Introduction

“Pause on the esplanade of La Sabika and gaze upon your surroundings. The city is a lady whose husband is the hill. She is clasped by the belt of the river, And flowers smile like jewels at her throat... La Sabika is a crown upon the brow of Granada, In which the stars yearn to be studded. And Alhambra — God watch over it! — Is a ruby at the crest of that crown.” wrote the poet Ibn Zamrak in the 14th century about the place where I decided to start this thesis. In reality, it seems that there could not be a better place to start it than in this town of Granada, where people live the modern times of distribution of products and services and the speed induced by such processes, and, at the same time, the inspiration and the tranquillity of the Arabic quarters, where palm trees and little vendors still coexist in an almost unreal harmony.

There is, in truth, some justification for this fact, for this work have been strongly motivated by the idea of conceiving and developing an approach to simulate Supply Chain systems in a way that it could be flexible enough to represent their variety and, in addition to that, analyse them in terms of what is currently referred to as “flexibility”. In this place, one is definitely able to identify from the old times human paper chain linking warehouses, retailers and consumers, to the most modern Information Technology (IT) and advertising Supply Chains of nowadays. It sounds somehow ironic, however, to realise that in many cases consumers still prefer the former approach.

Concerning the simulation of the Supply Chain, it is important to notice that we live in a time where many different approaches are already being used and explored worldwide, mainly due to the last decade’s explosion in the number of people using not only high level language programming but also the advantage of the information exchange made possible by the Internet. We live, in effect, in the times where people invade Internet cafés to constantly communicate with one another by email or by chat; in the last few years the universe of programmers have exploded, and the usage of simulation tools obviously started
to exhibit the same trend. Nowadays, if not yet simulating everything, humankind is at least already trying to simulate everything.

Nevertheless, and in a certain sense as a paradox, it is still very difficult to obtain detailed information about the concepts behind most of the Supply Chain simulators announced out there, for they easily turn into products of high value to those who develop them, as well as to the consultancy agencies who make them highly rentable. It is a fact that everybody wants to handle a model of his/her problem, from the United States Department of Defence (DoD), to the most recondite and anonymous flower producer of Beira Alta. Such a wide spread interest explains the “boom” in advertising these precious tools. On the other hand, the world of simulation has also changed dramatically during the last years, from the trustful and somehow innocent academic old-fashioned reliability to the present suspicious and voracious days of modern commerce. The pressure of advertising is so high that it frequently hides the quality of the product, and this is a general phenomenon also observed in simulation tools and certain other complex software tools. In reality, there is not any available books or articles or any other texts on how to project a Supply Chain simulator obviously, and, apart from a few extremist researchers that decide to free the source of their simulators on the Internet, the most reliable information about the structure of the products is only achieved in their Operation Manuals, which means, after buying them, or, with some luck, borrowing them from a friend. Of course the Operations Manual is not the appropriate document in which one can expect to find much about the structure of the internal processes involved in such tools, or how they have been conceived, but at least some information can be captured from it indirectly. This, and the difficulty of finding new interesting aspects in the literature more than the usual discrete approaches based on events, processes, Petri-nets, etc., as well as on some new trends using “intelligent” entities named Agents (Nwana, 1996), which I do not consider an attractive approach to simulate the dynamics of the Supply Chain, in the end the choice have been to build up my own personal approach from the ground.

This text intends to expose the ideas behind the development of such an approach, as well as to document the relevant steps that have been taken to reach that challenge, from the bibliographic review and the study of conceptual issues about Supply Chain systems, their structure and their management, as well as the current trends of simulation, to the conception and the development of a practical simulator written in C++ with which some results and conclusions have been obtained.

Relevance

The simulation of Supply Chain Systems is presently widely recognized as of great value, as these kinds of systems frequently exhibit complex behaviours, too difficult to be represented by analytical equations or other continuous mathematical techniques. The modelling approaches in use at the moment are diverse, as diverse still are the schools of modelling and the objectives for which simulation is used. In general, as we

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1 A Province of Portugal.
will seen soon in the chapter reserved for the literature review and the state of the art, events, Petri-nets, Bond graphs, Agents, etc., are concurrent paradigms with which modellers continue to try to represent their systems. There is not, however, any special reason for electing any of them as the primus-inter-pares, as their usage strongly depends on the school of modelling or on the sympathy the modeller has for a particular paradigm or tool. It was not so surprising to meet a senior researcher at a conference in Naples, three years ago, who kept on using an old version of SIMULA, since this language has continued to fulfil his needs and was already the “mother” of the Object Oriented Programming (OOP) paradigm.

