João Paulo Pereira dos Santos

Licenciatura em Ciências da Engenharia e Gestão Industrial

A simulation model for Lean, Agile, Resilient and Green Supply Chain Management: practices and interoperability assessment

Dissertação para obtenção do Grau de Mestre em Engenharia e Gestão Industrial

Orientador: Doutor António Carlos Bárbara Grilo, Professor Auxiliar, FCT-UNL

Júri:

Presidente: Prof. Doutor Virgílio António Cruz Machado
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FACULDADE DE CIÊNCIAS E TECNOLOGIA
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To my parents, for their support and encouragement.

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Abstract

In today's global market, the environment of unpredictable events has imposed a competitiveness improvement that requires a greater coordination and collaboration among Supply Chain (SC) entities, i.e., an effective Supply Chain Management (SCM). In this context, Lean, Agile, Resilient and Green (LARG) strategies emerged as a response. However, interoperability issues are always presents in operations among SC entities. From the Information Technology (IT) perspective, among all the multi-decisional techniques supporting a logistics network, simulation appears as an essential tool that allow the quantitative evaluation of benefits and issues deriving from a co-operative environment.

The present work provides a SC simulation model for analysing the effect of the interoperability degree of LARG practices in the SC performance, through Key Performance Indicators (KPI's) such as cost, lead time and service level. The creation of two scenarios with a different point of view about the LARG practices allowed to analyse which one contributes to the best SC performance. Since some of the inputs were assumed, it was made a sensitivity analysis to validate the output of the simulation model. Based on the creation of six types of math expressions, it was possible to establish the connection between the effect of the interoperability degree of LARG practices and the SC performance. This analysis was applied on a case study that was conducted at some entities of a Portuguese automotive SC. The software used to develop the simulation model is Arena, which is considered a user-friendly and dynamic tool.

It was concluded that SCM, interoperability and simulation subjects must be applied together to help organisations to achieve overall competitiveness, focusing their strategies on a co-operative environment.

Keywords: Supply Chain Management; Lean, Agile, Resilient and Green; interoperability; simulation; Key Performance Indicators; Arena.

Resumo

No mercado global de hoje, o ambiente de acontecimentos imprevisíveis tem imposto uma melhoria da competitividade que exige uma maior coordenação e colaboração entre as entidades da cadeia de abastecimento, ou seja, uma gestão da cadeia de abastecimento eficaz. Neste contexto, as estratégias *Lean, Agile, Resilient and Green* (LARG) surgiram como uma resposta. No entanto, as questões de interoperabilidade estão sempre presentes nas operações entre as entidades da cadeia de abastecimento. Na perspetiva da tecnologia de informação, entre todas as técnicas de tomada de decisão que suportam uma rede logística, a simulação aparece como uma ferramenta essencial que permite a avaliação quantitativa dos benefícios e das questões decorrentes de um ambiente cooperativo.

O presente trabalho apresenta um modelo de simulação de uma cadeia de abastecimento para analisar o efeito do grau de interoperabilidade das práticas LARG no desempenho da cadeia de abastecimento, através de indicadores-chave de desempenho como o custo, tempo de aprovisionamento e nível de serviço. A criação de dois cenários com um ponto de vista diferente acerca das práticas LARG permitiu analisar qual deles contribui para um melhor desempenho da cadeia de abastecimento. Uma vez que alguns dados foram estimados, foi feita uma análise de sensibilidade para validar o resultado do modelo de simulação. Com base na criação de seis tipos de expressões matemáticas, foi possível estabelecer uma ligação entre o efeito do grau de interoperabilidade das práticas LARG e o desempenho da cadeia de abastecimento. Esta análise foi aplicada num caso de estudo que foi realizado em algumas entidades de uma cadeia de abastecimento automóvel Portuguesa. O *software* usado para desenvolver o modelo de simulação é o *Arena*, que é considerada uma ferramenta dinâmica e de fácil utilização.

Concluiu-se que as áreas da gestão da cadeia de abastecimento, interoperabilidade e simulação devem ser conjuntamente aplicadas para ajudar as organizações a alcançar a competitividade global, focando as suas estratégias num ambiente cooperativo.

Palavras-chave: gestão da cadeia de abastecimento; *Lean, Agile, Resilient and Green*; interoperabilidade; simulação; indicadores-chave de desempenho; *Arena*.

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Acronyms

BOM	Bill Of Materials
DSS	Decision Support System
FF	Focal Firm
FIFO	First In First Out
GSCM	Green Supply Chain Management
ISO	International Organisation for Standardization
IS	Information Systems
IT	Information Technology
JIT	Just-In-Time
KPI’s	Key Performance Indicators
LARG	Lean, Agile, Resilient and Green
LARG SC	Lean, Agile, Resilient and Green Supply Chain
LARG SCM	Lean, Agile, Resilient and Green Supply Chain Management
LM	Lean Management
MU	Monetary Unit
NVA	Non-Value Added
SC	Supply Chain
SCM	Supply Chain Management
SIMAN	SIMulation ANalysis
SMED	Single Minute Exchange of Dies
SQL	Structured Query Language
TPM	Total Productive Maintenance
TQM	Total Quality Management
VA	Value Added
VBA	Visual Basic for Applications
XML	Extensible Markup Language
1tC	First tier Costumer
1tD	First tier Distributor
1tS	First tier Suppliers
2tS	Second tier Suppliers

Chapter 1. Introduction

1.1. Scope
1.2. Objectives
1.3. Methodology
1.4. Organisation of this dissertation

Since the end of the 20th century until today, the creation of collaborative networks, such as Supply Chains (SC's), where suppliers, manufacturers, distributors, retailers and wholesalers operate in joint activities and sharing information in real time, has been crucial to achieve global success (Espadinha-Cruz, 2012). Strategies as Lean, Agile, Resilient and Green have emerged as a response to gain competitiveness towards the demands of the market (Espadinha-Cruz, 2012). The integration of these four different methodologies on the same SC is very important in the strategic point of view (Espadinha-Cruz, 2012).

However, such complex networks are affected by problems of communication between partners and some other kinds of disturbance, like incoordination of activities (Espadinha-Cruz, 2012). This kind of disturbance is known by interoperability, i.e., the ability of two or more systems to share and use information in order to operate effectively together with the objective to create value. Therefore, every SC needs to cooperate in order to have significant positive effects on its performance.

The appearance of simulation turns out to be an essential tool in SC's management, allowing the enhancement of their global efficiency through evaluation and comparison of virtual scenarios. The development of Information Technology (IT) over the last decades is turning simulation into a high speed and relatively low cost tool.

This dissertation provides a SC simulation model for the analysis of the effect of the interoperability degree of Lean, Agile, Resilient and Green (LARG) practices in the SC performance. The model is based on the creation of two different scenarios to analyse which one will contribute to the best SC performance, in terms of cost, delivery time and service level to customers.

1.1. Scope

In the perspective of Supply Chain Management (SCM), which has become very popular in recent years, the environment of high volatile markets and unpredictable conditions has imposed that competitiveness improvement requires collaborative work and partnerships across SC's. To strengthen their business in the market, organisations have adopted strategies such as Lean, Agile, Resilient and Green. However, the strategies themselves do not provide all the solutions needed for every environment (Espadinha-Cruz, 2012). Thus, hybrid solutions are now the forefront in the struggle to achieve competitiveness and company's profit (Espadinha-Cruz, 2012).

In the context of LARG, the present dissertation was developed to integrate contradictory practices and corresponding Key Performance Indicators (KPI's).

The concept of interoperability is associated with information, material and services exchange. Every activity between actors occurs according to the adopted SCM strategy and the correspondent practices (Espadinha-Cruz, 2012). The alignment of these activities is a challenge for companies that deal with complex products, such as automakers (Espadinha-Cruz, 2012). Thus, in the context of interoperability, it is necessary to identify barriers in collaboration to achieve the best quality and service, resulting in lower costs for the final customer.

From the IT perspective, among all the quantitative methods, simulation is undoubtedly one of the most powerful techniques to apply, as a Decision Support System (DSS), within a SC environment (Terzi & Cavalieri, 2004).The ultimate success of SC simulation, however, is determined by a combination of the analyst's skills, the chain members' involvement, and the modelling capabilities of the simulation tool (Zee & Vorst, 2005). In this dissertation, Arena simulation software was used to satisfy the emergence of SCM needs.

The main focus of the present dissertation is based on the future research work proposed by Espadinha-Cruz (2012), whose methodology makes a practical exposition of how to assess interoperability in LARG practices using subjective information (Espadinha-Cruz, 2012). The SC simulation model provided in this dissertation address the second branch of conceptual framework proposed by Espadinha-Cruz (2012), which is related to the question "How do we evaluate the effect of the interoperability degree of LARG practices in the SC performance?". To answer this question it is necessary to establish a link between the interoperability degree of LARG practices and SC performance, through KPI's that help monitor the practices' implementation (Espadinha-Cruz, 2012). The combination of the methodology proposed by Espadinha-Cruz (2012) and the simulation model developed in this dissertation provide a complementary and seamless manner to monitor interoperability throughout the SC (Espadinha-Cruz, 2012).

1.2. Objectives

The aim of this dissertation lies on the construction of an automotive SC simulation model for the analysis of the effect of the interoperability degree of LARG practices in the SC performance, through KPI's such as cost, lead time and service level. The creation of two different scenarios allowed to analyse which one contributes to the best SC performance.

In the first scenario, it will be considered one practice of each paradigm, namely Lean, Agile, Resilient and Green. By assigning a different interoperability degree for each one of those four practices associated with every interaction between two partners in the automotive SC, it is possible to assess which is the best SCM strategy that should be adopted.

In the second scenario, it will only be considered one practice that can belong not only to the Resilient paradigm, but also to the remaining three paradigms, considering the different opinions of the authors that were found in the literature review. Note that these two scenarios were only considered to obtain different results in order to evaluate if the Resilient practice should be associated to the remaining paradigms. Thus, the question “How do we evaluate the effect of the interoperability degree of LARG practices in the SC performance?” is not directly related with the number of scenarios considered.

In order to simulate and compare these scenarios, it was used a simulation software, namely Rockwell Arena 9.0.

1.3. Methodology

The expected achievements for the present work involve the stages summarised in Figure 1.1.

The first stage consists only in the analysis of the master’s dissertation of Espadinha-Cruz (2012). After defining the objectives based on the future research work proposed by Espadinha-Cruz (2012), an extensive literature review must be made.

Therefore, in the next stage the aim is to understand the LARG practices and interoperability concepts. This literature review research is conducted using the contributions for the project LARG SCM. Then, using the B-on scientific database, Web of Knowledge research platform, run repository and some books, it was possible to make an in-depth study in the SC simulation area and also complement the information provided by the project LARG SCM.

After formulate the research questions, the automotive SC conceptual model is designed based on a journal article written by Carvalho, Barroso, Machado, Azevedo, & Cruz-Machado (2012). Some data and model parameters were defined based on that journal article and the remaining were assumed based on the information encountered in the conducted research.

The fourth stage focuses in the conversion of the automotive SC conceptual model in the simulation model, with the help of simulation software, namely Rockwell Arena 9.0 that uses a SIMulation ANalysis (SIMAN) programming language.

There follows the verification stage, which consists in evaluating if the simulation model is consistent with the designed conceptual model. It is also fundamental to understand if the correct model was built, i.e., validate the output of the simulation model.

Finally, the results must be analysed to draw the conclusions regarding the purpose of the entire dissertation. The future research work should not be ignored, because it will be interesting to develop other research questions that were not considered for the present work.

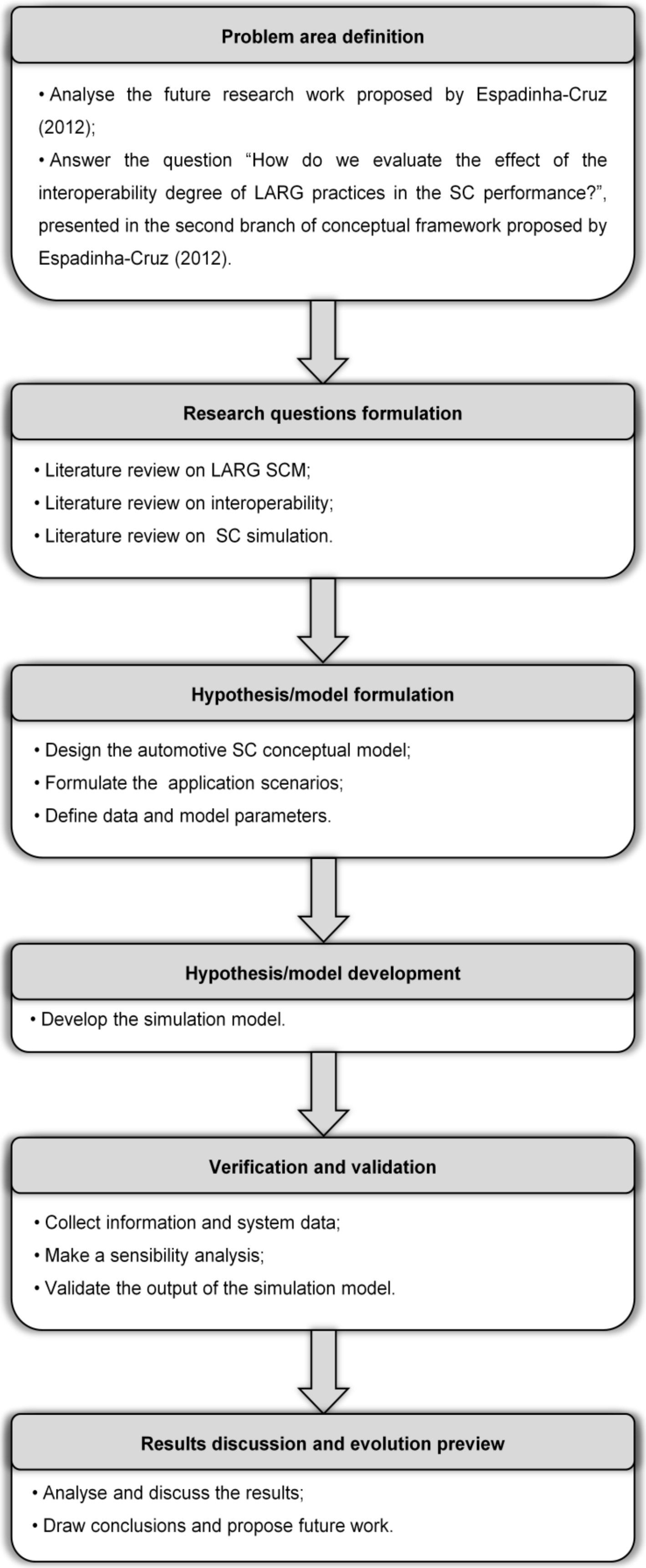

Figure 1.1 Outline of the dissertation

1.4. Organisation of this dissertation

The dissertation is organised in the following chapters:

- The first chapter provides a brief introduction, regarding the scope of the study, the objectives and the research methodology;
- Chapters 2 and 3 refer to the literature review of the topics SCM and interoperability, respectively;
- In chapter 4, a brief literature review about SC simulation is presented. Furthermore, this chapter describes the automotive SC along with the conceptual model and every data and parameters that are assumed for the simulation model development. Finally, the simulation model results are presented, followed by a sensibility analysis;
- The main conclusions and suggested research work are presented in the final chapter;
- The dissertation ends with the references used in literature review.

Chapter 2. Supply Chain Management

2.1. Paradigms and practices review
2.1.1. Lean
2.1.2. Agile
2.1.3. Resilient
2.1.4. Green
2.2. Paradigms combination
2.3. Characteristics
2.4. Performance measurement

In today's global market, organisations have focused their strategies on inter-functional and inter-organisational integration and coordination across the intricate network of business relationships (Lambert & Cooper, 2000; Min & Zhou, 2002). This new way of doing business allows answering to an increasing rate of change, providing the right products and services on time, with the required specifications, at the right place to the customer (Carvalho, Azevedo, & Cruz-Machado, 2011). In this context, Supply Chains (SC's) have become a key concept among the organisations to achieve overall competitiveness.

A SC can be described as a network that links various agents, from the customer to the supplier, through manufacturing and services so that the flow of materials, money and information can be effectively managed to meet the business requirements (Stevens, 1989). In other words, extends from the original supplier or source to the ultimate customer (Blanchard, 2010).

Currently there is the assumption that SC's compete instead of organisations (Christopher & Towill, 2000). So, the term Supply Chain Management (SCM) appears to determine, mainly by the market, the success or failure of SC. In literature review there are present many definitions of SCM, in which some of them are presenting in Table 2.1. All these definitions have some concepts in common, such as strategic collaboration, business process management and coordination, production and inventory management and Value Added (VA) for final customer (Cabral, 2011).

In order to satisfy the customer requirements, which are continuously changing, businesses must adapt their strategies to live and succeed. However, the increasing of the VA is only possible with an effective and efficient management.

Table 2.1 Definitions of SCM

Definition	Source
"Process for designing, developing, optimising and managing the internal and external components of the supply system, including material supply, transforming materials and distributing finished products or services to customers, that is consistent with overall objectives and strategies."	(Spekman, Jr, & Myhr, 1998)
"The systemic, strategic coordination of the traditional business functions and the tactics across these business functions within a particular company and across businesses within the SC, for the purposes of improving the long-term performance of the individual companies and the SC as a whole."	(Mentzer et al., 2001)
"Based on the integration of all activities that add value to customers starting from product design to delivery."	(Gunasekaran & Ngai, 2004)
"The coordination of production, inventory, location, and transportation among the participants in a SC to achieve the best mix of responsiveness and efficiency for the market being served."	(Hugos, 2006)
"A set of approaches utilized to efficiently integrate suppliers, manufacturers, warehouses, and stores, so that merchandise is produced and distributed at the right quantities, to right locations, and at the right time, in order to minimize system wide costs while satisfying the service level requirements."	(Simchi-Levi, Kaminsky, & Simchi-Levi, 2008)

2.1. Paradigms and practices review

In the definition of SCM there are four paradigms that have emerged to achieve the upmost competitiveness. The Lean, Agile, Resilient and Green (LARG) paradigms have thus far been explored individually, or by integrating only a couple, e.g., Lean vs. Agile (Naylor, Naim, & Berry, 1999) or Lean vs. Green (Kainuma & Tawara, 2006). Nevertheless, the ability to integrate these four different management paradigms may help SC to become more efficient, streamlined and sustainable (Carvalho, et al., 2011).

The following sections describe each paradigm from a SCM perspective and a set of principles (SCM practices) based on literature review (Azevedo, Carvalho, & Cruz-Machado, 2011a) are pointed out. All practices suggested contributes to a SC with less waste (Non-Value Added, NVA, activities), more responsive to the customer requirements, able to overcome disruption conditions and also to reduce environmental impacts (Azevedo, Carvalho, & Cruz-Machado, 2011b).

The implementation of these practices, which can belong to one or more paradigm, and the measurement of different impact on each paradigm, can improve SCM performance (Cabral, 2011).

2.1.1. Lean

The Lean Management (LM) paradigm, developed by Ohno (1998) of the Toyota Motor Corporation in Japan, forms the basis for the Toyota Production System with two main pillars: ‘autonomation’ and ‘Just-In-Time (JIT)’ production.

There are many definitions of Lean philosophy in literature and all of them have the same principles. According to Womack, Jones, & Roos (1991), the Lean paradigm is an approach which provides a way to do more with less human effort, equipment, time and space, while coming closer to customer requirement. Motwani (2003) argued that LM is an enhanced of mass production. Reichhart & Holweg (2007) had extended the concept of Lean production to the downstream or distribution level: “We define Lean distribution as minimizing waste in the downstream SC, while making the right product available to the end customer at the right time and location”.

Several authors have highlighted Lean key principles, such as: respect for people (Treville & Antonakis, 2006), quality management (Brown & Mitchell, 1991), pull production (Brown & Mitchell, 1991) and mistake-proofing (Stewart & Grout, 2001). At the operational level, these principles led to a number of techniques, like: Kanban, 5S, visual control, takt-time, Poke-yoke and Single Minute Exchange of Dies (SMED) (Melton, 2005). In addition to these techniques manufacturing practices, such as JIT, Total Productive Maintenance (TPM) and Total Quality Management (TQM) are used to eliminate various types of waste (Melton, 2005).

