applied in one large defense company in Greece.

The managers' perspective concerning the feasibility of using a measurement tool for supply chain interoperability and the patterns of decision making that are closely connected with interoperability are explored. A complex set of supply chain interoperability constructs are discovered followed by a demonstrative example.

6.2 Implications

Nowadays organizations and academics have attempted to adopt supply chain management concepts and practices into their business processes. This subject is not easily implemented and encompasses an enormous breadth of topics requiring new thinking for its holistic assessment. SCM involves challenges such as developing trust and collaboration among supply chain partners, identifying ways to facilitate supply chain process alignment and integration, and successfully implementing modern information systems and technologies that drive performance. The definition and measuring method of supply chain interoperability and the careful selection of the supply chain constructs used for the characterization of the companies, are useful for establishing interoperability as a performance metric of a supply chain "structure that determines behavior" (Holmerg, 2000) and answers various calls for a means of assigning values to the various levels of collaboration among participating firms (Barratt, 2004; Mentzer et al., 2000).

Managers are offered a strategic and holistic method to evaluate their respective firm's progress toward successful supply chain management implementation. Managers are equipped with a new tool assessing both tangible concepts like IT technology and intangible concepts like business culture, policies and values. The results may be used for a supply chain audit across participating firms. The overall goal of measuring supply chain interoperability (Chalyvidis, Ogden and Johnson, 2013) is to better understand how changes can be made to firms to improve Supply Chain Management implementation.

There are various efforts to qualitatively describe interoperability between systems and Ford et al. (2009) provided a means to quantitatively measure the interoperability of not only technical systems, but non-technical systems or mixed sets of systems and to put the interoperability measurement in the context of military operations. Here, the proposed measurement method improves upon extant interoperability assessment techniques by refining current quantification methodologies to include both deterministic and stochastic characters. It is hoped that the ability to measure system interoperability presented in this research would help improve the supply chains of defense systems and military operations.

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14. ABSTRACT Academia recognizes that although supply chains have an inherent need to be validated for their performance, supply chain performance measurement systems are still inadequate and one of the major barriers to successful supply chain collaboration. In this research, theory of Systems Architecture is used to make the first step towards an innovative supply chain performance measure defined as supply chain interoperability. Interoperability is considered a similarity metric with regard to a set of deterministic and stochastic characters (criteria) describing supply chain participants, a methodology that adapts and expands an interoperability measurement tool initially developed in and for a military context. A process that could be used to develop a set of initial supply chain interoperability characters to be included in the interoperability measurement is demonstrated based on interviews from managers of various functional roles at a single defense company in Greece. The presented measurement methodology can assist in efficiently directing resources to best improve interoperability between and among the various elements of a supply chain.					
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