In that sense, the approach presented in this work is still based on the classical next-event paradigm, although it will be seen that the conceptual model of the Supply Chain already includes some novel features, as it tries to follow issues like just-in-time (JIT), KANBAN, flexibility and even what some people call demand pipelines, for example. These are seen as recent tendencies for research in this field of knowledge, and practically ignored in the common Supply Chain simulators.

Another important note is the fact that most of the present simulators seem to persist in using the common methods to create the model, mainly based on some sort of queue-activity diagrams from which the dynamics naturally emerge. To the contrary, the present approach has been conceived in order to encapsulate such “low-level” diagrams and enable the user to faster and easily employ a logic similar to that of the real system, thus reducing the modelling process to the handling of “real” elements such as transport paths or even complete facilities. Each element is also stochastic, and a set of graphical output data attached to it will be available. Thus, in a certain sense, from the point of view of the modeller, the present approach can be considered not only a paradigm of “real objects” but also, and in a certain way, of “real reasoning”.

A last issue that must be mentioned is the universe of applicability of this proposal. This simulator have been developed based on the next-event dynamics, and thus it is prepared to handle quite well not only events separated by some seconds, minutes or hours, but also those separated by weeks, months or years. That will depend, of course, on how the modeller configures each element in the simulator, on how he defines the appropriate transportation, or on how he considers the patterns of demand. Therefore, and also since every element is configured by “default”, at least theoretically it will be possible to simulate the systems at the operational perspective, as well as for tactical or strategic purposes. In reality, it will not be difficult to obtain results with this approach from a simulation of “some days” to a simulation of “some years”. The treatment of the output data and the process of its analyses will be the last term that will establish the point of view in fact considered. It is, however, important to keep in mind that usually the uncertainty of the results will grow as the period of simulation increases.
Hypotheses

“Flexible Supply Chain Simulation” has been chosen as the title of this research for two main reasons. Firstly, the adjective “flexible” must be applied to the simulation itself, since its structure has been conceived with the intent to allow a wide range of scenarios to be modelled without losing the simplicity of the modelling process, not only in terms of different Supply Chain network structures, but also regarding the usage of different stock and production policies, from the classical approaches of producing-to-stock, to the modern trends of JIT. In this first sense, the hypotheses can be described by the following two statements:

**H1** the simulator will be able to represent diverse kinds of Supply Chains in terms of different network structures, and allow the analyst to draw conclusions about their performances at least based on some standard Supply Chain measures.

**H2** the simulator will also be able to represent different stocking and producing policies at each facility, as well as to test different kinds of vehicles for delivery, in order for these to be compared by means of some standard measures.

Secondly, the adjective “flexibility” must be applied to the Supply Chain itself, and that means that the present approach is expected to give the user some quantitative indications about the degree of “flexibility” of a certain scenario. The third point of the Hypothesis is, therefore:

**H3** by means of this simulator it will be possible to obtain a quantitative measure of the “flexibility” to demand variations, not only related with each facility but as well with the entire Supply Chain structure. Different scenarios are expected to be possibly compared based on these sorts of measures.

Methodology

To achieve the objectives expressed in these hypotheses, a first plan for the program of research was established, inspired by the believe that “one must first understand the system so that later one is able to model it”. This implied the orientation of the research in two main directions:

a) **Simulation**: study of the literature and investigation on the “state of the art” by reading articles published in conferences, journals, magazines and on the Internet, as well as about its basis in relevant books, by means of which it was finally possible to classify the various recent tendencies of simulation applied (or applicable) to Supply Chain, and to recognize the merits of each of them.

b) **Logistics and Supply Chain**: study of the basis of Logistics and Supply Chain management in some relevant books on the field, followed by an extensive literature review focused on scientific articles obtained from magazines, conferences, journals, Internet, etc., with the intent of learning as much as possible (given the time constraints) about the kinds of systems that were to be simulated. This study has been extended to most matters concerning Supply Chain management, but in the end it has been mostly focused on production and inventory policies, on different delivering vehicles and on the understanding of the
various Supply Chain structures, as well as the actual trends and philosophies involving the field. A historical overview on the Supply Chain management has also been accomplished.

Once the knowledge concerning these matters had reached a satisfactory level, a new process was started in parallel, leading to real contacts with people, centres of knowledge, universities and enterprises, with the intent to definitely take a real measure of the problems and ideas occurring in the field, often quite distant from the usually optimistic literature.

These contacts included meetings and discussions with people strongly related to the management of Supply Chains, most notably with the Management School of Porto - EGP (Portugal), the University of Erlangen Nuremberg (Germany), the enterprises BARKAWI & Partners and BMW from Munich (Germany), the Centre for Logistics and Supply Chain Management of the University of Cranfield (UK), and, finally, some interviews with the GalpEnergia company (Portugal).