Table 2.2 shows a set of Lean practices that was selected to assess various levels of the SC to contribute to waste elimination and cost reduction.

Table 2.2 Lean practices

SCM practice	Source
L_1: Customer relationships	(Anand & Kodali, 2008; Berry, Christiansen, Bruun, & Ward, 2003; Doolen & Hacker, 2005)
L_2: JIT (Focal Firm, FF)	(Anand & Kodali, 2008; Berry, et al., 2003; Gurumurthy & Kodali, 2009; Mahidhar, 2005; Shah & Ward, 2003)
L_3: JIT (FF→ First tier Costumer, 1tC)	(Anand & Kodali, 2008; Berry, et al., 2003; Gurumurthy & Kodali, 2009; Mahidhar, 2005; Shah & Ward, 2003)

SCM practice	Source
L_4: JIT (First tier Suppliers, 1tS→ FF)	(Anand & Kodali, 2008; Berry, et al., 2003; Gurumurthy & Kodali, 2009; Mahidhar, 2005; Shah & Ward, 2003)
L_5: Pull flow	(Anand & Kodali, 2008; Doolen & Hacker, 2005; Gurumurthy & Kodali, 2009; Mahidhar, 2005; Shah & Ward, 2003)
L_6: Supplier relationships/long-term business relationships	(Anand & Kodali, 2008; Berry, et al., 2003; Gurumurthy & Kodali, 2009; Mahidhar, 2005; Shah & Ward, 2003)
L_7: TQM	(Berry, et al., 2003; Doolen & Hacker, 2005; Gurumurthy & Kodali, 2009; Mahidhar, 2005; Shah & Ward, 2003)

2.1.2. Agile

The SC objective is to delivering the right product, in the right quality, in the right condition, in the right place, at the right time, for the right cost (Azevedo, et al., 2011a). To overcome these conditions, SC's must be adaptable to future changes to respond appropriately to market requirements and changes (Azevedo, et al., 2011a). In this context, the concept of Agile manufacturing was coined by a group of researchers at Iaccoca Institute of Lehigh University in USA, in 1991 (Yusuf, Sarhadi, & Gunasekaran, 1999).

The origins of agility as a business concept lies in flexibility, named Flexible Manufacturing Systems (Christopher, 2000). Agility is a business-wide capability that embraces organisational structures, Information Systems (IS), logistics processes, and, in particular, mindsets (Christopher, 2000).

In terms of contributions of agility to SC, Agarwal, Shankar, & Tiwari (2007) have shown that the disposition of Agile SCM paradigm depends on the following variables: market sensitiveness, delivery speed, data accuracy, new product introduction, centralized and collaborative planning, process integration, use of Information Technology (IT) tools, lead time reduction, service level improvement, cost minimization, customer satisfaction, quality improvement, minimizing uncertainly, trust development, and minimizing resistance to change. In the most general sense, according to Ngai, Chau, & Chan (2011), SC agility is defined as the capability of SC functions to provide a strategic advantage by converting unexpected market uncertainties and potential and actual disruptions into competitive opportunities through assembling requisite assets, knowledge, and relationships with speed and surprise.

Nonetheless, a SCM paradigm should not be considered as a unique solution to a system. In this perspective, the designation Leagile emerged to divide the part of the SC that responds directly to the customer (demand is variable and high product variety) from the part that uses forward planning and strategic stock to buffer against the demand variability (demand is smooth and products are standard) (Naylor, et al., 1999). This means the Lean principles are followed up to the decoupling point and Agile practices are followed after that point.

Agile practices reflect the ability to respond quickly to unpredictable changes. Table 2.3 shows some Agile practices that can be implemented in different levels of the SC.

Table 2.3 Agile practices

SCM practice	Source
A_1: Ability to change delivery times of supplier's order	(Swafford, Ghosh, & Murthy, 2008)
A_2: Centralized and collaborative planning	(Agarwal, et al., 2007)
A_3: To increase frequencies of new product introduction	(Agarwal, et al., 2007; C.-T. Lin, Chiu, & Chu, 2006; Swafford, et al., 2008)
A_4: To reduce development cycle times	(Swafford, et al., 2008)
A_5: To speed in improving customer service	(Agarwal, et al., 2007; Swafford, et al., 2008)
A_6: To use IT to coordinate/integrate activities in design and development	(Agarwal, et al., 2007; Swafford, et al., 2008)
A_7: To use IT to coordinate/integrate activities in manufacturing	(Agarwal, et al., 2007; C.-T. Lin, et al., 2006; Swafford, et al., 2008)

2.1.3. Resilient

Many organisations designed their SC's with the principal objective of minimizing cost or optimising service (Tang, 2006). However, today's market is continuously affected by environmental and external actions, which inserts the concept of resilience as a way to cope with higher levels of turbulence and volatility. Resilience is seen in materials science and engineering as the ability of a material to return to its original state, when it is changed or deformed elastically.

This concept was adapted to a SCM perspective, defining it as the ability of a system to return to its original state or move to a new, more desirable state after being disturbed (Christopher & Peck, 2004). Using multidisciplinary perspectives, SC resilience is the adaptive capability of the SC to prepare for unexpected events, respond to disruptions, and recover from them by maintaining continuity of operations at the desired level of connectedness and control over structure and function (Ponomarov & Holcomb, 2009).

The goal of SC resilience analysis and management is to prevent the shifting to undesirable states, i.e., the ones where failure modes could occur (Azevedo, et al., 2011b). In SC's systems, the purpose is to react efficiently to the negative effects of disturbances (which could be more or less severe) (Azevedo, et al., 2011b). The aim of resilience strategies has two manifolds (Haimes, 2006):

- To recover the desired values of the states of a system that has been disturbed, within an acceptable time period and at an acceptable cost;
- To reduce the effectiveness of the disturbance by changing the level of the effectiveness of a potential threat.

The principles of designing resilience in SC are outlined by (Christopher & Peck, 2004): selecting SC strategies that keep several options open; re-examining the 'efficiency vs. redundancy' trade-off; developing collaborative working across SC's to help mitigating risk; developing visibility to a clear view of upstream and downstream inventories, demand and supply conditions, and production and purchasing schedules; improving SC velocity through streamlined processes, reduced in-bound lead times and NVA time reduction.

However, resilience is not always desirable if an organisation intends to increase profitability. For instance, Lean paradigm purpose is to have a low inventory level for reducing inventory cost, which makes it less Resilient. Therefore, the implementation of hybrid solutions that combine the previous paradigms with resilience could be difficult in some production scenarios (Espadinha-Cruz, 2012).

Table 2.4 shows a set of Resilient practices that can be implemented in different level in the chain, reflecting the entity ability to cope with unexpected disturbances.

Table 2.4 Resilient practices

SCM practice	Source
R_1: Creating total SC visibility	(Iakovou, Vlachos, & Xanthopoulos, 2007)
R_2: Developing visibility to a clear view of downstream inventories and demand conditions	(Christopher & Peck, 2004)
R_3: Flexible supply base/flexible sourcing	(Tang, 2006)
R_4: Flexible transportation	(Tang, 2006)
R_5: Lead time reduction	(Christopher & Peck, 2004; Tang, 2006)
R_6: Sourcing strategies to allow switching of suppliers	(Rice & Caniato, 2003)
R_7: Strategic stock	(Christopher & Peck, 2004; Iakovou, et al., 2007; Tang, 2006)

2.1.4. Green

In the past decades, environmental issues and global warming are becoming a subject of concern to organisations. Environment is the main focus of Green Supply Chain Management (GSCM) but, instead of focusing on the way environmental agents affect SC's, Green concerns with the effects of SC's activity on environment (Rao & Holt, 2005). The increased pressure from society and environmentally conscious consumers had lead to rigorous environmental regulations, such as the Waste Electrical and Electronic Equipment Directive in the European Union, forcing the manufacturers to effectively integrate environmental concerns into their management practices (Paulraj, 2009; Rao & Holt, 2005).

Although ecologically adopted legislative requirements, ecological responsiveness also led to sustained competitive advantage, improving their long-term profitability (Paulraj, 2009). GSCM has emerged as an organisational philosophy by which to achieve corporate profit and market-share objectives by reducing environmental risks and impacts while improving the ecological efficiency of such organisations and their partners (Rao & Holt, 2005; Sarkis, 2003).

According to Srivastava (2007), GSCM is an integrating environment thinking into SCM, including product design, material sourcing and selection, manufacturing processes, delivery of the final product to the consumers as well as end-of-life management of the product after its useful life. GSCM can reduce the ecological impact on industrial activity without sacrificing quality, cost, reliability, performance or energy utilization efficiency; meeting environmental regulations to not only minimize ecological damage but also to ensure overall economic profit (Srivastava, 2007).

In term, the impact of the antecedents and drivers for a Green SC may be diverse across different SC's with different manufacturing processes, with different raw materials, conversion processes, product characteristics, logistics/reverse logistics activities (Routroy, 2009).

The GSCM practices should aim at the reduction of environment impact. Table 2.5 shows some GSCM practices.

Table 2.5 Green practices

SCM practice	Source
G_1: Environmental collaboration with suppliers	(Holt & Ghobadian, 2009; Hu & Hsu, 2010; Lippmann, 1999; Vachon, 2007; Zhu, Sarkis, & Lai, 2007, 2008a, 2008b)
G_2: Environmental collaboration with the customer	(Holt & Ghobadian, 2009; Vachon, 2007; Zhu, et al., 2007, 2008a)

SCM practice	Source
G_3: Environmental monitoring upon suppliers	(Holt & Ghobadian, 2009; Hu & Hsu, 2010; Paulraj, 2009; Vachon, 2007; Zhu, et al., 2008a)
G_4: ISO 14001 certification	(Holt & Ghobadian, 2009; Hu & Hsu, 2010; Rao & Holt, 2005; Vachon, 2007; Zhu, et al., 2007, 2008a, 2008b)
G_5: Reverse logistics	(Hu & Hsu, 2010; Lippmann, 1999; Rao & Holt, 2005; Routroy, 2009; Vachon, 2007; Zhu, et al., 2007)
G_6: To reduce energy consumption	(González, Sarkis, & Adenso-Díaz, 2008; Holt & Ghobadian, 2009; Paulraj, 2009; Rao & Holt, 2005)
G_7: To reuse/recycling materials and packaging	(Holt & Ghobadian, 2009; Paulraj, 2009; Rao & Holt, 2005; Vachon, 2007)

2.2. Paradigms combination

In today's business environment the challenge is to integrate the previous four paradigms on the same SC. It may be difficult to categorize an organisation as being Lean, Agile, Resilient or Green. Therefore, it is essential to extend knowledge of the trade-offs between these four paradigms, assessing their contribute for efficiency, streamlining and sustainability of SC's.

Table 2.6 presents the principal attributes of Lean, Agile, Resilient and Green Supply Chains (LARG SC's), based on 10 attributes.

Table 2.6 LARG attributes (Carvalho, et al., 2011)

Attributes	SCM paradigm			
	Lean	Agile	Resilient	Green
Purpose	Focus on cost reduction and flexibility, for already available products through continuous elimination of waste or NVA activities across the chain.	Understands customer requirements by interfacing with customers and the market are being adaptable to future changes.	System ability to return to its original state or to a new, more desirable one, after experiencing a disturbance, and avoiding the occurrence or failure modes.	Focuses on sustainable development – the reduction of an ecological impact on industrial activity.

Attributes	SCM paradigm			
	Lean	**Agile**	**Resilient**	**Green**
Manufacturing focus	Maintains a high average utilization rate uses JIT practices, “pulling” the goods through the system based on demand.	Has the ability to respond quickly to varying customer needs (mass customization); it deploys excess buffer capacity to respond to market requirements.	The emphasis is on flexibility (minimal batch sizes and capacity redundancies); the schedule planning is based on shared information.	Focuses on efficiency and waste reduction for environmental benefit and development of remanufacturing capabilities to integrate reusable/remanufactu red components.
Alliance (with suppliers and customers)	May participate in traditional alliances such as partnerships and joint ventures at the operational level.	Exploits a dynamic type of alliance known as “virtual organisation” for product design.	SC partners join an alliance network to develop security practices and share knowledge.	Inter-organisational collaboration involving transferring or/and disseminating Green knowledge to partners and costumer cooperation.
Organisational structure	Uses a static organisational structure with few levels in the hierarchy.	Creates virtual organisations with partners that vary with different product offerings that change frequently.	Creates a SC risk management culture.	Creates an internal environmental management system and develops environmental criteria for risk-sharing.
Approach to choosing suppliers	Supplier attributes involve low cost and high quality.	Supplier attributes involve speed, flexibility, and quality.	Flexible sourcing.	Green purchasing.

Attributes	SCM paradigm			
	Lean	**Agile**	**Resilient**	**Green**
Inventory strategy	Generates high turns and minimizes inventory throughout the chain.	Makes decisions in response to customer demands.	Strategic emergency stock in potential critical points.	Introduces reusable/remanufactured parts in the material inventory; reduces replenishment frequencies to decrease carbon dioxide emissions; reduces redundant materials.
Lead time focus	Shortens lead time as long as it does not increase cost.	Invests aggressively in ways to reduce lead times.	Reduces lead time.	Reduces transportation lead time as long it does not increase carbon dioxide emissions.
Product design strategy	Maximizes performance and minimizes cost.	Designs products to meet individual customer needs.	Postponement.	Eco-design and incorporation of complete material life cycle for evaluating ecological risks and impact.
Product variety	Low.	High.	High.	For a multiproduct analysis environmental management decisions become increasingly complex.
Market	Serves only the current market segments, with a predictable demand.	Acquires new competencies, develops new product lines, and opens up new markets with a volatile demand.	Have the capabilities to act on and anticipate changes in markets and overcome demand risk.	Demands more environmentally-friendly practices.

From Table 2.6, it is possible to identify some interesting conflicts between the paradigms, for instance, Lean, Agile and Resilient paradigms require low inventory, but Resilience demands the existence of enough inventories to react to the unexpected disturbances.

In terms of product variety, an Agile and Resilient organisation must produce a high variety of products, while Lean paradigm is focused to produce improvements in resource productivity. As concerns about the Green, multiproduct analysis depends on the environmental impact.

Although these four paradigms seem to be contradictory, it would be ideal to combine two or more paradigms. The managers have to overcome these challenges, reconciling divergent paradigms to find the best strategies for their SC's.

2.3. Characteristics

To develop a fully integrated SC, it is necessary the evaluation of the paradigms practices contribution for SC performance. Since it would be difficult to analyse all possible relationships between performance measures and the paradigm implementation (designed by "management characteristics"), the study was limited to the principal paths between the Key Performance Indicators (KPI's) and management characteristics (Carvalho, et al., 2011).

Figure 2.1 contains the causal diagram with the performance indicators, namely service level, lead time and cost, and management characteristics relationships.

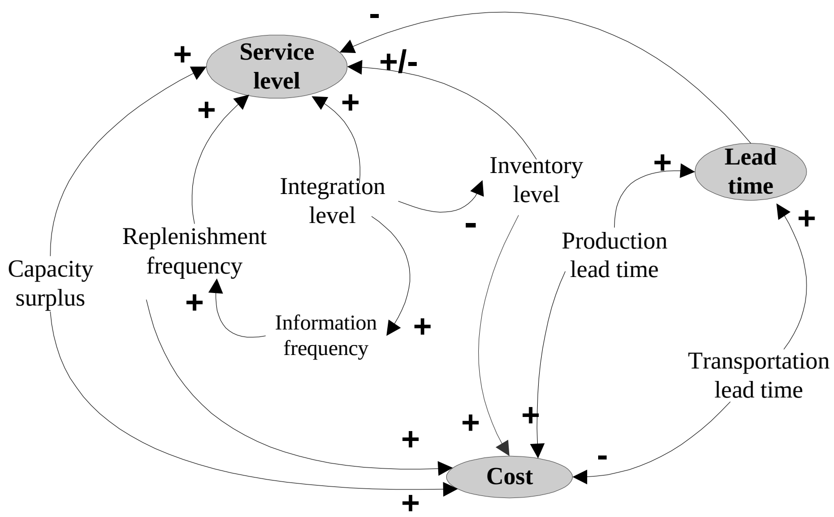

Figure 2.1 Performance indicators and management characteristics relationships (Carvalho, et al., 2011)

The causal diagram represented in Figure 2.1 depicts that, for example, the KPI "service level" is affected positively by the replenishment frequency (it increases the capacity to fulfil rapidly the material needs in SC) (Holweg, 2005), capacity surplus (a slack in resources will increases the capacity for extra orders production) (Jeffery, Butler, & Malone, 2008) and integration level (the ability to co-ordinate operations and workflow at different tiers of the SC allow to respond to changes in customer' requirements) (Gunasekaran, Lai, & Edwincheng, 2008). The lead time reduction improves the service level (Agarwal, et al., 2007).

The mark +/- is used to show that the inventory level has two opposite effects in the service level. Since it increases materials availability a higher service level is expected (Jeffery, et al., 2008). But this relation happens only under stable customer demands (Carvalho, et al., 2011).

High inventory levels generate uncertainties (Vorst & Beulens, 2002), leaving the SC more vulnerable to sudden changes (Marley, 2006), and therefore reducing the service level in volatile conditions. There are some relationships between the management characteristics, for instance, the inventory level is affected negatively by the increasing of the integration level (since it increases the procurement flexibility, minimizing the need for material buffers), decreasing the flexibility to meet current customers' demand (Carvalho, et al., 2011). This impact will reflect in Lean (we should have low inventory level to decrease the carrying cost) and Resilient (with low inventory level, we lose our capacity to respond to unexpected disruptions) paradigms and/or perhaps in Green (Cabral, 2011).

The trade-offs between LARG paradigms must be understood to help companies and SC's to become more efficient, streamlined and sustainable (Carvalho, et al., 2011). To this end, it is necessary to develop a deep understanding of the relationships (conflicts and commitments) between the LARG paradigms, exploring and researching their contribute for the sustainable competitiveness of the overall production systems in the SC (Carvalho, et al., 2011).

Table 2.7 shows an overview of main synergies and divergences between the LARG paradigms.

Table 2.7 Paradigms synergies and divergences overview (Carvalho, et al., 2011)

	Lean	Agile	Resilient	Green	
Information frequency	↑	↑	↑	-	Synergies
Integration level	↑	↑	↑	↑	
Production lead time	↓	↓	↓	↓	
Transportation lead time	↓	↓	↓	↓	
Capacity surplus	↓	↑	↑	↓	Divergences
Inventory level	↓	↓	↑	↓	
Replenishment frequency	↑	↑	↑	↓	

There are evidences that the LARG paradigms are completed by each other (Carvalho, et al., 2011). The implementation of these paradigms in the SC creates synergies in the way that some SC characteristics should be managed, namely, "information frequency", "integration level", "production lead time" and "transportation lead time" (Carvalho, et al., 2011). However, the impact of each paradigm implementation in the characteristic's magnitude may be different (Carvalho, et al., 2011). For example, the Lean paradigm seeks compulsively the reduction of production and transportation lead times to reducing the total lead time and minimizing the total waste (Carvalho, et al., 2011).

However, the Resilient paradigm, although it prescribes this reduction in lead times, it is not so compulsive, since the objective is to increase the SC visibility and capability to respond to unexpected disturbance (Carvalho, et al., 2011).

2.4. Performance measurement

The performance evaluation is an indispensable management tool to better SCM. Hence, performance measures are established to achieve goals and are provided with the intent to monitor, guide and improve across the different entities on the SC, and can encompass a variety of different metrics (Espadinha-Cruz, 2012). Research contributions from Azevedo, et al. (2011b) provide a set of performance measures that can be seen in Table 2.8.

Table 2.8 SC performance measures (Azevedo, et al., 2011b)

	Measures	Metrics	Source
Economic Performance	Cost	Cost per operating hour	(Pochampally, Nukala, & Gupta, 2009)
		Manufacturing cost	(Christiansen, Berry, Bruun, & Ward, 2003)
		New product flexibility	(Pochampally, et al., 2009)
	Efficiency	Operating expenses	(Jiang, Frazier, & Prater, 2006)
		Overhead expense	(Jiang, et al., 2006)
	Environmental costs	Costs for purchasing environmentally friendly materials	(Zhu, Sarkis, & Geng, 2005)
		Cost of scrap/rework	(Christiansen, et al., 2003)
		Disposal costs	(Tsai & Hung, 2009)
		Fines and penalties	(Hervani, Helms, & Sarkis, 2005)
		R & D expenses ratio	(Pochampally, et al., 2009)
		Recycling cost = transport + storage costs	(Tsai & Hung, 2009)
	Environmental revenues	Cost avoidance from environmental action	(Hervani, et al., 2005)
		Recycling revenues	(Hervani, et al., 2005)

	Measures	Metrics	Source
Environmental Performance	Environmental revenues	Revenues from 'green' products	(Hervani, et al., 2005)
	Business wastage	Hazardous and toxic material output	(Hervani, et al., 2005; Zhu, et al., 2005)
		Percentage of materials recycled/re-used	(Beamon, 1999)
		Percentage of materials remanufactured	(Hervani, et al., 2005)
		Solid and liquid wastes	(Zhu, et al., 2005)
		Total flow quantity of scrap	(Beamon, 1999; Tsai & Hung, 2009)
	Emissions	Air emission	(Zhu, et al., 2005)
		Energy consumption	(Hervani, et al., 2005; Zhu, et al., 2005)
		Green house gas emissions	(Hervani, et al., 2005)
	Green image	Number of fairs/symposiums related to environmentally conscious manufacturing the organisation participate	(Pochampally, et al., 2009)
Operational Performance	Customer satisfaction	After-sales service efficiency	(Pochampally, et al., 2009)
		Out-of-stock ratio	(Kainuma & Tawara, 2006)
		Rates of customer complaints	(Cai, Liu, Xiao, & Liu, 2009; Soni & Kodali, 2009)
	Delivery	Delivery reliability	(Soni & Kodali, 2009)
		On time delivery	(Pochampally, et al., 2009; Soni & Kodali, 2009)
		Responsiveness to urgent deliveries	(Soni & Kodali, 2009)
	Inventory levels	Finished goods equivalent units	(Goldsby, Griffis, & Roath, 2006)

	Measures	Metrics	Source
Operational Performance	Inventory levels	Level of safety stocks	(Sheffi & Rice, 2005)
		Order-to-ship	(Goldsby, et al., 2006)
	Quality	Customer reject rate	(Christiansen, et al., 2003)
		In plant defect fallow rate	(Christiansen, et al., 2003; Hugo & Pistikopoulos, 2005)
		Increment products quality	(Pochampally, et al., 2009)
	Time	Cycle times	(Martin & Patterson, 2009)
		Delivery lead time	(Soni & Kodali, 2009)
		Lead time	(Naylor, et al., 1999)

Chapter 3. Interoperability

3.1. Concept review
3.2. Business interoperability
3.3. Interoperability measurement
3.4. Perspectives of interoperability
3.4.1. Syntax
3.4.2. Semantics
3.4.3. Pragmatics

Interoperability issues arise whenever systems or organisations need to exchange information and work together to achieve common goals (Espadinha-Cruz, 2012). In today's economy, networked business models are becoming an indisputable reality which allows organisations to offer innovate products and services and the efficient business conduction (Legner & Lebreton, 2007). However, there are many barriers in internal and external relationships, namely conceptual, technological and organisational.

In Supply Chain Management (SCM) context, it is needed to be as efficient as possible in the planning and execution processes, in order to have an internal and external stable network (Espadinha-Cruz, 2012). However, even in a well-structured and integrated network, interoperability issues are always presents (Espadinha-Cruz, 2012).

Interoperability has been often discussed from a purely technical perspective, focusing on technical standards and Information Systems (IS) architectures (Legner & Lebreton, 2007). During its research, Legner & Lebreton (2007) feel that there was a lack of systematic analysis of strategic, organisational and operational issues associated with interoperability. Most of publications have explored interoperability in specific industry domains where compatibility is still low, such as: public sector (Guijarro, 2007; Kaliontzoglou, Sklavos, Karantjias, & Polemi, 2005; Otjacques, Hitzelberger, & Feltz, 2007; Roy, 2006), health care (Eckman, Bennett, Kaufman, & Tenner, 2007; Egyhazy & Mukherji, 2004), manufacturing (Brunnermeier & Martin, 2002; H.-K. Lin, Harding, & Shahbaz, 2004) and telecommunications (Moseley, Randall, & Wiles, 2004).

3.1. Concept review

In literature review, several definitions of the concept of interoperability exist. This concept has been constantly varying as the concern for the subject increases (Espadinha-Cruz, 2012). Most organisations extend this preoccupation to business level (Espadinha-Cruz, 2012).

Some of the definitions found in literature are presented in Table 3.1.

Table 3.1 Interoperability definitions

Definition	Source
"The ability of two or more systems or components to exchange information and to use the information that has been exchanged."	(IEEE, 1990)
"The capability to communicate, execute programs, or transfer data among various functional units in a manner that requires the user to have little or no knowledge of the unique characteristics of those units."	(ISO, 1993)
"The ability of a system to communicate with peer systems and access their functionality."	(Vernadat, 1996)
"The ability of systems, units, or forces to provide services to and accept services from other systems, units, or forces, and to use the services so exchanged to enable them to operate effectively together."	(DoD, 1998)
"Ability of interaction between enterprise software applications."	(IDEAS, 2003)
"The ability of information and communication technology systems and of the business processes they support to exchange data and to enable sharing of information and knowledge."	(IDA, 2004)
"(1) The ability to share information and services; (2) The ability of two or more systems or components to exchange and use information; (3) The ability of systems to provide and receive services from other systems and to use the services so interchanged to enable them to operate effectively together."	(OpenGroup, 2009)

Looking at all these definitions, one can deduce that the interoperability is the ability of two or more systems to share and use information in order to operate effectively together with the objective to create value. Nevertheless, to DoD (1998) interoperability is more than systems and interaction with systems to electronic exchange information. In this definition it is also exposed the human perspective. These perspectives have been extended to the enterprise reality, enclosing Information Technology (IT) structures, business processes and strategy (Espadinha-Cruz, 2012).

3.2. Business interoperability

The concept of business interoperability has emerged as an evolution in the contents studied in the various approaches, allowing to face major challenges (Espadinha-Cruz, 2012).

In the context of the ATHENA project, business interoperability is defined as “the organisational and operational ability of an enterprise to cooperate with its business partners and to efficiently establish, conduct and develop IT-supported business relationships with the objective to create value” (ATHENA, 2006). Based on this definition, business interoperability involves specific characteristics of the inter-organisational design of a company’s external relationships (ATHENA, 2006). It extends the more technical focussed notion of interoperability to cover organisational and operational aspects of setting up and running IT-supported relationships (ATHENA, 2006). As such, business interoperability builds on the concept of networkability (Osterle, Fleisch, & Alt, 2001; Wigand, Picot, & Reichwald, 1997) which is a continuation of coordination theory and sees coordination as the management of relationships of dependence (ATHENA, 2006).

Figure 3.1 depicts the hierarchical nature of business interoperability that most architectural and model based approaches to the subject stress at (Zutshi, 2010).

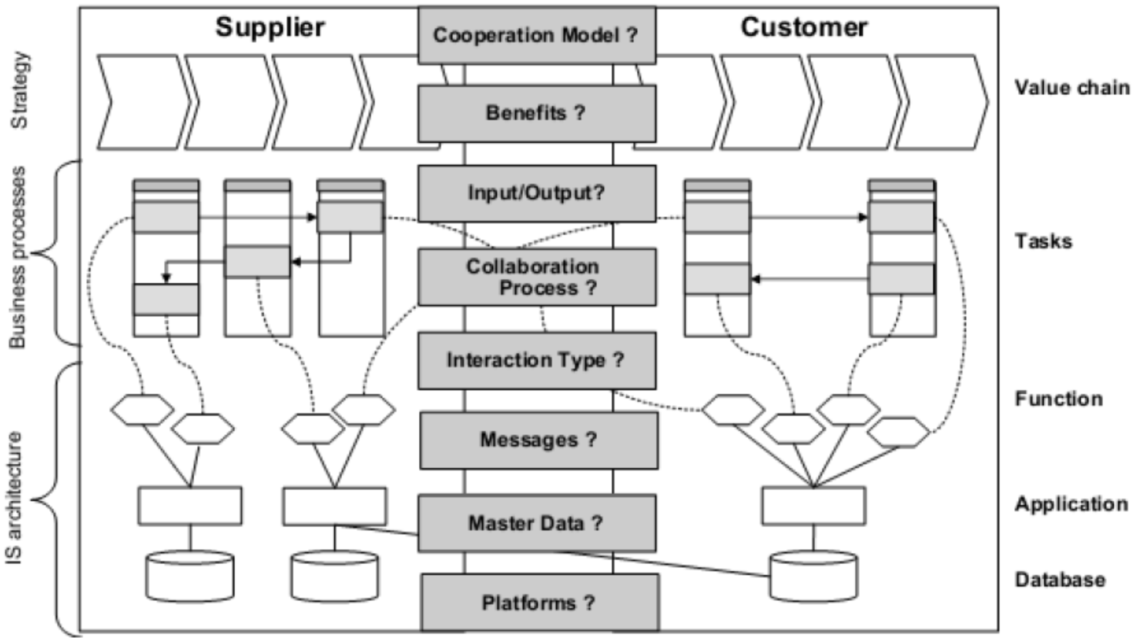

Figure 3.1 Different aspects of interoperability (ATHENA, 2006)

This figure shows that any model of business interoperability would comprise of the strategy at the highest level, followed by business process and the IS architecture coming at the lowest level (Zutshi, 2010). Business interoperability requires the multi-layered collaboration with each level complementing the other for the smooth functioning of the overall collaboration (Zutshi, 2010).

The increasing use of IT had led to various interoperability issues that had to be solved in order to achieve seamlessly integrated collaboration (Legner & Lebreton, 2007). This direct to various approaches to interoperability to pass through several stages: syntactic, semantic and pragmatic (Espadinha-Cruz, 2012).

3.3. Interoperability measurement

The measurement of interoperability is part of the sensitive analysis of identification and improvement of problems of interoperability (Espadinha-Cruz, 2012). In the context of business interoperability, Legner & Lebreton (2007) argue that research efforts must be spent in finding out which level of interoperability a firm struggle for. The first proposed step is to define where a firm currently is and where it should be (Legner & Lebreton, 2007). For this purpose, interoperability frameworks, such as DoD (1998) and EIF (2004), already provide a concept to perform such kind of assessment but the determination of the target level of interoperability still remains, to a greater extent, heuristic. For instance, in a strongly IT-supported automotive Supply Chain (SC), interoperability level is expected to be high, in order to deal with the complexity of products (Espadinha-Cruz, 2012).

This considerations lead to the introduction of the concept of optimal interoperability (Espadinha-Cruz, 2012). Since is not possible to assign a target to optimal level of interoperability valid for all types of collaboration, this level should be established for each type of business (Espadinha-Cruz, 2012). For example, IS in the tourism industry especially related to hotel booking cannot be so tightly integrated as tourism agencies want to target the maximum reach of hotels and lodges (Zutshi, 2010).

In the literature, interoperability measurement is addressed by two different kinds: qualitative and quantitative. Whereas the first approach refers to model-driven approaches, the quantitative approach is used to estimate states of lack of interoperability (Espadinha-Cruz, 2012).

3.4. Perspectives of interoperability

In literature review it is possible to conclude that the study of interoperability consists on three principal phases: syntactic, semantic and pragmatic (Espadinha-Cruz, 2012).

In the communication theory, the semiotics view defines it as a transmitting message from a sender to a receiver using a channel (ATHENA, 2006). As depicted in Figure 3.2, this communication involves three subjects (ATHENA, 2006):

- **Syntax –** studies the structure of the message;
- **Semantics –** refers to the relation between signs and the objects to which they apply and enable the receiver of a message to understand it;
- **Pragmatics -** adds some aspects of the practice to a better understanding of the theory.

These three constitute the relation of signs and interpreters, so that the message has a meaning for the receiver and therefore allows him to react with regards to the content of the message (ATHENA, 2006).

Similarly, in business interoperability aspects of semantics and pragmatics are related to a message, whereas technical interoperability is more related to syntactical and infrastructure aspects (ATHENA, 2006)

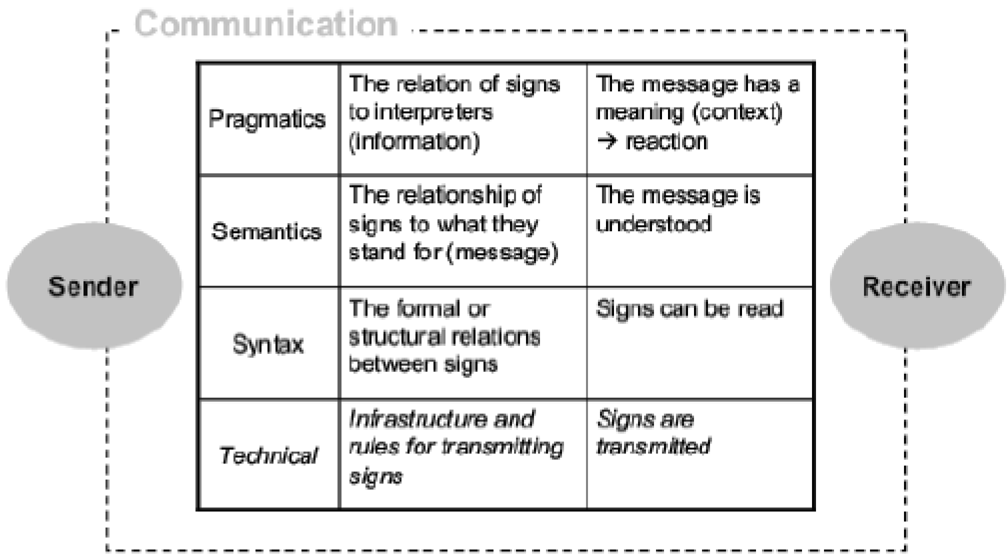

Figure 3.2 Semiotic aspects of communication (ATHENA, 2006)

3.4.1. Syntax

In traditional grammar, syntax is the "arrangement of words (in their appropriate forms) by which their connection and relation in a sentence are shown" or "the department of grammar which deals with the established usages of grammatical construction and the rules deducted therefrom" (Oxford English Dictionary). Veltman (2001) refers to it as "grammars to convey semantics and structure".

In interoperability, the syntactic phase is characterized by describing various sets of rules and principles that describe the language and structure for the information (Espadinha-Cruz, 2012). If two or more systems are capable of communicating and exchanging data, they exhibit syntactic interoperability (Espadinha-Cruz, 2012). For instance, XML (Extensible Markup Language) is seen as a mark-up idiom for structured data on web (Veltman, 2001). Hence, with syntax in the traditional sense, the challenges of syntactic interoperability become (Veltman, 2001):

a) Identifying all the elements in various systems;
b) Establishing rules for structuring these elements;
c) Mapping, bridging, creating crosswalks between equivalent elements using schemes etc.;
d) Agreeing on equivalent rules to bridge different cataloguing and registry systems.

Using these guidelines, syntactic interoperability is ensured when collaborating systems should have a compatible way of structuring data during exchange, i.e., the manner in which data is be codified using a grammar or vocabulary is compatible (Asuncion & van Sinderen, 2010).

3.4.2. Semantics

Semantics is defined as the meanings of terms and expressions (Veltman, 2001). It focuses on the relation between signifiers (in linguistic, words, phrases and symbols), and what they stand for, their denotation (Espadinha-Cruz, 2012). Hence, semantic interoperability is “the ability of IS to exchange information on the basis of shared, pre-established and negotiated meanings of terms and expressions”, and is needed in order to achieve other types of interoperability work (Veltman, 2001).

Besides the technological perspective, in medicine, for instance, the definition of the aorta must be the same around the world if doctors in Berlin, Rio, Shanghai, Sydney and Los Angeles all have to operate on the heart (Veltman, 2001).

The role of semantic interoperability is to develop a deep understanding of the structure beyond the information (Espadinha-Cruz, 2012). If the syntax, on the one hand, governs the structure of data (XML and Structured Query Language, SQL), on the other hand, the semantics should regulate the meaning of the terms in the expression, and make it compatible between systems (Espadinha-Cruz, 2012). To achieve semantic interoperability, both sides must refer to a common information exchange reference model (Espadinha-Cruz, 2012). The content of the information exchange requests are explicitly defined: what is sent is the same as what is understood (Espadinha-Cruz, 2012). If there is any context sensitivity to the way terms are used, then the context must also be specified as part of the information using those terms (Espadinha-Cruz, 2012). To ensure semantic interoperability, the meaning of the syntactic elements should be understood by collaborating systems (Asuncion & van Sinderen, 2010).

3.4.3. Pragmatics

Pragmatics or pragmatism is derived from the Greek etymology that means “to do”, "to act” or “to be practical” (Asuncion & van Sinderen, 2010). It describes the process where theory is extracted from practice, and applied back to practice to form what is called intelligent practice (Espadinha-Cruz, 2012).

To ensure pragmatic interoperability, message sent by a system causes the effect intended by that system (Asuncion & van Sinderen, 2010). Therefore, pragmatic interoperability can only be achieved if systems are also syntactically and semantically interoperable (Pokraev, 2009).

Chapter 4. Supply Chain simulation

4.1. General overview
4.2. Storyline
4.3. Model development: an automotive Supply Chain
4.3.1. Supply Chain characterization
4.3.2. Characteristics and assumptions
4.3.3. Conceptual model
4.3.4. Input data and parameters
4.3.5. Simulation model
4.4. Results and discussion

In Supply Chain Management (SCM) context, there are still evident problems to overcome, particularly in designing, evaluating and optimising Supply Chains (SC's). From the Information Technology (IT) perspective, among all the multi-decisional techniques supporting a logistics network, simulation appears as an essential tool that allow the quantitative evaluation of benefits and issues deriving from a co-operative environment. This combination should provide the basis for a realistic simulation model, which is both transparent and complete (Zee & Vorst, 2005). The need for transparency is especially strong for SC's as they involve (semi)autonomous parties each having their own objectives (Zee & Vorst, 2005). Mutual trust and model effectiveness are strongly influenced by the degree of completeness of each party's insight into the key decision variables (Zee & Vorst, 2005).

The choice of the level of detail is also an important issue in SC models (Persson & Araldi, 2009). Despite the model's level of detail being one of the major difficulties is SC simulation, it is not uncommon to simulate at a level of detail that does not match the objective of the analysis (Persson & Araldi, 2009).

4.1. General overview

In the past two decades, a large number of simulation tools for SC analysis have been developed (Zee & Vorst, 2005). Some of these tools are internal packages developed and used by a single company (Zee & Vorst, 2005). Besides these, some commercially available packages were also developed (Zee & Vorst, 2005). Most of these packages are not built from scratch, but concern applications of general-purpose simulation languages, such as, for example, Arena (Kelton, Sadowski, & Sadowski, 1998), Micro Saint (Micro Analysis & Design, 1998), and Extend (Imagine That, 1997).

Simulation is preferred to deal with stochastic natures existing in the SC (Lee, Cho, Kim, & Kim, 2002). Most SC simulation models have been developed on the basis of discrete-event simulation, which allows evaluating queuing situations and other phenomena dependent upon uncertainty in operation and transportation times (Lee, et al., 2002; Persson & Olhager, 2002).

The main reasons to use discrete-event simulation for system analysis in SCM are (Persson & Araldi, 2009):

- The possibility to include dynamics;
- The simplicity of modelling.

However, its suitability does not guarantee adequate decision support, that is, mutually accepted candidate SC scenarios for which a high performance is indicated (Zee & Vorst, 2005). After all, simulation boils-down to a heuristic search for good quality solutions led by people (Zee & Vorst, 2005). Therefore, the success of a simulation study largely depends on the joint availability and use of the skills of the analyst and the chain members, as well as the facilities offered by the simulation tool (Zee & Vorst, 2005).