Parallel to this, the process of implementing and day-by-day improving the C++ Supply Chain simulation application started. This would later lead to the very first version of the Supply Chain simulator, which basis had then been presented at the “European Simulation and Modelling Conference”, Naples (Italy), in 2003 (Feliz-Teixeira & Brito, 2003).

This method of framing the research reveals a top-down strategy in the process of learning, followed by a bottom-up strategy in the development and the implementation. Although only after the learning process reaches the bottom level one can start to implement, this method is probably the most interesting and reliable method to use in projects of this kind, as, without doubt, it ensures that the results will be derived from a good background of knowledge. This scheme also provides the researcher with enough information about the relevant matters, giving him or her the ability to better handle the real problems and even to formulate new suggestions. That was the case of the theory of Supply Chain flexibility proposed in this work, and meanwhile published in Feliz-Teixeira & Brito (2004), even if this matter was not specifically related to simulation; and also the case of a small study comparing an inline classical Supply Chain with an imaginary demand pipeline chain (Feliz-Teixeira & Brito, 2005) since the last is indicated by some authors as the Supply Chain of the future (Hewitt, 2001).

In order to enable the exploration of any interesting concepts that could meanwhile emerge from the research, efforts have been made to ensure the methodology was kept flexible enough, instead of a priori reducing it to a predefined set of constraints. This fact has also made possible the development of a distributed Supply Chain Game (Feliz-Teixeira et al., 2004), for example, with which a class of students seated at different computers could exercise inventory management in a didactical Supply Chain.

Apart from this, several procedures of verification have been carried out in the proposed simulation approach, in which the
simulator internal processes were approved, and a first validation of its outputs have been achieved by means of simulating some practical cases, as far as possible. The most significant of these was a real case study based on data provided by the company GalpEnergia, which resulted in the confirmation of the practical value of the approach, and contributed to testing and confirming the hypotheses.

The hypotheses were finally tested and inferred as true by means of analysing the data obtained in the GalpEnergia case, as well as in the demand pipeline case and some other appropriate Supply Chain “small paradigms”; and, finally, by the success in the calculation of a quantitative measure of flexibility for a didactic Supply Chain, known as the “Cranfield Blocks Game” (Saw, 2002).

**Thesis structure**

The thesis begins with an introduction to Logistics and Supply Chain Management (SCM) as an overview of how the concepts related to these matters have evolved since the end of the Second World War, as well as of how the computer Simulation, scientific development and even certain aspects of common life have progressed concurrently. This opening results from a general literature review focused on those issues with the intent to establish a general view on the evolution of the times and the state of the arts (chapter1).

Since the present work involves a significant specific knowledge in two different fields, the field of Logistics and SCM and the field of Simulation, and since it is expected that people specifically from these fields do not necessary dominate both matters to an extent adequate for understanding the present work, it was considered justifiable and even convenient that each field would be firstly presented in some detail before moving to the presentation of the work. In a way, this text may, therefore, also be considered didactic. The thesis is mainly about Simulation, but it is applied to a specific type of system, which is known as Supply Chain. It is, therefore, essential to ensure the convergence of knowledge of the two fields to a point that Supply Chain managers and Simulation experts can both understand and use this text. Chapter 2 is, for this reason, dedicated to an overview of the relevant issues concerning both the Supply Chain and the various modelling and simulation technologies used to model these kinds of systems.

In chapter 3, the proposed approach for Supply Chain modelling and simulation is conceptually presented, with each of its elements explained and analysed in detail, with emphasis on its central element, the general Supply Chain facility that we have named Customer Supplier Unit (CSU). Modelling the fixed and the variable costs of the Supply Chain, the products, the facility resources, as well as the facility dynamics and the vehicles dynamics, and finally, presenting the theory of flexibility, are the type of subjects presented in this chapter.

Chapter 4 is dedicated to the C++ implementation of the current simulation approach, and includes an overview of the structure of the simulator, as well as the code and comments on the most important
object classes in the application. Although there is a good extent of C++ code in this chapter, each important object or structure has also been described by means of accessible diagrams, so that non-C++ users may also benefit from its information. A short overview of the final application for modelling and simulation concludes this chapter.

Following a brief discussion concerning the verification and the validation of the simulator application, the rest of chapter 5 is reserved for the presentation of some experimental results achieved by simulating a few practical cases. Relevant comments and discussions will be dispersed throughout this chapter.

Finally, chapter 6 is entirely dedicated to the final conclusions and the perspectives for future research. It is here that the verification of the hypotheses is also done, as well as some ideas related with holistic measures presented.

NOTE: Bibliographic references are presented at the end of each chapter and also at the end of the thesis.
References:


Saw, R. (2002). Cranfield Blocks Game: Centre for Logistics and Supply Chain Management (CSCM), University of Cranfield, UK.