Figure 4.1 illustrates the basic process flow that is useful for SC simulation (Lee, et al., 2002). This procedure first reads all data required by a graphic user interface (Lee, et al., 2002). This includes products, market, sales data, and detailed data on the operation of each facility in the SC (Lee, et al., 2002). Customer demand is then calculated through a forecasting method based on historical data (Lee, et al., 2002). After that optimisation modules (supplier selection, location, inventory, transportation, etc.) are run with the configuring and planning parameter in the database (Lee, et al., 2002).

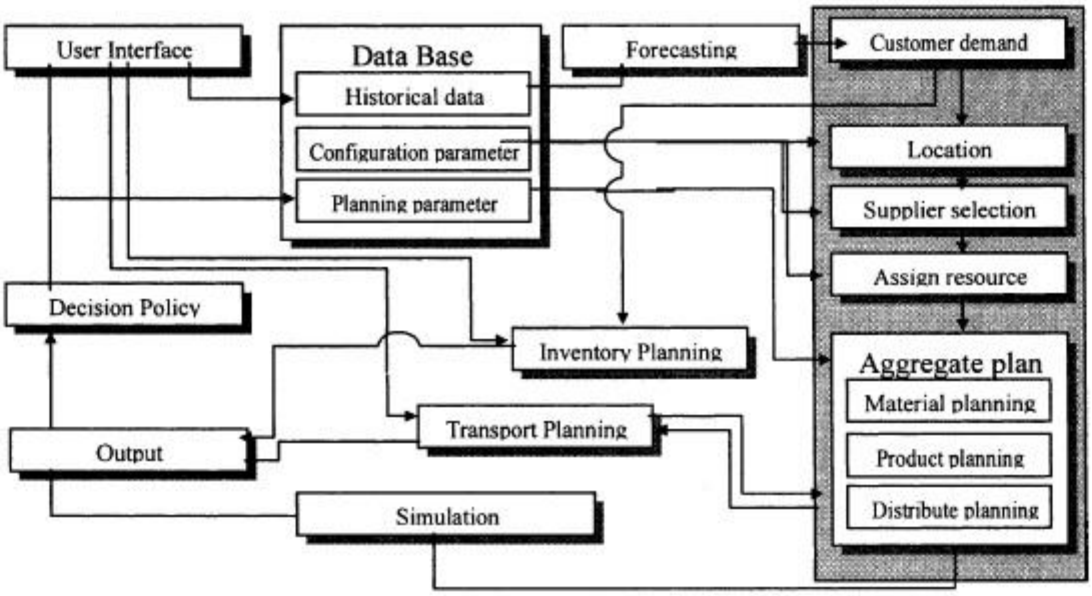

Figure 4.1 Basic process flow for SC simulation (Lee, et al., 2002)

4.2. Storyline

Before starting the model development, it is important to understand the contribution of each chapter to this thesis. Figure 4.2 depicts the contributions of chapters 2, 3 and 4 to this work and the way they relate.

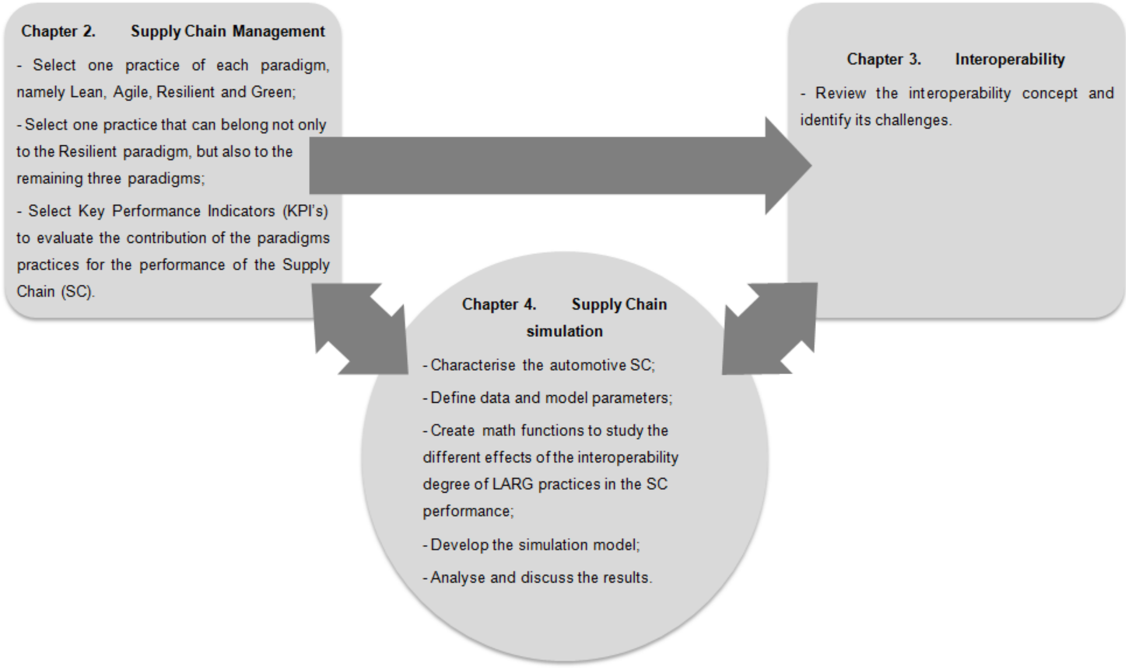

Figure 4.2 Summary of contributions to this thesis

From Figure 4.2 it can be seen that, in the context of this dissertation, SCM, interoperability and SC simulation may be directly and/or indirectly related. To achieve global success, SC's need to overcome many barriers in internal and external relationships, namely conceptual, technological and organisational. Therefore, the implementation of Lean, Agile, Resilient and Green (LARG) practices without interoperability issues is extremely important to an effective SCM. In this perspective, simulation can help in the decision-making processes through the evaluation and comparison of virtual scenarios.

From the Information Technology (IT) perspective, among all the multi-decisional techniques supporting a logistics network, simulation appears as an essential tool that allow the quantitative evaluation of benefits and issues deriving from a co-operative environment.

In first instance, some LARG practices were selected from a SCM perspective. Considering these LARG practices, which were selected based on literature review, it were defined two different scenarios. Note that the selected LARG practices, as well as the scenarios description will be discussed with more detail at the middle of chapter 4. The analysis of both scenarios was made through Key Performance Indicators (KPI's) such as cost, lead time and service level. These KPI's were selected in order to evaluate the performance of the automotive SC.

Looking at the aim of this dissertation, it was also necessary to study the interoperability concept and its challenges. Therefore, chapter 3 provided the know-how that allowed defining the classification of the interoperability degree of LARG practices, which will be also discussed on chapter 4.

Finally, SCM and interoperability concepts will be converged in a SC simulation context. From this perspective, chapter 4 is mainly focused on the development of the automotive SC simulation model, with the help of Rockwell Arena 9.0 simulation software. However, the development process of a simulation model must follow a set of steps that starts with the problem formulation, which includes the definition of the objectives and the involved variables. In this case, it was conducted a study at a Portuguese automotive SC, which will be described below. After the description of the main characteristics, assumptions and model components, it should be developed the conceptual model, which requires an initial validation. The next step consists in the specification of the model parameters, based on the collection of data. Note that some of the inputs were defined based on a journal article written by Carvalho, Barroso, Machado, Azevedo, & Cruz-Machado (2012), and others were assumed based on the information encountered in the conducted research. Once the previous steps are completed, it can be made the conversion of the model specifications in a computational model, followed by the model verification and validation. The verification step should answer the question related to the fact if the model is correctly built. On the other hand, the validation allows answering the question related to the construction of the correct model. The development process of a simulation model ends with the analysis of the simulation results.

Since simulation modelling is a research work, it can be necessary to adapt SCM and/or interoperability concepts regarding the possible limitations that may appear during the simulation model development.

4.3. Model development: an automotive Supply Chain

In order to study the proposed objectives, an exploratory case study was conducted at some entities of a Portuguese automotive SC. The Portuguese auto components industry exports 98.9% of productions, and plays a strategic role in the economy, representing 1.4% of the country's Gross Domestic Product.

Besides the economic relevance of this sector, the automotive SC also presents (Carvalho, et al., 2012):

- A Lean production environment;
- Pressure to reduce costs and lead times;
- End customers' demand for highly customized products.

Since the automotive SC is very complex, with hundred of parts, components and materials flowing from hundreds of suppliers, located in different countries, to the automaker only a subset of the SC was selected and analysed (Carvalho, et al., 2012). The boundaries were defined according to the automaker. First the vehicle model to be studied was defined. Then critical First tier Suppliers (1tS) were identified. In turn, these 1tS identified their critical direct suppliers, namely Second tier Suppliers (2tS).

4.3.1. Supply Chain characterization

One of the entities of the automotive SC is an automaker which is located in Portugal and is responsible for the production of four different models of vehicle, with an installed capacity for over 180.000 vehicles per year (Carvalho, et al., 2012). All vehicles produced are customized according to the end customer's requirements, namely body colour, interior trim instrument panel and engine characteristics. The automaker manages its operations according to the Just-In-Time (JIT) and Lean philosophies, and customer orders.

In a virtual zero stocks environment, and with a highly customized, demanding production environment, it is necessary to coordinate the material flow along the whole SC, assuring that the automaker has the right components at the right time to fulfil customer orders (Carvalho, et al., 2012). To obtain high quality components and materials, with low cost and high reliability in deliveries, the automaker developed long-term relationships with about 670 suppliers (Carvalho, et al., 2012).

As represented in Figure 4.3, the subset automotive SC involved in this work is a five-echelon SC, composed by two 2tS (suppliers 2_1 and 2_2), two 1tS (suppliers 1_1 and 1_2), the automaker, one First tier Distributor (1tD) and the end customer. The customer demand, which comes from different countries or continents, has an associated uncertainty that follows an Exponential distribution with mean 30 days.

Regarding to the 1tS, in spite of they are located in the same geographic region as the automaker, they have critical suppliers (2tS), with a long time correspondent to the transportation of materials (Carvalho, et al., 2012).

Figure 4.4 shows part of the vehicle Bill Of Materials (BOM) with the critical sub-assemblies, components and materials that that flow in the subset SC (Carvalho, et al., 2012).In fact, one unit of the vehicle subset requires one component and one sub-assembly. In turn, one component requires one material 2 and one sub-assembly requires one material 1.

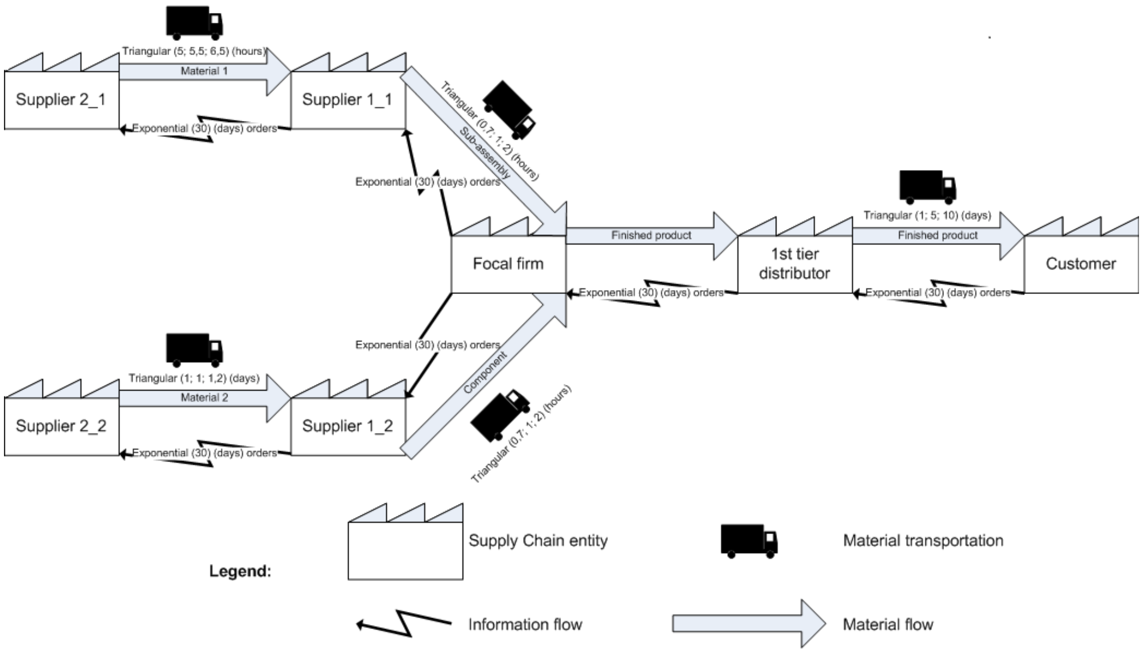

Figure 4.3 Automotive SC

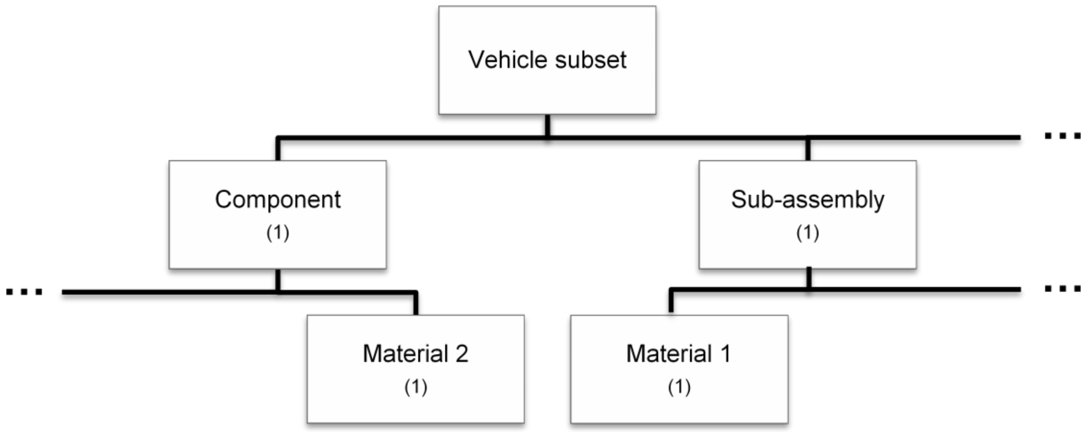

Figure 4.4 BOM

4.3.2. Characteristics and assumptions

In all simulation studies it is relevant to specifically point out the model characteristics and assumptions made in order to get the simulation model to operate (Persson & Olhager, 2002).

The characteristics of the automotive SC include:

- Customer demands are pulled through the SC (Carvalho, et al., 2012);
- Final product demand is completely fulfilled. A material/product shortage will be backordered and delivered as soon as possible (Carvalho, et al., 2012);
- All entities, except the customer and 2tS, behave, on one hand, like a customer, placing orders and receiving materials and, on the other hand, like a supplier, delivering products;
- The Focal Firm (FF) and suppliers' production planning follows a make-to-order policy;

- The orders are processed using a First In First Out (FIFO) rule;
- All resources assigned to a process have a fixed capacity of one unit;
- The resources costs are equal to one Monetary Unit (MU);
- The processing and maintenance times follow a Triangular distribution. The breakdowns and customer orders follow an Exponential distribution;
- Two different scenarios are considered to assess practices and interoperability. In the first scenario, it will be considered one practice of each paradigm and in the second, it will only be considered one practice that can belong to the four paradigms.

In order to manage Arena simulation complexity, several assumptions were made:

- It is not considered the rejection of orders placed by the customer;
- Each order is composed by a constant amount of a single type of product;
- The model has a work day of twenty-four hours, a seven-day work week and a twelve-month work year;
- Days are the basic time unit in the model;
- The simulation is replicated for a time period of 470 days;
- Human resources have an attendance index of 100%;
- No planned level of safety stock is assumed;
- There is no time delay associated with transferring batches between production, quality control or reworking processes.

4.3.3. Conceptual model

Before developing the automotive SC simulation model, it is necessary to design the conceptual model in order to define data and model parameters. The use of flowcharts describes part of reality or real system that can be used in the creation of SC simulation models.

The flowchart depicted in Figure 4.5 represents the processes and global functioning of the automotive SC. It should be noted that interoperability issues are only associated with the logistics processes that are involved in placing and reception orders. Looking at Figure 4.5, one can verify that automotive SC processes are executed by each entity, excepting the customer and FF, always respecting the three steps represented by the separators. The first step, namely “Receive order”, starts when the 1tD receives the customer order. Since customer demands are pulled through the SC, the 1tD places an order to the FF and the downstream entities, which in this case are the 1tS, receive the order from their upstream entity, the FF, and place an order to the 2tS. After receiving the order from 1tS, the 2tS start the step “Process order” with the production process. If the entities adopt a quality control policy, the products need to be inspected and, in case of non conformity, they should be reworked. The last step includes the products delivery to the upstream entities, i.e., the 1tS, whose logic is similar. When the FF has the products available, the 1tD is responsible for deliver the product to the customer at the right quantities, to right locations, and at the right time.

It should be noted that each process is composed by a set of duly organised activities whose processing involves the use of resources, during a certain period of time and, consequently, with a cost associated (Carvalho, et al., 2012).

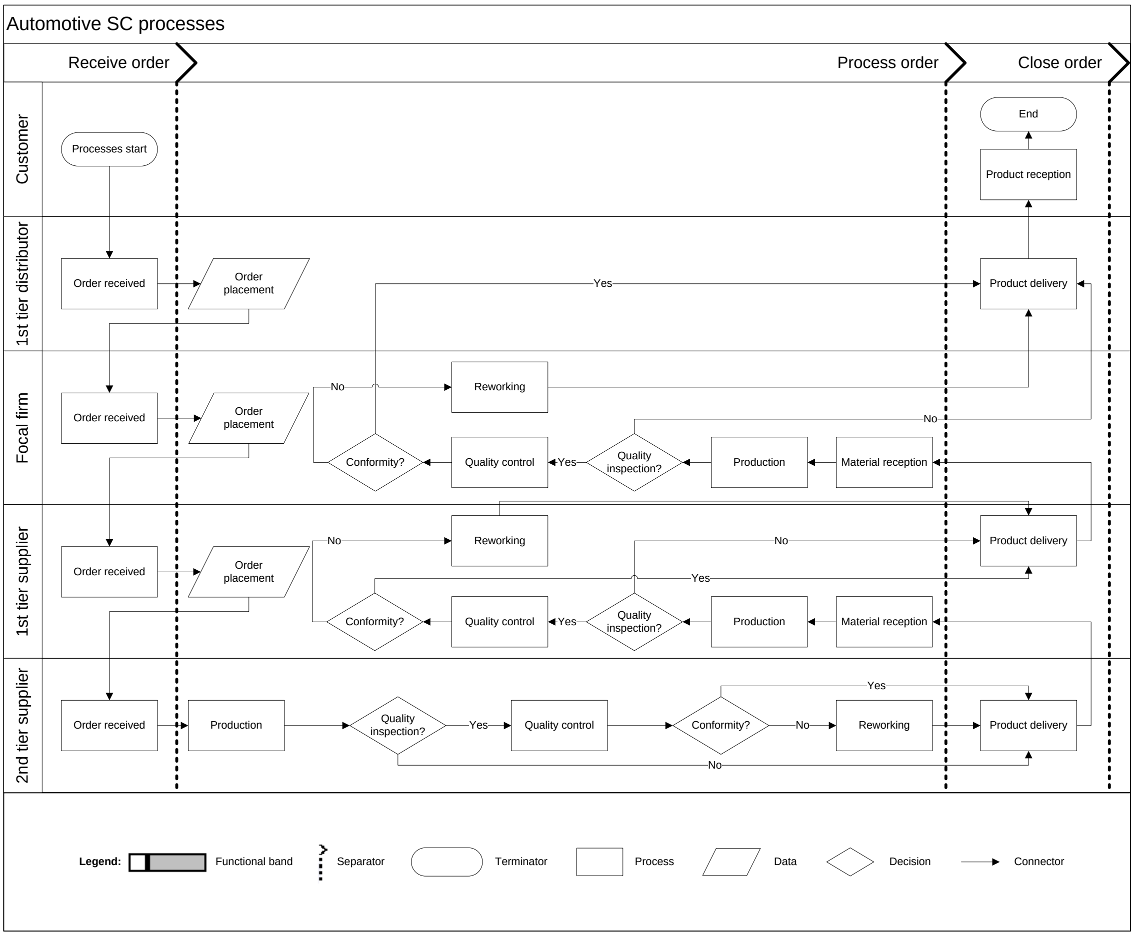

Figure 4.5 Automotive SC flowchart

4.3.4. Input data and parameters

Since the purpose of this dissertation is to assess LARG practices and interoperability, some of the inputs were defined based on a journal article written by Carvalho, Barroso, Machado, Azevedo, & Cruz-Machado (2012), and others were assumed based on the information encountered in the conducted research.

Tables 4.1, 4.2, 4.3 and 4.4 show the simulation model data displayed on the spreadsheet view of the Arena modelling environment, such as times, costs, and other parameters.

Table 4.1 Entity spreadsheet

	Entity Type	Initial Picture	Holding Cost / Hour	Initial VA Cost	Initial NVA Cost	Initial Waiting Cost	Initial Tran Cost	Initial Other Cost
1	Customer order specification	Picture.Report	0.0	0.0	0.0	0.0	0.0	0.0

It is assumed that all customer orders have no initial costs associated, as well as holding cost per hour.

Table 4.2 Queue spreadsheet

	Name	Type
1	Close order.Queue	First In First Out
2	Products quality control.Queue	First In First Out
3	Products manufacturing.Queue	First In First Out
4	Sub assemblies receive.Queue	First In First Out
5	Materials 1 quality control.Queue	First In First Out
6	Components manufacturing.Queue	First In First Out
7	Components quality control.Queue	First In First Out
8	Materials 1 manufacturing.Queue	First In First Out
9	Material 1 receive.Queue	First In First Out
10	Products reworking.Queue	First In First Out
11	Components reworking.Queue	First In First Out
12	Materials 1 reworking.Queue	First In First Out
13	Material 1 receive_Maximum interoperability degree.Queue	First In First Out
14	Material 2 receive_Maximum interoperability degree.Queue	First In First Out
15	Material 2 receive.Queue	First In First Out
16	Close order_Maximum interoperability degree.Queue	First In First Out
17	Sub assemblies receive_Maximum interoperability degree.Queue	First In First Out
18	Components receive_Maximum interoperability degree.Queue	First In First Out
19	Components receive.Queue	First In First Out
20	End of materials 1 manufacturing process.Queue	First In First Out
21	Materials 2 manufacturing.Queue	First In First Out
22	Materials 2 quality control.Queue	First In First Out
23	Materials 2 reworking.Queue	First In First Out
24	End of materials 2 manufacturing process.Queue	First In First Out
25	Sub assemblies manufacturing.Queue	First In First Out
26	Sub assemblies quality control.Queue	First In First Out
27	Sub assemblies reworking.Queue	First In First Out
28	End of sub assemblies manufacturing process.Queue	First In First Out
29	End of components manufacturing process.Queue	First In First Out
30	End of products manufacturing process.Queue	First In First Out
31	Batch 1st tier suppliers deliveries.Queue	First In First Out
32	Batch 1st tier suppliers deliveries_Maximum interoperability degree.Queue	First In First Out

One can verify that the orders are processed using a FIFO rule, as pointed out in the characteristics of the automotive SC.

From Table 4.3, it can be seen that all resources have a fixed capacity of one unit and a cost equal to one MU, as also mentioned in the model characteristics. Note that all human resources have always a unit cost, whether they are busy or idle. Regarding the remaining resources, it is assumed that the equipments and transporters have only costs when they are busy, while the required materials have a unit cost associated with their use. The column “Failures” indicates the number of failures, particularly maintenance or breakdowns, associated to each resource.

Table 4.3 Resource spreadsheet

	Name	Type	Capacity	Busy / Hour	Idle / Hour	Per Use	StateSet Name	Failures
1	1st tier distributor firm employees	Fixed Capacity	1	1	1	0.0		0 rows
2	1st tier distributor firm transporters	Fixed Capacity	1	1	0.0	0.0		2 rows
3	Supplier 1_1 firm transporters	Fixed Capacity	1	1	0.0	0.0		2 rows
4	Supplier 1_2 firm transporters	Fixed Capacity	1	1	0.0	0.0		2 rows
5	Focal firm manufacturing equipments	Fixed Capacity	1	1	0.0	0.0		2 rows
6	Focal firm manufacturing employees	Fixed Capacity	1	1	1	0.0		0 rows
7	Focal firm quality managers	Fixed Capacity	1	1	1	0.0		0 rows
8	Supplier 1_1 firm logistic employees	Fixed Capacity	1	1	1	0.0		0 rows
9	Supplier 1_2 firm logistic employees	Fixed Capacity	1	1	1	0.0		0 rows
10	Supplier 2_1 firm logistic employees	Fixed Capacity	1	1	1	0.0		0 rows
11	Supplier 2_1 firm transporters	Fixed Capacity	1	1	0.0	0.0		2 rows
12	Supplier 1_1 firm manufacturing equipments	Fixed Capacity	1	1	0.0	0.0		2 rows
13	Supplier 1_1 firm manufacturing employees	Fixed Capacity	1	1	1	0.0		0 rows
14	Supplier 1_1 firm quality managers	Fixed Capacity	1	1	1	0.0		0 rows
15	Supplier 2_2 firm logistic employees	Fixed Capacity	1	1	1	0.0		0 rows
16	Supplier 2_2 firm transporters	Fixed Capacity	1	1	0.0	0.0		2 rows
17	Supplier 1_2 firm manufacturing employees	Fixed Capacity	1	1	1	0.0		0 rows
18	Supplier 1_2 firm manufacturing equipments	Fixed Capacity	1	1	0.0	0.0		2 rows
19	Supplier 1_2 firm quality managers	Fixed Capacity	1	1	1	0.0		0 rows
20	Supplier 2_1 firm manufacturing employees	Fixed Capacity	1	1	1	0.0		0 rows
21	Supplier 2_1 firm manufacturing equipments	Fixed Capacity	1	1	0.0	0.0		2 rows
22	Supplier 2_1 firm quality managers	Fixed Capacity	1	1	1	0.0		0 rows
23	Supplier 2_2 firm manufacturing equipments	Fixed Capacity	1	1	0.0	0.0		2 rows
24	Supplier 2_2 firm manufacturing employees	Fixed Capacity	1	1	1	0.0		0 rows
25	Supplier 2_2 firm quality managers	Fixed Capacity	1	1	1	0.0		0 rows
26	Focal firm required materials	Fixed Capacity	1	0.0	0.0	1		0 rows
27	Supplier 1_1 required materials	Fixed Capacity	1	0.0	0.0	1		0 rows
28	Supplier 1_2 required materials	Fixed Capacity	1	0.0	0.0	1		0 rows
29	Supplier 2_1 required materials	Fixed Capacity	1	0.0	0.0	1		0 rows
30	Supplier 2_2 required materials	Fixed Capacity	1	0.0	0.0	1		0 rows
31	Focal firm quality inspection equipments	Fixed Capacity	1	1	0.0	0.0		2 rows
32	Supplier 1_1 firm quality inspection equipments	Fixed Capacity	1	1	0.0	0.0		2 rows
33	Supplier 2_1 firm quality control equipments	Fixed Capacity	1	1	0.0	0.0		2 rows
34	Supplier 1_2 firm quality inspection equipments	Fixed Capacity	1	1	0.0	0.0		2 rows
35	Supplier 2_2 firm quality control equipments	Fixed Capacity	1	1	0.0	0.0		2 rows

Looking at Table 4.4, one can verify that human resources have an attendance index of 100%; which corresponds to a model assumption. On the other hand, the equipments and transporters have breakdowns, so, it should be made a maintenance plan. Note that the breakdowns were only considered to make the automotive SC simulation model more realistic. All breakdowns and maintenance plans are modelled by exponential and triangular distributions, respectively. Triangular distribution requires three parameters: a minimum, a modal (most likely) and a maximum value. Exponential distribution requires only the mean parameter. For instance, in case of 1tD firm transporters breakdown (row 16), the inter-event time in random breakdown processes is 365 days, requiring 10 hours for its repair, or 2 and 32 in the best and worst cases, respectively.

In the model window, there is another main region beyond the spreadsheet view, namely the flowchart view. The flowchart view contains all of model graphics, including the process flowchart, animation and other drawing elements (Rockwell Automation Technologies Inc., 2007). All information required to simulate the automotive SC processes is stored in modules, which are the flowchart and data objects.

Table 4.4 Failure spreadsheet

	Name	Type	Up Time	Up Time Units	Down Time	Down Time Units
1	1st tier distributor firm transporters maintenance	Time	TRIA(89,90,93)	Days	TRIA(2,3,5)	Hours
2	Supplier 1_1 firm transporters maintenance	Time	TRIA(364,365,368)	Days	TRIA(1,1,3)	Hours
3	Supplier 1_2 firm transporters maintenance	Time	TRIA(364,365,368)	Days	TRIA(1,1,3)	Hours
4	Supplier 2_1 firm transporters maintenance	Time	TRIA(364,365,368)	Days	TRIA(1,1,3)	Hours
5	Supplier 2_2 firm transporters maintenance	Time	TRIA(179,180,183)	Days	TRIA(1,2,4)	Hours
6	Supplier 2_2 firm quality control equipments maintenance	Time	TRIA(89,90,93)	Days	TRIA(25,30,40)	Minutes
7	Supplier 1_2 firm quality inspection equipments maintenance	Time	TRIA(89,90,93)	Days	TRIA(25,30,40)	Minutes
8	Supplier 2_1 firm quality control equipments maintenance	Time	TRIA(89,90,93)	Days	TRIA(25,30,40)	Minutes
9	Supplier 1_1 firm quality inspection equipments maintenance	Time	TRIA(89,90,93)	Days	TRIA(25,30,40)	Minutes
10	Focal firm quality inspection equipments maintenance	Time	TRIA(89,90,93)	Days	TRIA(25,30,40)	Minutes
11	Focal firm manufacturing equipments maintenance	Time	TRIA(59,60,63)	Days	TRIA(70,75,85)	Minutes
12	Supplier 1_1 firm manufacturing equipments maintenance	Time	TRIA(59,60,63)	Days	TRIA(70,75,85)	Minutes
13	Supplier 1_2 firm manufacturing equipments maintenance	Time	TRIA(59,60,63)	Days	TRIA(70,75,85)	Minutes
14	Supplier 2_1 firm manufacturing equipments maintenance	Time	TRIA(59,60,63)	Days	TRIA(70,75,85)	Minutes
15	Supplier 2_2 firm manufacturing equipments maintenance	Time	TRIA(59,60,63)	Days	TRIA(70,75,85)	Minutes
16	1st tier distributor firm transporters breakdown	Time	EXPO(365)	Days	TRIA(2 , 10 , 32)	Hours
17	Supplier 1_1 firm transporters breakdown	Time	EXPO(122)	Days	TRIA(1 , 6 , 16)	Hours
18	Supplier 1_2 firm transporters breakdown	Time	EXPO(122)	Days	TRIA(1 , 6 , 16)	Hours
19	Focal firm manufacturing equipments breakdown	Time	EXPO(122)	Days	TRIA(70 , 180 , 360)	Minutes
20	Supplier 2_1 firm transporters breakdown	Time	EXPO(122)	Days	TRIA(1 , 6 , 16)	Hours
21	Supplier 1_1 firm manufacturing equipments breakdown	Time	EXPO(122)	Days	TRIA(70 , 180 , 360)	Minutes
22	Supplier 2_2 firm transporters breakdown	Time	EXPO(183)	Days	TRIA(1 , 8 , 24)	Hours
23	Supplier 1_2 firm manufacturing equipments breakdown	Time	EXPO(122)	Days	TRIA(70 , 180 , 360)	Minutes
24	Supplier 2_1 firm manufacturing equipments breakdown	Time	EXPO(122)	Days	TRIA(70 , 180 , 360)	Minutes
25	Supplier 2_2 firm manufacturing equipments breakdown	Time	EXPO(122)	Days	TRIA(70 , 180 , 360)	Minutes
26	Focal firm quality inspection equipments breakdown	Time	EXPO(183)	Days	TRIA(25 , 60 , 180)	Minutes
27	Supplier 1_1 firm quality inspection equipments breakdown	Time	EXPO(183)	Days	TRIA(25 , 60 , 180)	Minutes
28	Supplier 2_1 firm quality control equipments breakdown	Time	EXPO(183)	Days	TRIA(25 , 60 , 180)	Minutes
29	Supplier 1_2 firm quality inspection equipments breakdown	Time	EXPO(183)	Days	TRIA(25 , 60 , 180)	Minutes
30	Supplier 2_2 firm quality control equipments breakdown	Time	EXPO(183)	Days	TRIA(25 , 60 , 180)	Minutes

Tables 4.5, 4.6 and 4.7 contain the data associated to the main modules used to build the flowcharts for each SC entity.

Table 4.5 Create module spreadsheet

SC entity	Module name	Entity type	Type	Value	Units	Entities per Arrival	Max Arrivals	First Creation
Customer	Customer order receive	Customer order specification	Random (Expo)	30	Days	1	Infinite	0.01

The create module is intended as the starting point for entities in a simulation model (Rockwell Automation Technologies Inc., 2007).

The first entity, which in this case is the customer order, arrives into the SC at 0.01 days (basic time unit in the model). The arrival of the next orders is modelled by an exponential distribution with a mean of 30 days.

From Table 4.5, it can also be seen that the number of orders received by the 1tD at a given time with each arrival is only one and there is no limit to the maximum number of orders that the “Create” module generates.

Table 4.6 Process module spreadsheet

SC entity	Module name	Action	Priority	Number of resources	Delay Type	Units	Allocation	Minimum	Value	Maximum
1tD	Close order_Maximum interoperability degree	Seize Delay Release	Medium (2)	2	Triangular	Days	Transfer	1	5	10
1tD	Make order to the FF	Delay	-	-	Triangular	Minutes	Non-Value Added (NVA)	1	10	20
FF	Components receive_Maximum interoperability degree	Seize Delay Release	Medium (2)	2	Triangular	Hours	Transfer	0.7	1	2
FF	Make order to the supplier 1_1	Delay	-	-	Triangular	Minutes	NVA	3	5	10
FF	Make order to the supplier 1_2	Delay	-	-	Triangular	Minutes	NVA	3	5	10
FF	Products manufacturing	Seize Delay Release	Medium (2)	3	Triangular	Minutes	Value Added (VA)	1.9	2	3
FF	Products quality control	Seize Delay Release	Medium (2)	2	Triangular	Minutes	NVA	4.9	5	6
FF	Products reworking	Seize Delay Release	High (1)	2	Triangular	Minutes	NVA	0.5	1	3
FF	Sub assemblies receive_Maximum interoperability degree	Seize Delay Release	Medium (2)	2	Triangular	Hours	Transfer	0.7	1	2
Supplier 1_1	Make order to the supplier 2_1	Delay	-	-	Triangular	Minutes	NVA	1	10	20
Supplier 1_1	Material 1 receive_Maximum interoperability degree	Seize Delay Release	Medium (2)	2	Triangular	Hours	Transfer	5	5.5	6.5
Supplier 1_1	Sub assemblies manufacturing	Seize Delay Release	Medium (2)	3	Triangular	Minutes	VA	5	6	8
Supplier 1_1	Sub assemblies quality control	Seize Delay Release	Medium (2)	2	Triangular	Minutes	NVA	3.7	4	5
Supplier 1_1	Sub assemblies reworking	Seize Delay Release	High (1)	2	Triangular	Minutes	NVA	0.9	1	5
Supplier 1_2	Components manufacturing	Seize Delay Release	Medium (2)	3	Triangular	Minutes	VA	2	4	6
Supplier 1_2	Components quality control	Seize Delay Release	Medium (2)	2	Triangular	Minutes	NVA	1	2	3
Supplier 1_2	Components reworking	Seize Delay Release	High (1)	2	Triangular	Minutes	NVA	0.9	1	3
Supplier 1_2	Make order to the supplier 2_2	Delay	-	-	Triangular	Minutes	NVA	1	10	20
Supplier 1_2	Material 2 receive_Maximum interoperability degree	Seize Delay Release	Medium (2)	2	Triangular	Days	Transfer	1	1	1.2
Supplier 2_1	Materials 1 manufacturing	Seize Delay Release	Medium (2)	3	Triangular	Minutes	VA	9	10	12
Supplier 2_1	Materials 1 quality control	Seize Delay Release	Medium (2)	2	Triangular	Minutes	NVA	5	6	9

SC entity	Module name	Action	Priority	Number of resources	Delay Type	Units	Allocation	Minimum	Value	Maximum
Supplier 2_1	Materials 1 reworking	Seize Delay Release	High (1)	2	Triangular	Minutes	NVA	0.9	1	3
Supplier 2_2	Materials 2 manufacturing	Seize Delay Release	Medium (2)	3	Triangular	Minutes	VA	7	8	10
Supplier 2_2	Materials 2 quality control	Seize Delay Release	Medium (2)	2	Triangular	Minutes	NVA	4	5	7
Supplier 2_2	Materials 2 reworking	Seize Delay Release	High (1)	2	Triangular	Minutes	NVA	0.9	1	2

The process module is intended as the main processing method in simulation (Rockwell Automation Technologies Inc., 2007).

Looking at the FF presented in Table 4.6, particularly to the “Products reworking” module name, one can verify that the type of processing that occur within the module is “Seize Delay Release”, indicating that the two resources are allocated followed by a process delay and then the allocated resources are released (Rockwell Automation Technologies Inc., 2007). Since both resources are also used in the “Products manufacturing” module, it is necessary to establish a priority value to the orders that are waiting for the same resources. In case of non conformity products, they should be immediately reworked, and after the resources are released, they can be used by another order that is waiting to be processed in “Products manufacturing” module. This processing time, which is modelled by a triangular distribution, is allocated to the entity, i.e., the customer order, and is considered to be NVA. The associated cost is added to the NVA category for the entity and process (Rockwell Automation Technologies Inc., 2007).

Table 4.7 Decide module spreadsheet

SC entity	Module name	Type	Percent True	If	Is	Value
1tD	Maximum interoperability degree between customer and 1tD?	2-way by Condition	-	Attribute	==	1
FF	Maximum interoperability degree between FF and supplier 1_1?	2-way by Condition	-	Attribute	==	1
FF	Maximum interoperability degree between FF and supplier 1_2?	2-way by Condition	-	Attribute	==	1
FF	Products conformity?	2-way by Chance	100	-	-	-
FF	Products quality inspection?	2-way by Chance	100	-	-	-
Supplier 1_1	Maximum interoperability degree between supplier 1_1 and supplier 2_1?	2-way by Condition	-	Attribute	==	1

SC entity	Module name	Type	Percent True	If	Is	Value
Supplier 1_1	Sub assemblies' conformity?	2-way by Chance	95	-	-	-
Supplier 1_1	Sub assemblies' quality inspection?	2-way by Chance	100	-	-	-
Supplier 1_2	Components conformity?	2-way by Chance	95	-	-	-
Supplier 1_2	Components quality inspection?	2-way by Chance	100	-	-	-
Supplier 1_2	Maximum interoperability degree between supplier 1_2 and supplier 2_2?	2-way by Condition	-	Attribute	==	1
Supplier 2_1	Materials 1 conformity?	2-way by Chance	90	-	-	-
Supplier 2_1	Materials 1 quality inspection?	2-way by Chance	50	-	-	-
Supplier 2_2	Materials 2 conformity?	2-way by Chance	90	-	-	-
Supplier 2_2	Materials 2 quality inspection?	2-way by Chance	40	-	-	-

The decide module allows for a decision-making processes in the system, including options to make decisions based on one or more conditions or based on one or more probabilities (Rockwell Automation Technologies Inc., 2007).

Whenever the decision module type is “2-way by Condition”, it is assumed that the interoperability degree between two entities of the automotive SC is maximum if the attribute value is equal to one. On the other hand, the decision module type “2-way by Chance” is based on one probability that correspond to the exit point for “True” entities. The other exit point for “False” entities is related to the remaining percentage.

Beyond these modules, it were used other basic flowcharts and data modules that is not directly related to the input data and parameters of the simulation model, such as (Rockwell Automation Technologies Inc., 2007):

- **Assign –** used for assigning new values to variables, entity attributes, entity types, entity pictures, or other system variables;
- **Batch –** grouping mechanism within the simulation model, which can be permanent or temporary;
- **Dispose –** ending point for entities in a simulation model;

- **Record –** used to collect statistics in the simulation model, like time between exits through the model, entity statistics (time, costing, etc.),general observations, interval statistics (from some time stamp to the current simulation time), and count statistics;
- **Separate –** used to either copy an incoming entity into multiple entities or to split a previously batched entity.

After the definition of input data and parameters required to the simulation model, it is necessary to classifying the interoperability of LARG practices according to their implementation degree. Based on interoperability degree classification proposed by Espadinha-Cruz (2012), each practice is classified from 0 to 1, indicating that the level of interactions between two entities of the automotive SC is null to very high. When the interoperability degree between two entities is 0, they cannot even interoperate. On the other hand, when the interoperability degree is 1, there are no barriers in the interaction between two entities and, consequently, the involved cost is minimum or does not exist. This classification helps to establish a link between the interoperability degree of LARG practices and SC performance, which is the main focus of this dissertation. Although there may be different ways to define this relation, the most rational is the use of math functions. Thus, it will be possible to define a logical link between the interoperability degree of LARG practices and SC performance and, consequently, eliminate this gap.

One way to monitor interoperability throughout SC is based on the analysis of the effect of the interoperability degree of LARG practices in KPI's such as cost, lead time and service level. Using the assign module in the Arena modelling environment, it is possible to attribute the interoperability degree of LARG practices when an entity executes the module. This assignment value of the attribute must be associated to the processes in which the LARG practices selected have a direct impact.

From the perspective of Arena simulation, the analysis of the effect of the interoperability degree of LARG practices in the SC performance, through the three KPI's above mentioned, can add more complexity to the model. Since the model simplification allows reducing the uncertainty, it was only considered the effect of the interoperability degree on the time variable. However, this variable has a direct influence on the SC performance, in terms of cost, delivery time and service level to customers. For instance, if the processing time of all logistics processes increases, the cost and lead time will increase and the service level will consequently be lower.

The interaction between interoperability degree and time variable, associated with the delay time of each process, can be made using the "Build Expression..." option, which is present in the main modules used to build the automotive SC simulation model. Thus, the increasing of the interoperability degree of one LARG practice implemented, leads to the decreasing of the processing time of the correspondent activity.

Since some of the inputs are assumed, it is recommended to use quantitative techniques, like sensitivity analysis, to validate the output of the simulation model. In this case, the sensitivity analysis was based on six types of math expressions, which were created to study the system in terms of the effect of the interoperability degree of LARG practices in the SC performance. It should be noted that all math expressions used in the "Build Expression..." option, were created according to the same logic, i.e., the time associated to each process corresponds to the very high interoperability degree of LARG practices.

The math functions depicted in Figures 4.6, 4.7, 4.8, 4.9, 4.10 and 4.11 were built according to the data associated with an example presented in Table 4.6 relating to the FF, namely the "Products quality control" module. Since the processing time considered is modelled by a triangular distribution, it was only used the modal (most likely) parameter at the math functions, in order to facilitate the visualisation process. However, in the simulation point of view, the Arena software generates random numbers for the triangular distribution, which represent the time variable at the math functions, i.e., the variable "T". This variable corresponds to the delay time associated to each process of the automotive SC. As mentioned previously, the other variable considered is the interoperability degree of LARG practices, which is represented by the variable "ID". From this point of view, the selection of the variable "ID" represents the main input of the simulation model, which is related with the implementation degree of LARG practices. On the other hand, the variable "T" corresponds to the output of the simulation model in terms of SC performance, since it has a direct influence on the cost, delivery time and service level.

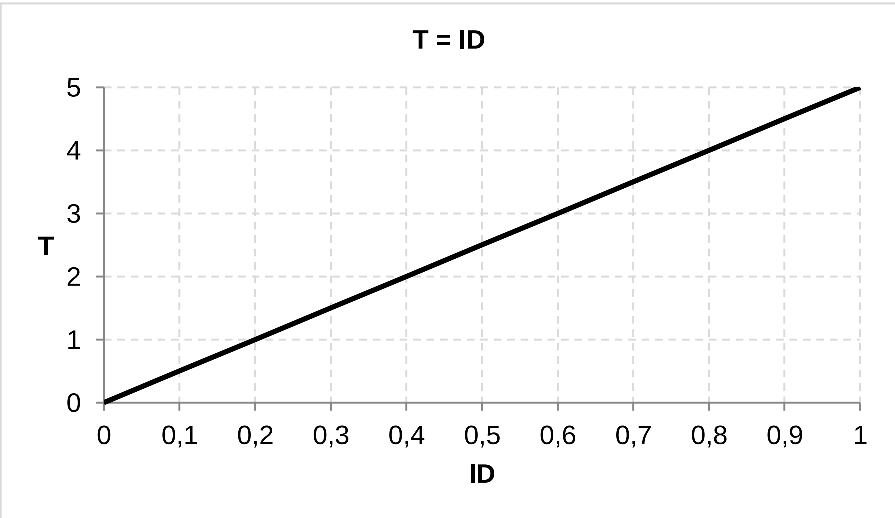

Figure 4.6 Graphic representation of math function T = ID

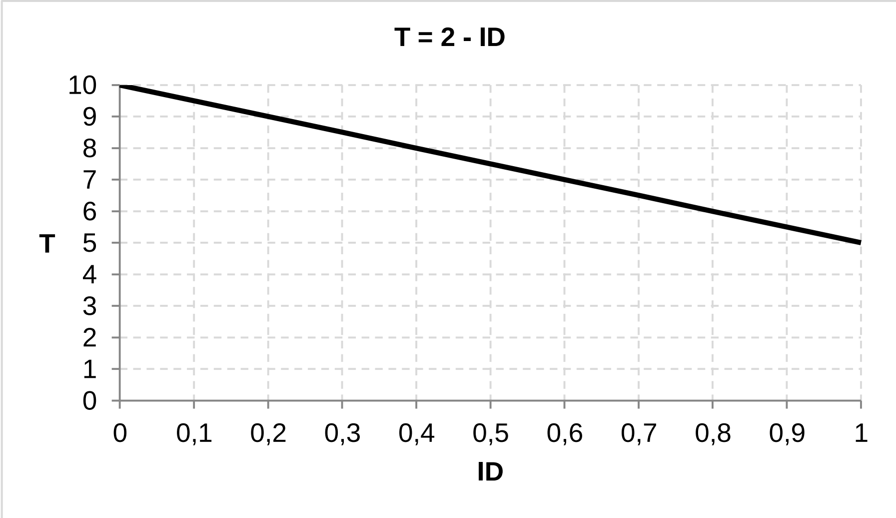

Figure 4.7 Graphic representation of math function T = 2 - ID

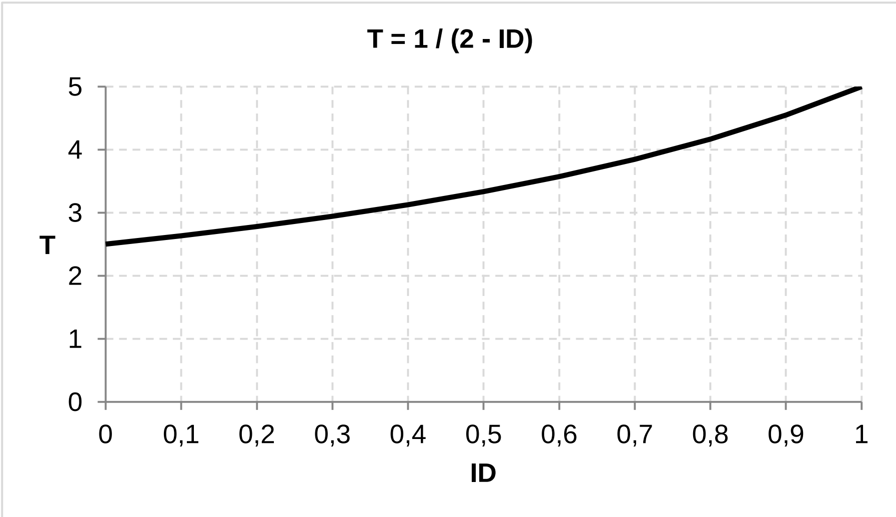

Figure 4.8 Graphic representation of math function T = 1 / (2 – ID)

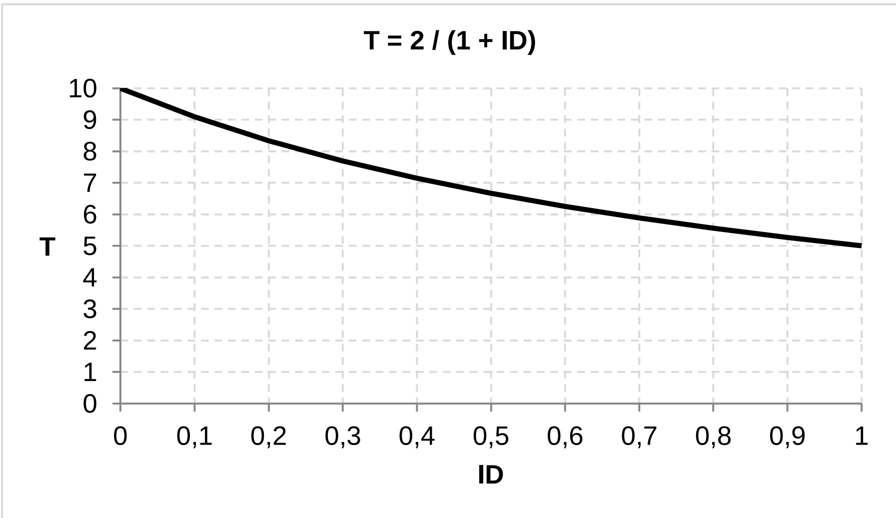

Figure 4.9 Graphic representation of math function T = 2 / (1 + ID)

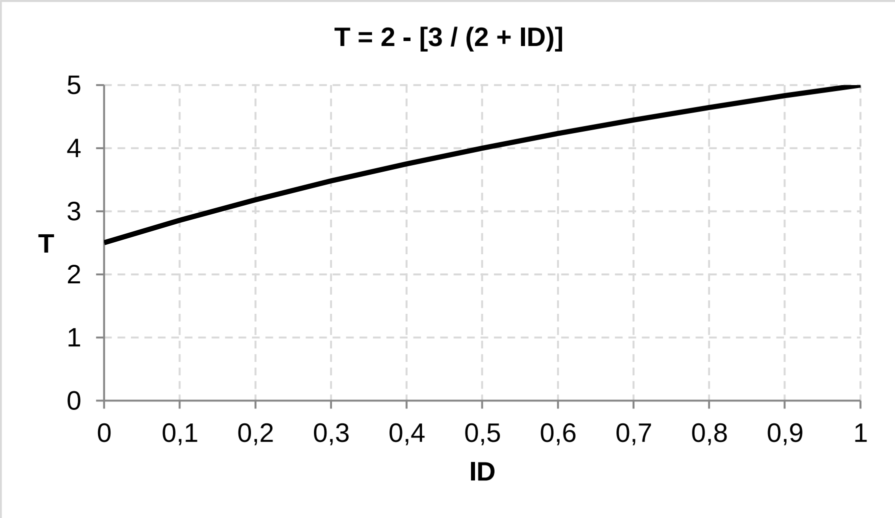

Figure 4.10 Graphic representation of math function T = 2 – [3 / (2 + ID)]

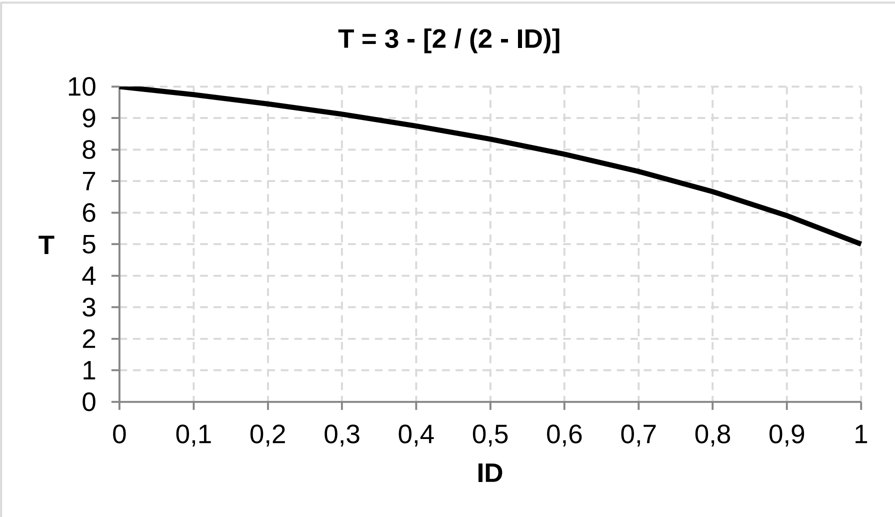

Figure 4.11 Graphic representation of math function T = 3 – [2 / (2 - ID)]

4.3.5. Simulation model

The development of the automotive SC simulation model is based on the conversion of the model specifications previously made, in a computational model. As previously mentioned, two different scenarios are considered to assess practices and interoperability. However, the number of scenarios is not directly related with the main objective of this dissertation. Thus, it was only considered two scenarios to obtain different results, in order to evaluate if the Resilient practice should be associated to the remaining paradigms.

In the first scenario, it will be considered one practice of each paradigm, namely Lean, Agile, Resilient and Green. By assigning different interoperability degree for each one of those four practices, it is possible to calculate the interoperability degree of LARG practices through the average of interoperability degree of the four practices considered. It should be noted that the four practices selected from the Tables 2.2, 2.3, 2.4 and 2.5, respectively, are associated with the logistics processes that are involved in placing orders and materials reception.

Therefore, each practice was selected according to this principle, which represents the core of any interaction between two entities of the SC.

The four practices selected for LARG paradigms, respectively, are:

- L6: Supplier relationships/long-term business relationships;
- A1: Ability to change delivery times of supplier's order;
- R4: Flexible transportation;
- G1: Environmental collaboration with suppliers.

In the second scenario, it will only be considered the practice R4 above mentioned, which can belong to the four paradigms. Before proving this affirmation, it is important to understand what means "flexible transportation". This practice ensures and increases the flexibility on materials flow/transportation along the whole SC, being directly associated with the orders reception. The increase of flexibility can be ensured by:

- Multiple routes;
- Different means of transportation, for example, truck, train or airplane;
- Transportation types that accommodate different materials types.

Besides the flexible transportation being considered a Resilient practice, it can also be seen as a Lean practice if, for example, the used transportation type accommodate different materials types. Consequently, the number of means of transportation on the routes will decrease, which results not only in a reduction of fuel consumption, but also in a decrease of human resources necessary to ensure the materials transportation. This example shows that flexible transportation could be considered a Lean practice, since it contributes to waste elimination and cost reduction.

On the other hand, flexible transportation can also belong to the Agile paradigm, since the ability to respond quickly to an order is strongly dependent on the number of means of transportation and existing routes.

Relatively to the Resilient paradigm, flexible transportation is seen as the ability to change the transportation types or routes, in order to satisfy the customer orders without disturbances.

As above mentioned, the decrease in the number of means of transportation on the routes, results in a reduction of fuel consumption and, consequently, in a decrease in the gas emissions into the atmosphere. Thus, flexible transportation can be considered a Green practice because it aims at the reduction of environment impact.

Before starting the development of the automotive SC simulation model, it is important to understand what means a null or very high interoperability degree for each one of the four practices selected for LARG paradigms.

Looking for the Portuguese automotive SC that was described at the beginning of chapter 4, it is easy to obtain some practical examples that help understanding the level of interactions between two entities. For instance, an interoperability degree of 0 for the practices L6 and A1 can be related with communication problems, i.e., different languages or cultures, or even with different rules and procedures. On the other hand, a very high interoperability degree corresponds to a customised and personalised support based on common experience form the co-operative environment. Regarding the practice R4, if entities cannot even interoperate, there is no real-time coordination. Therefore, the ability to respond quickly to an order when an unexpected event occurs will have impact on the transportation time and cost. However, the use of Information Systems (IS) allows rapid and inexpensive communication system integration. The real-time data processing can help, for example, in the definition of new transportation types or routes if there is an accident that precludes the satisfaction of the customer orders without disturbances. In this case, there are no barriers in the interaction between two entities and, consequently, the interoperability degree is very high, i.e., 1. Finally, looking at the practice G1, it is expectable that the existence of industry-specific, national or applicable international environmental regulation and standards, are not considered by entities whenever the interoperability degree is 0. On the other hand, a very high interoperability degree in environmental collaboration among entities, may result in a decrease in the gas emissions into the atmosphere and, consequently, in the reduction of environment impact.

Considering the first scenario, it was used Rockwell Arena 9.0 simulation software to build the model represented in Figure 4.12, and the sub models represented in Figures 4.13, 4.14, 4.15, 4.16 and 4.17.

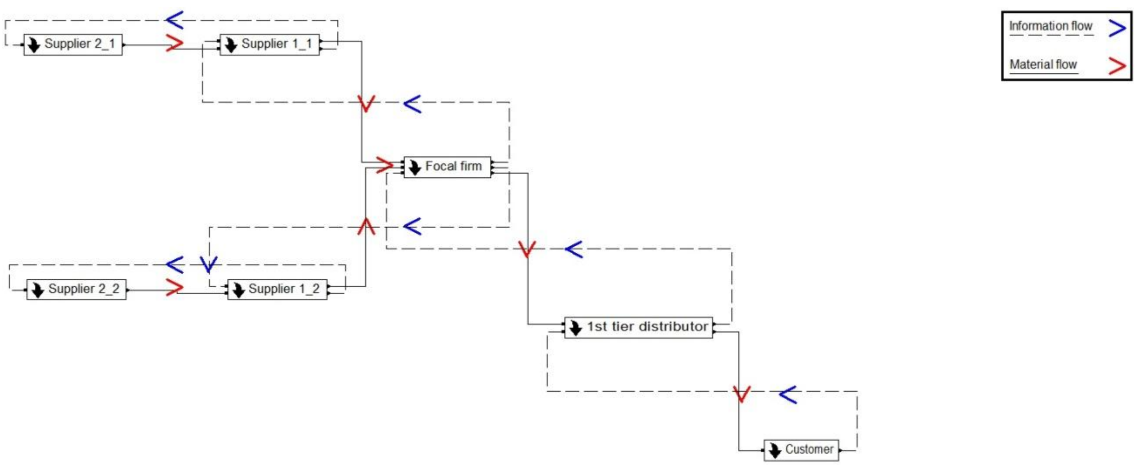

Figure 4.12 Automotive SC simulation model

One can verify that customer demands are pulled through the SC, according to the JIT and Lean philosophies. It is necessary to coordinate the material flow along the whole SC since, in a virtual environment, the entities possess no stock.

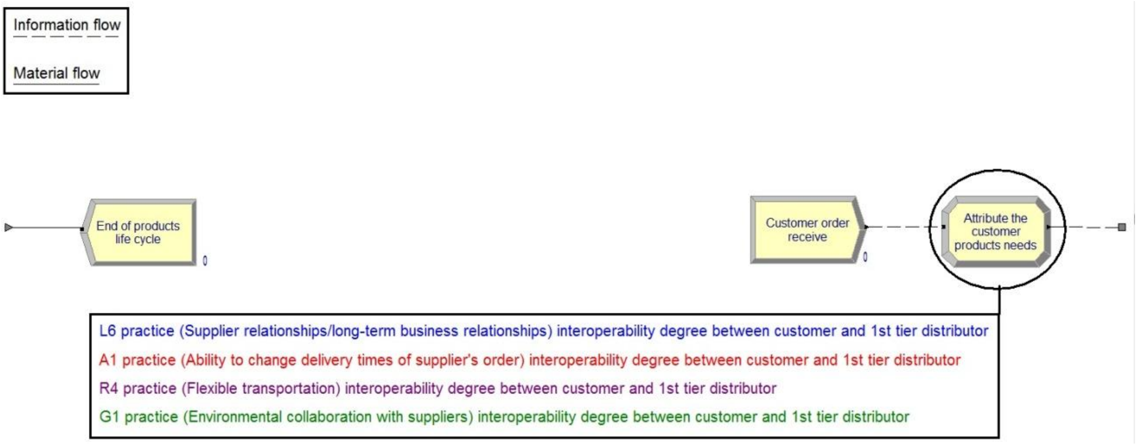

Figure 4.13 Customer simulation sub model

From Figure 4.13, despite it only be seen that the assign module was used to assign the interoperability degree for each practice associated with the logistics interactions between customer and 1tD, it is important to know that the same module was also used to attribute the product amount that composes each order. This module allow not only inserting the classification of the interoperability of LARG practices according to their implementation degree, which ranges from 0 to 1, but also creating an attribute with the customer needs, that will be required during the simulation run.

The create and dispose modules, i.e., “Customer order receive” and “End of products life cycle” respectively, show that the information and material flow starts when customer places an order and ends when the customer needs is completely fulfilled.

In 1tD simulation sub model depicted in Figure 4.14, the time associated to “Close order_ Maximum LARG practices interoperability degree” process corresponds to the very high interoperability degree of LARG practices, i.e., 1. Whenever it is considered the “True” condition of the decide module, the process “Close order” will be performed within the expected time. In this case, the product is delivered to the customer at the right time, and the order is closed. If the interoperability degree of each practice that was inserted on the assign module used in the customer simulation sub model is different from 1, the effect of the interoperability degree of LARG practices in the SC performance is based on the math expressions previously mentioned. Whenever it is considered the “False” condition, the time associated to the process “Close order” corresponds to the product between the expected time to perform this process and the six types of math expressions. Thus, it is possible to make a sensitivity analysis according to the different results that will be obtained based on the behaviour of each type of math expression.

The assign module was used to attribute the product amount that 1tD needs which, in this case, is the same that composes customer order. This attribute includes the product amount that must integrate the FF backorder.

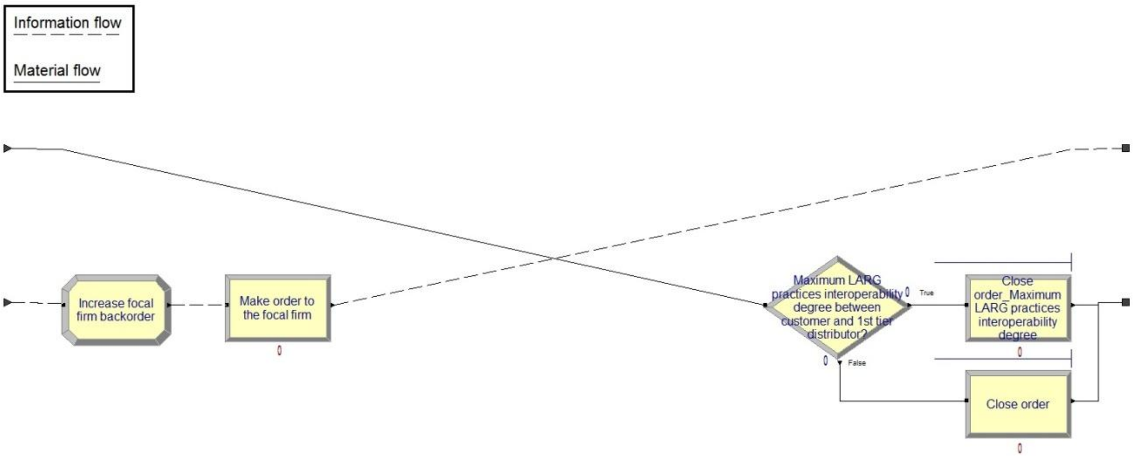

Figure 4.14 1tD simulation sub model

Looking at Figure 4.15, one can verify that FF receives the 1tD order and places an order to the 1tS, according to the vehicle BOM represented in Figure 4.4. The assign module was also used to attribute the interoperability degree for each practice associated with the logistics interactions between FF and 1tS.

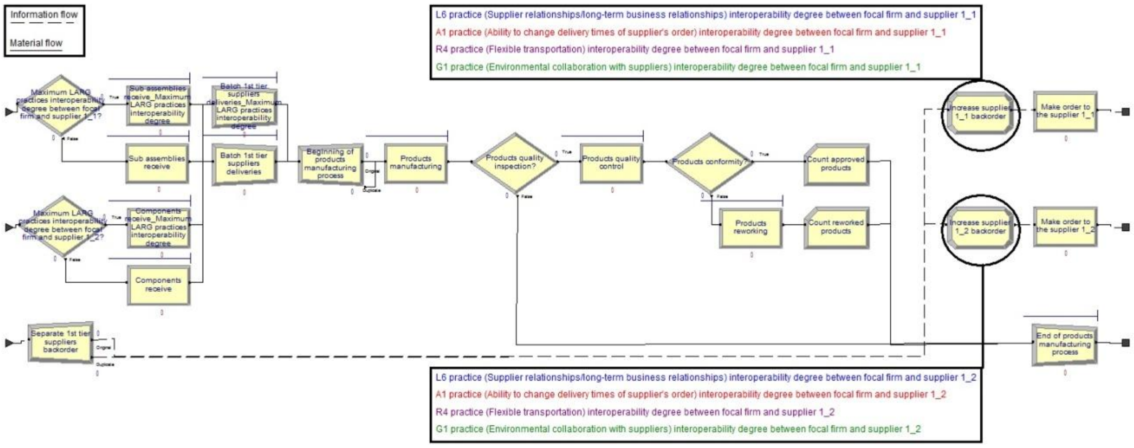

Figure 4.15 FF simulation sub model

After the delivery of sub-assemblies and components to the FF, whose the time associated to "Sub-assemblies receive" and "Components receive" processes also corresponds to the very high interoperability degree of LARG practices, starts the production process. If FF adopts a quality control policy, the products need to be inspected and, in case of non conformity, they should be reworked.

Note that the logic implied on decide modules "Maximum LARG practices interoperability degree between focal firm and supplier 1_1?" and "Maximum LARG practices interoperability degree between focal firm and supplier 1_2?", is similar to the decide module used in 1tD simulation sub model (see Figure 4.14).

The separate, batch and record modules were only used from the perspective of Arena modelling environment.

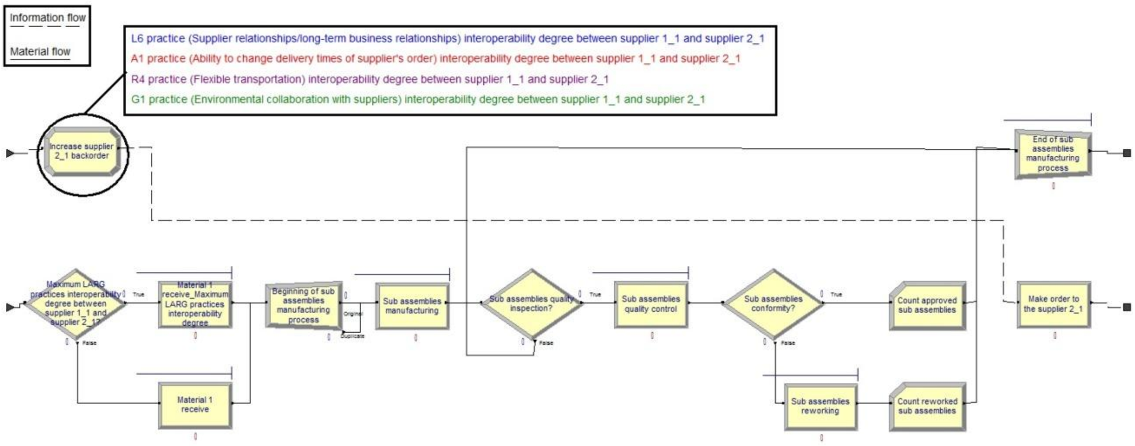

Figure 4.16 Supplier 1_1 simulation sub model

The supplier 1_1 simulation sub model depicts that the information and material flow has the same logic as the FF simulation sub model. However, the supplier 1_1 places an order to the supplier 2_1, according to the vehicle BOM represented in Figure 4.4, and receives the material 1 that is necessary to produce the sub-assemblies that FF demanded.

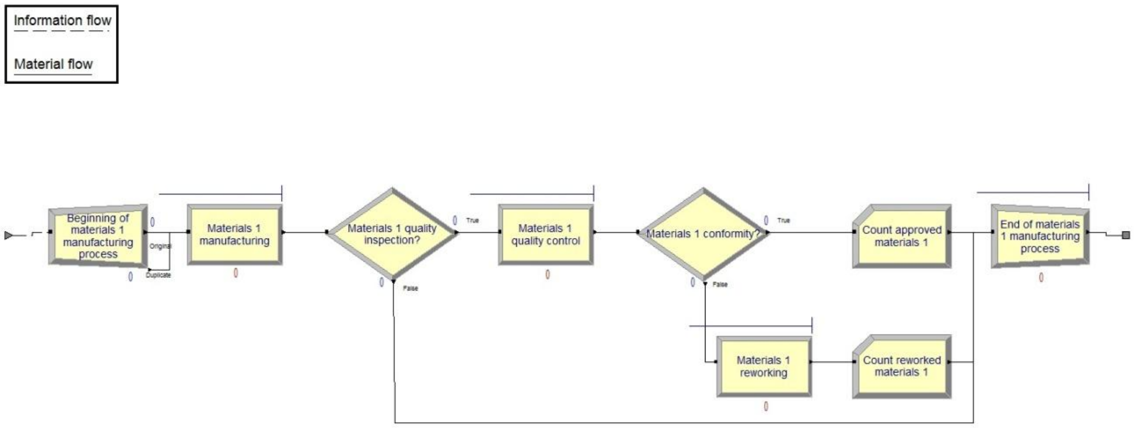

Figure 4.17 Supplier 2_1 simulation sub model

From Figure 4.17, it can be seen that the supplier 2_1 represents the end of information flow and, at the same time, the beginning of material flow. The supplier 2_1 receives an order from supplier 1_1 and starts the material 1 production process, using its own raw material.

The suppliers 1_2 and 2_2 simulation sub models regarding the first scenario can be verified in Annex 1.

The second scenario is a copy of first scenario from the perspective of Arena simulation, excepting the assign module which, in this case, was used to attribute the interoperability degree for practice R4 associated with the logistics interactions between two entities of the automotive SC. Considering the automotive SC simulation model represented in Figure 4.12, it were built the sub models presented in Annex 2. The 1tD, and suppliers 2_1 and 2_2 simulation sub models are equal to the simulation sub models represented in Figures 4.14, 4.17 and Annex 1.2, respectively.

Regarding the KPI’s, it is important to understand that cost and lead time were obtained based on internal variables that are automatically created and updated by Rockwell Arena 9.0 simulation software. The internal variables selected for generate these two KPI’s allow storing the cost and total time accumulated during the simulation run. Relatively to the service level, it was necessary to calculate the ratio between the number of orders placed by the customer and the number of customer orders that were fulfilled.

After the automotive SC simulation model building, considering both scenarios previously described, it must be determined the adequate warm-up period and the number of replications. These two external studies were performed in order to analyse the effect of the interoperability degree of LARG practices in the SC performance, when the system operates in steady-state for a long simulation length. In this simulation model, the desired simulation length is 365 days, i.e., 1 year, which is believed to be long enough to eliminate or reduce the impact of initial conditions on the outputs.

During the warm-up period in simulation, all statistics are cleared since the model outputs suffer transient effects until they reach the steady-state. After the warm-up period, KPI’s are to be adapted to the model input data and parameters, i.e., it must be verified a repeated pattern.

The “Output Analyzer” application of Arena 9.0 is an approach that can be used to determine the adequate warm-up period for the automotive SC simulation model. This application provides a visual inspection of the simulation outputs that should be carefully analysed using a graphical method. In this case, it would be necessary to consider all scenarios to choose the ultimate warm-up period that corresponds to the worst time required to stabilize the model outputs. Once the combination between the interoperability degree of LARG practices and the math expressions depicted in Figures 4.6, 4.7, 4.8, 4.9, 4.10 and 4.11 allows generating a huge number of scenarios, it was assumed a warm-up period of 105 days, i.e., 3 months and a half. It should be noted that the simulation length must includes the warm-up period. Therefore, the time period of 470 days that was assumed for the simulation model, was obtained by adding the desired simulation length of 365 days with the warm-up period of 105 days.

Finally, it must be determined the amount of times the simulation is repeated, i.e., the number of replications. Multiple replications were used to develop a statistical analysis with more precision. Each replication uses different sequences of random numbers, allowing the generation of different outputs.

The confidence interval calculation is a statistic tool that can be used to determine the accurate number of replications for this simulation model. The objective is to achieve a confidence interval with a reduced range, in order to increase the precision. Using a specified level of significance, it is necessary to ensure that there is a minimum amount of data and also there is no correlation among them. The determination of the ultimate number of replications is similar to the warm-up period, i.e., it should be chosen the worst number of replications required to stabilize the model outputs.

As previously mentioned, it would be necessary to analyse a huge number of scenarios. Thus, it was assumed that the simulation model requires 100 replications. This consideration was obtained through trial and error.

4.4. Results and discussion

The presentation of the automotive SC simulation model results consists in two parts. Thus, in order to effectively answer the aim of this dissertation, the respective results were analysed and discussed in terms of KPI's, namely cost, lead time and service level. Since some of the inputs used in the simulation model were assumed, the results are not as realistic as expected. However, this factor does not affect the credibility of results.

In first instance, practices and interoperability were assessed for the first scenario. Considering the four practices selected for LARG paradigms, the interoperability degree classification and the six types of math expressions, several reports were extracted from Rockwell Arena 9.0 simulation software. These reports, which are denominated by "Category Overview", are a combination among each one of the math expressions and different interoperability degree for each one of the four practices associated with logistics interaction between two partners in the automotive SC. Therefore, it is possible to study the different effects of the interoperability degree of LARG practices in the SC performance, whenever are assumed different interoperability degree and/or math expressions. Note that these variations should be made simultaneously in all logistics interaction between two partners in the automotive SC, in order to simplify the results analysis and reduce consequently the variability.

However, the six types of math expressions must be ignored on the results analysis since they were only created to establish a link between the interoperability degree of LARG practices and SC performance. It should be noted that it was only considered the effect of the interoperability degree on the time variable. Since these math expressions have a limited range, the KPI "lead time" will be not 0 or infinite whenever the interoperability degree of LARG practices is 0 or 1, respectively. Regarding the service level, one can deduce that an interoperability degree of 0 or 1 may not correspond to a service level of 0 or 100%, because there are many processes in the SC in which the LARG practices selected have not a direct impact. Analysing the KIP "cost", it will be impossible to obtain an infinite cost when it is assumed an interoperability degree of 0, since there is not a direct effect of the interoperability degree on the cost. If the interoperability degree is 1, the cost will be not 0 because some of the costs that are represented in Table 4.3 are not associated to the processes in which the LARG practices selected have a direct impact.

The results of the second scenario were based on the same logic, considering only one practice that can belong to the four paradigms.

Regarding the first part, the results presented in Tables 4.8, 4.9, 4.10, 4.11, 4.12 and 4.13 were obtained by varying the interoperability degree of practices L6, A1, R4 and G1 and the type of math expressions used in the logistics processes that are involved in placing orders and materials reception.

Table 4.8 First scenario KPI's comparison considering math function T = ID

Interoperability degree	Cost (MU)	Lead time (Days)	Service level (%)
L6 = A1 = R4 = G1 = 0	30340.16	129.31	85.5309
L6 = A1 = R4 = G1 = 0.2	30413.28	133.37	92.9129
L6 = A1 = R4 = G1 = 0.4	30476.87	127.61	92.3562
L6 = A1 = R4 = G1 = 0.6	30546.54	130.23	88.8768
L6 = A1 = R4 = G1 = 0.8	30609.42	130.25	97.9803
L6 = A1 = R4 = G1 = 1	30679.23	134.93	92.6112
L6 = A1 = G1 = 1 R4 = 0	30593.85	133.43	93.3861
L6 = A1 = G1 = 0 R4 = 1	30441.11	127.04	98.4438
L6 = 0.2 A1 = 0.4 R4 = 0.6 G1 = 0.8	30519.29	130.96	94.8537

Table 4.9 First scenario KPI's comparison considering math function T = 2 - ID

Interoperability degree	Cost (MU)	Lead time (Days)	Service level (%)
L6 = A1 = R4 = G1 = 0	31004.74	139.19	95.1081
L6 = A1 = R4 = G1 = 0.2	30934.54	134.82	90.0058
L6 = A1 = R4 = G1 = 0.4	30888.72	131.61	93.7623
L6 = A1 = R4 = G1 = 0.6	30806.36	135.40	91.6401
L6 = A1 = R4 = G1 = 0.8	30744.58	137.16	91.7543
L6 = A1 = R4 = G1 = 1	30679.23	134.93	92.6112
L6 = A1 = G1 = 1 R4 = 0	30756.79	131.78	90.8238

Interoperability degree	Cost (MU)	Lead time (Days)	Service level (%)
L6 = A1 = G1 = 0 R4 = 1	30930.95	133.96	90.1873
L6 = 0.2 A1 = 0.4 R4 = 0.6 G1 = 0.8	30846.57	137.65	90.9622

Table 4.10 First scenario KPI's comparison considering math function T = 1 / (2 – ID)

Interoperability degree	Cost (MU)	Lead time (Days)	Service level (%)
L6 = A1 = R4 = G1 = 0	30519.29	130.96	94.8537
L6 = A1 = R4 = G1 = 0.2	30528.51	132.87	94.3860
L6 = A1 = R4 = G1 = 0.4	30555.80	128.61	93.4580
L6 = A1 = R4 = G1 = 0.6	30583.65	133.98	87.9313
L6 = A1 = R4 = G1 = 0.8	30630.44	132.67	91.8360
L6 = A1 = R4 = G1 = 1	30679.23	134.93	92.6112
L6 = A1 = G1 = 1 R4 = 0	30609.42	130.25	97.9803
L6 = A1 = G1 = 0 R4 = 1	30538.60	127.68	92.1717
L6 = 0.2 A1 = 0.4 R4 = 0.6 G1 = 0.8	30571.70	129.89	91.1757

Table 4.11 First scenario KPI's comparison considering math function T = 2 / (1 + ID)

Interoperability degree	Cost (MU)	Lead time (Days)	Service level (%)
L6 = A1 = R4 = G1 = 0	31004.74	139.19	95.1081
L6 = A1 = R4 = G1 = 0.2	30901.72	136.06	91.3925
L6 = A1 = R4 = G1 = 0.4	30828.43	132.72	87.1714

Interoperability degree	Cost (MU)	Lead time (Days)	Service level (%)
L6 = A1 = R4 = G1 = 0.6	30756.79	131.78	90.8238
L6 = A1 = R4 = G1 = 0.8	30717.31	131.85	91.7778
L6 = A1 = R4 = G1 = 1	30679.23	134.93	92.6112
L6 = A1 = G1 = 1 R4 = 0	30727.73	134.33	95.1757
L6 = A1 = G1 = 0 R4 = 1	30888.72	131.61	93.7623
L6 = 0.2 A1 = 0.4 R4 = 0.6 G1 = 0.8	30791.11	134.21	96.0905

Table 4.12 First scenario KPI's comparison considering math function T = 2 – [3 / (2 + ID)]

Interoperability degree	Cost (MU)	Lead time (Days)	Service level (%)
L6 = A1 = R4 = G1 = 0	30519.29	130.96	94.8537
L6 = A1 = R4 = G1 = 0.2	30569.34	130.28	96.0623
L6 = A1 = R4 = G1 = 0.4	30593.85	133.43	93.3861
L6 = A1 = R4 = G1 = 0.6	30632.78	135.32	91.0241
L6 = A1 = R4 = G1 = 0.8	30659.55	132.59	96.3040
L6 = A1 = R4 = G1 = 1	30679.23	134.93	92.6112
L6 = A1 = G1 = 1 R4 = 0	30649.80	135.35	90.3097
L6 = A1 = G1 = 0 R4 = 1	30571.70	129.89	91.1757
L6 = 0.2 A1 = 0.4 R4 = 0.6 G1 = 0.8	30609.42	130.25	97.9803

Table 4.13 First scenario KPI's comparison considering math function T = 3 – [2 / (2 - ID)]

Interoperability degree	Cost (MU)	Lead time (Days)	Service level (%)
L6 = A1 = R4 = G1 = 0	31004.74	139.19	95.1081
L6 = A1 = R4 = G1 = 0.2	30976.71	136.82	90.3013
L6 = A1 = R4 = G1 = 0.4	30930.95	133.96	90.1873
L6 = A1 = R4 = G1 = 0.6	30873.47	134.84	88.5591
L6 = A1 = R4 = G1 = 0.8	30791.11	134.21	96.0905
L6 = A1 = R4 = G1 = 1	30679.23	134.93	92.6112
L6 = A1 = G1 = 1 R4 = 0	30806.36	135.40	91.6401
L6 = A1 = G1 = 0 R4 = 1	30953.08	138.33	88.7026
L6 = 0.2 A1 = 0.4 R4 = 0.6 G1 = 0.8	30901.72	136.06	91.3925

Looking at Tables 4.8, 4.9, 4.10, 4.11, 4.12 and 4.13, one can verify that the maximum cost of 31004.47 MU corresponds to a null interoperability degree for all practices, which was expectable. In this case, the lack of coordination and cooperation in internal and external relationships, involves more costs for business support.

If it is considered an interoperability degree of 0.4 for all practices, the cost is also very high. Therefore, it is more profitable to implement the four practices selected for LARG paradigms with a high level of logistics interaction between automotive SC entities.

From Table 4.13, it can also be seen that practice R4 has not a significant impact on cost, i.e., if it has a maximum interoperability degree, the cost will remain high because the remaining practices have a null interoperability degree that contributes to the cost increasing.

Regarding the lead time, it is expectable that a maximum interoperability degree for all practices corresponds to a maximum value of this KPI. For instance, the practice G1, which is related to environmental collaboration with suppliers, is responsible for the lead time increasing.

As previously mentioned, the reduction of environment impact is only possible with a decrease in the number of means of transportation on the routes, which results on a delivery time delay of customer orders. It should be noted that an interoperability degree of 1 for practices L6 and A1 also contributes to the increasing of lead time and vice versa. Looking at Table 4.8, it is possible to prove that a low interoperability degree contributes to the decreasing of the lead time. For instance, if the interoperability degree for the practices L6, A1 and G1 is 0, the lead time will be minimum, i.e., 127.04 days.

Besides this fact, it is possible to see that if practice R4 has a maximum interoperability degree and the remaining practices have a null interoperability degree, the lead time will be lower. Regarding the practice R4, for instance, entities should have the ability to change the transportation types or routes in order to satisfy the customer orders without disturbances. So, an interoperability degree of 1 for the practice R4, i.e., flexible transportation, also has an important contribution on the lead time decreasing.

Analysing the KPI “service level”, one can verify that the minimum value of 85.53% corresponds to a null interoperability degree for all practices, which was expectable. However, the maximum service level of 98.4438% is also associated to a null interoperability for the practices L6, A1 and G1. This means that the practice R4 is extremely important to the service level, considering that the maximum interoperability degree of this practice prevails over the null interoperability degree of the remaining practices. As above mentioned, entities should have a flexible transportation to satisfy the customer orders without disturbances, which implies having a great service level.

From Table 4.8, it can be seen that an interoperability degree of 0.8 for all practices also contributes to the increasing of the service level. Therefore, it is better to implement only the practice R4 with a maximum interoperability degree, instead of implementing the four practices selected for LARG paradigms with a high level of logistics interaction between SC entities.

Note that the minimum value of lead time present in Table 4.8 corresponds to the maximum service level of 98.4438%, as proved by Carvalho, et al. (2011) in Figure 2.1.

In the second part, different interoperability degrees of practice R4 and math expressions used in the logistics interaction between two entities in the automotive SC were assumed. Tables 4.14, 4.15, 4.16, 4.17, 4.18 and 4.19 present the results obtained for the second scenario.

Table 4.14 Second scenario KPI’s comparison considering math function T = ID

Interoperability degree	Cost (MU)	Lead time (Days)	Service level (%)
R4 = 0	30340.16	129.31	85.5309
R4 = 0.2	30413.28	133.37	92.9129
R4 = 0.4	30476.87	127.61	92.3562

Interoperability degree	Cost (MU)	Lead time (Days)	Service level (%)
R4 = 0.6	30546.54	130.23	88.8768
R4 = 0.8	30609.42	130.25	97.9803
R4 = 1	30679.23	134.93	92.6112

Table 4.15 Second scenario KPI's comparison considering math function T = 2 - ID

Interoperability degree	Cost (MU)	Lead time (Days)	Service level (%)
R4 = 0	31004.74	139.19	95.1081
R4 = 0.2	30934.54	134.82	94.0058
R4 = 0.4	30888.72	131.61	93.7623
R4 = 0.6	30806.36	135.40	91.6401
R4 = 0.8	30744.58	137.16	91.7543
R4 = 1	30679.23	134.93	92.6112

Table 4.16 Second scenario KPI's comparison considering math function T = 1 / (2 – ID)

Interoperability degree	Cost (MU)	Lead time (Days)	Service level (%)
R4 = 0	30519.29	130.96	94.8537
R4 = 0.2	30528.51	132.87	94.3860
R4 = 0.4	30555.80	128.61	93.4580
R4 = 0.6	30583.65	133.98	87.9313
R4 = 0.8	30630.44	132.67	91.8360
R4 = 1	30679.23	134.93	92.6112

Table 4.17 Second scenario KPI's comparison considering math function T = 2 / (1 + ID)

Interoperability degree	Cost (MU)	Lead time (Days)	Service level (%)
R4 = 0	31004.74	139.19	95.1081
R4 = 0.2	30901.72	136.06	91.3925
R4 = 0.4	30828.43	132.72	87.1714
R4 = 0.6	30756.79	131.78	90.8238
R4 = 0.8	30717.31	131.85	91.7778

Interoperability degree	Cost (MU)	Lead time (Days)	Service level (%)
R4 = 1	30679.23	134.93	92.6112

Table 4.18 Second scenario KPI's comparison considering math function T = 2 – [3 / (2 + ID)]

Interoperability degree	Cost (MU)	Lead time (Days)	Service level (%)
R4 = 0	30519.29	130.96	94.8537
R4 = 0.2	30569.34	130.28	96.0623
R4 = 0.4	30593.85	133.43	93.3861
R4 = 0.6	30632.78	135.32	91.0241
R4 = 0.8	30659.65	132.59	96.3040
R4 = 1	30679.23	134.93	92.6112

Table 4.19 Second scenario KPI's comparison considering math function T = 3 – [2 / (2 - ID)]

Interoperability degree	Cost (MU)	Lead time (Days)	Service level (%)
R4 = 0	31004.74	139.19	95.1081
R4 = 0.2	30976.61	136.82	90.3013
R4 = 0.4	30930.95	133.96	90.1873
R4 = 0.6	30873.47	134.84	88.5591
R4 = 0.8	30791.11	134.21	96.0905
R4 = 1	30679.23	134.93	92.6112

Looking at Tables 4.14, 4.15, 4.16, 4.17, 4.18 and 4.19, one can verify that the maximum cost of 31004.74 MU corresponds to a null interoperability degree for practice R4. If it is considered an interoperability degree of 0.2 or 0.4, the cost is also very high. However, the minimum cost of 30340.16 MU also corresponds to a null interoperability degree for practice R4. This outlier must be ignored, as explained in the first scenario.

Regarding the lead time, it is possible to see that the minimum value of 127.61 days corresponds to a low interoperability degree of 0.4. So it must be ignored this unexpected result. On the other hand, the maximum value of 139.19 days is associated to a null interoperability degree for practice R4. Tables 4.15, 4.17 and 4.19 show this relation among null interoperability degree and maximum lead time. In fact, entities should have a flexible transportation to satisfy the customer orders whenever an unexpected event occurs.

It should be noted that the maximum cost present in Tables 4.15, 4.17 and 4.19 corresponds to the maximum lead time of 139.19 days. This means that the increasing of the time between the reception and the delivery of a customer order contributes to the cost increasing.

Looking at the KPI "service level", one can verify that the minimum value of 85.5309% corresponds to a null interoperability degree for practice R4, as observed in the first scenario. On the other hand, it is not necessary to implement the practice R4 with a maximum interoperability degree to obtain a maximum service level of 97.9803%. From Table 4.14, it can be seen that it is more profitable to implement the practice R4 with an interoperability degree of 0.8, instead of implementing it with an interoperability degree of 1.

Chapter 5. Overall conclusions

5.1. Conclusions
5.2. Future work

5.1. Conclusions

The present dissertation contributes to the interoperability assessment, making use of simulation applied to Lean, Agile, Resilient and Green Supply Chain Management (LARG SCM).

From the literature review on Supply Chain Management (SCM) it was possible to analyse the synergies and divergences among Lean, Agile, Resilient and Green (LARG) paradigms. Also, it were identified the LARG practices that involve logistics interactions between Supply Chain (SC) entities, highlighting the Resilient practice "Flexible transportation". To develop a fully integrated SC, it is necessary the evaluation of the paradigms practices contribution for SC performance. Thus, it was selected the following Key Performance Indicators (KPI's): cost, lead time and service level.

Every SC needs to be interoperable in order to have significant positive effects on their performance. Therefore, it was made a research on interoperability and business interoperability. The literature reveals that the problems of communication that affect complex networks involve three subjects: syntax, semantics and pragmatics. From the research, it was also addressed the interoperability measurement, which can be quantitative or qualitative. It should be noted that is not possible to assign an interoperability level valid for all types of business.

After the literature review on SCM and interoperability, it is used the simulation tool to study the actual global business environment, applying these two concepts. In this work, an exploratory case study was conducted at some entities of a Portuguese automotive SC.

The simulation model was developed with the help of Rockwell Arena 9.0 simulation software. Regarding the large number of simulation tools that have been developed for SC analysis, Arena software is considered a user-friendly and dynamic tool. Although it has many advantages that were not explored, such as animation, Arena has some limitations that should not be ignored. For instance, if the simulation model requires many replications with a long replication length, a sensitivity analysis will take too long. Furthermore, a large number of entities involved in the simulation model can also overload the results extraction contributing, consequently, to a sensitivity analysis more complex and lengthy.

Another limitation of this study is related with the inputs of the simulation model.

Since was not possible to gather all data at entities of the Portuguese automotive SC, the simulation model was made considering a potential set of values, in order to assess the impact of input data changes on the model results.

Therefore, the consistency between the simulation model and the conceptual model, which was designed based on the automotive SC characterisation, is not as good as expected. The remaining input data and parameters that were used in the simulation model were quantified based on interviews with logistics and operations managers of the SC entities. Note that to make an assessment in SCM and interoperability it is required a deep knowledge in these subjects not only from the interviewer, but also from the professionals interviewed.

Despite all these limitations, it is possible to say that the objectives of this dissertation were achieved almost entirely. The development of a simulation model that accurately represents the real system depends on the confidence of the inputs. If the simulation model is built only using real input data, the uncertainty of the outputs will be lower. Since some of the inputs were assumed, this simulation model should be used as a basis to deepen the knowledge on SCM and interoperability concepts, using the simulation tool. SCM, interoperability and simulation subjects must be applied together to help organisations to achieve overall competitiveness, focusing their strategies on a co-operative environment.

5.2. Future work

Regarding future work, it could be interesting to continue studying SCM and interoperability using simulation software with a different simulation language, such as, for example, SIMSCRIPT or ProModel. An additional extension of this study may be the combination of the simulation tool Arena and the procedural programming language Visual Basic for Applications (VBA). Thus, it will be easier to program complex algorithms in VBA.

The graphical animation is also a possible extension of the work developed. Animation is needed to visualise and analyse the process dynamics. Thus, it will be easier to entice others in the organisation to be interested in process improvement.

Finally, it would be interesting to select more LARG practices and/or KPI’s, like quality, in order to monitor interoperability throughout SC. Since the automotive SC simulation model makes a virtual study of how to access interoperability in LARG practices using subjective information, it would also be interesting to apply this study to an enterprise of other sectors, such as, for example, Information Systems (IS) or pharmaceutical industry.

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Annexes

Annex 1 First scenario simulation sub models

Annex 1.1 Supplier 1_2 simulation sub model

Annex 1.2 Supplier 2_2 simulation sub model

Annex 2 Second scenario simulation sub models

Annex 2.1 Customer simulation sub model

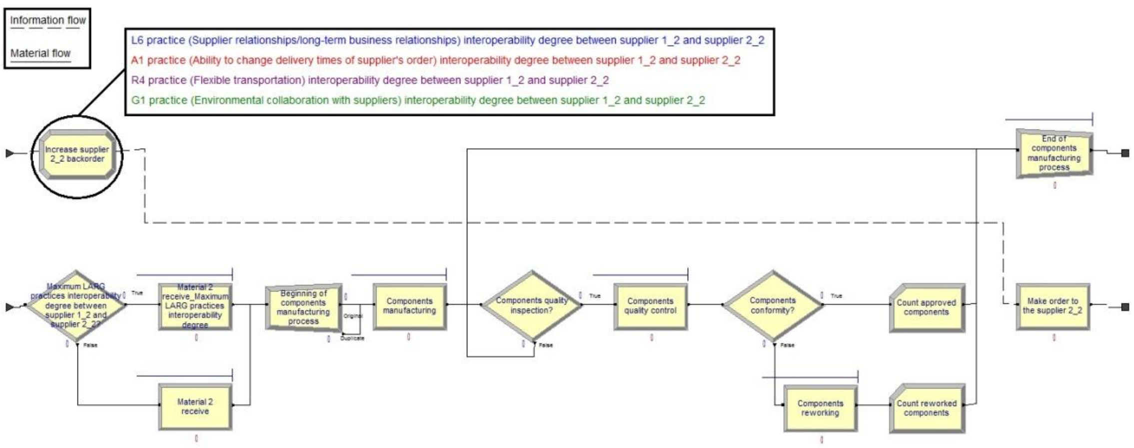
Annex 2.2 FF simulation sub model

Annex 2.3 Supplier 1_1 simulation sub model

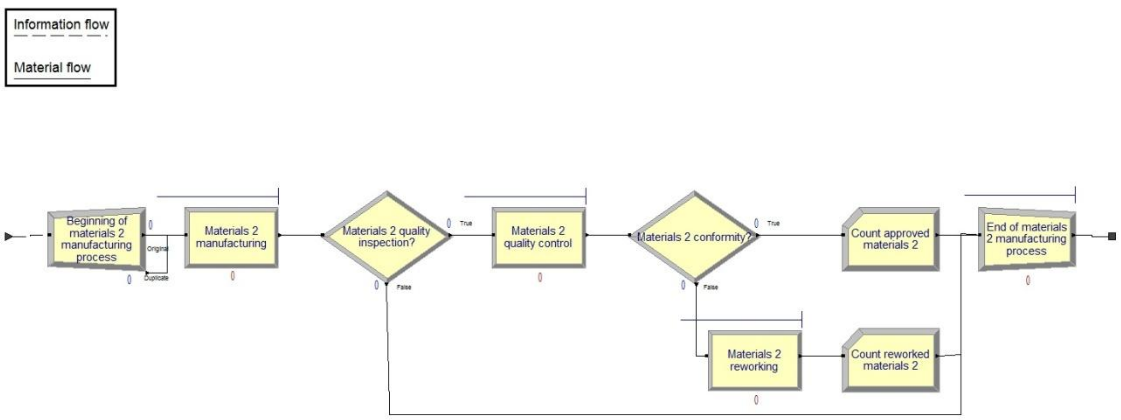
Annex 2.4 Supplier 1_2 simulation sub model

Annex 1 First scenario simulation sub models

Annex 1.1 Supplier 1_2 simulation sub model

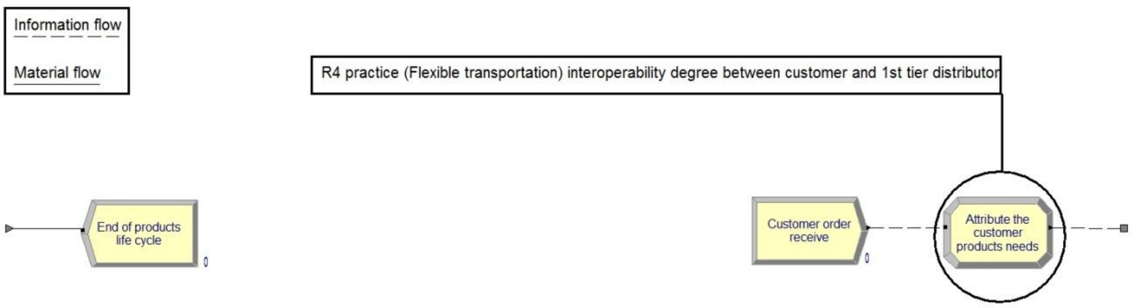


Annex 1.2 Supplier 2_2 simulation sub model

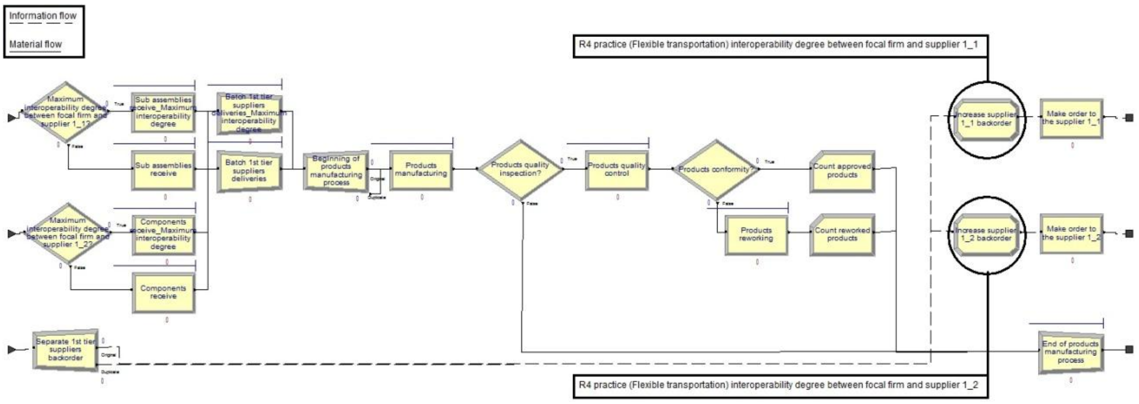


Annex 2 Second scenario simulation sub models

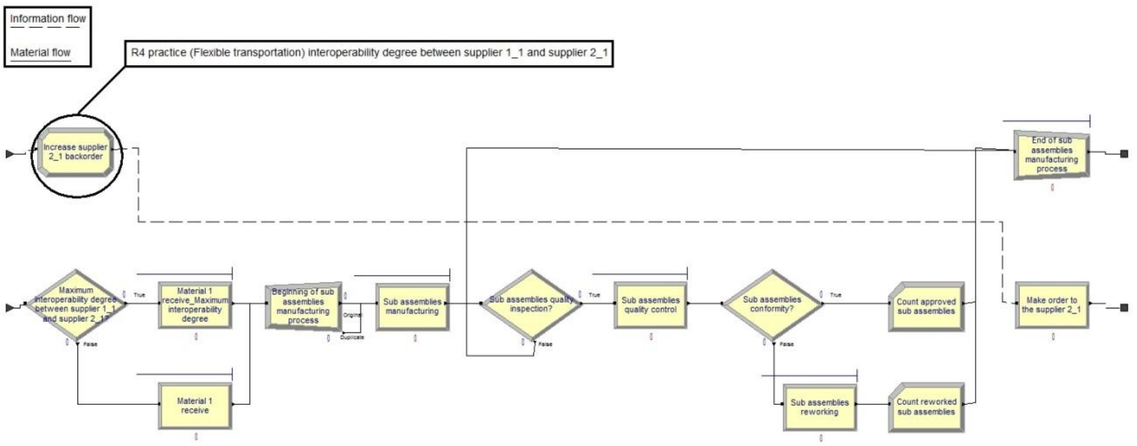
Annex 2.1 Customer simulation sub model



Annex 2.2 FF simulation sub model



Annex 2.3 Supplier 1_1 simulation sub model



Annex 2.4 Supplier 1_2 simulation sub model