INTEGRAL OPTIMIZATION AND SOME SUPPLY CHAIN DEVELOPMENTS

by

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DEDICATION

I would like to dedicate this thesis to my parents, my brothers and to my daughter Maria Paula and my wife Mónica, without whose support I would not have been able to complete this work.

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This thesis would not have come into being without the support and help from several persons and I would therefore like to thank all of them.

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Publications

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Torres, S., García, R.G., Quintero, J.J. (2007). Costos de transacción en los servicios de consulta externa: el caso de los hospitales de tercer nivel en Bogotá, Colombia. (2006). Cuadernos de Economía: Latinoamerican Journal of Economics. In press.

Olaya, E.S., García, R.G., Torres, N.S., Ferro, D.C., Torres, S. (2006). Caracterización del proceso productivo, logístico y regulatorio de los medicamentos. Vitae. 13(2) 69- 82.

García, R.G., Olaya, E.S. (2006). Caracterización de las cadenas de valor y abastecimiento del sector agroindustrial del café. Cuadernos de Administración. 19(31) 197-217.

García, R.G. Monroy I.M., Guio, O.F. (2005). Análisis del sector generador de energía eléctrica en Colombia. Revista de la Escuela Colombiana de Ingeniería. 57(1), 35-46

Torres, S., García, R.G., Quintero, J.J. (2005). Formas de CONTRATACIÓN de los servicios de urgencias: una APROXIMACIÓN desde la economía de los costos de transacción. Revista de Economía Institucional. 7,12: 209-237.

García, R.G. Caro, MP., Díaz, H., Sánchez, L.L., Carrillo, M.P.(2004). Metodología de marco de referencia para localización de instalaciones. Ingeniería y Universidad. 8(2),139 – 157.

García, R.G., Correal, M.E. (2003). Análisis de los Componentes del PIB Colombiano. Revista Ingeniería y Desarrollo, Universidad del Norte. 13(Enero – Julio), 69-84.

García, R.G., López, M., Torres, J.F. (2003). Aproximación a un Modelo de optimización del despacho de agua en una red de acueducto. Ingeniería. 8(1), 58-63.

Pérez, Y.O, García, R.G. (2002). Medición de la eficiencia relativa de agentes generadores de energía eléctrica en Colombia. Energética, 28(Diciembre), 27- 46.

Carrillo, M.P., Fiorillo, G.R. García, R.G. (2002). Modelo Analítico de Administración de cadenas de abastecimiento en PIMES. Revista Ingeniería y Universidad de la Pontificia Universidad Javeriana. Volumen 6, Numero 2, Julio- Diciembre

Software

García, R.G., Nieto, F., García, O.L. (2006). CMTD - ACADEMIC

García, R.G., Torres, S., Ferro, D.C. (2006). PREFERENTIAL DECISION - ACADEMIC

Presentations

Intercambio de servicios de cirugía programada en hospitales de Bogotá, un análisis soportado en SMAA. XIII CLAIO, Montevideo (Uruguay). 2006.

Economic analysis of link between end product dealers and health service promoters of pharmaceutical supply chain of Bogotá, Colombia. 1er CNC-LOGISTICA. Zaragoza (Spain). 2007.

Operations Research in Agroindustrial Supply Chain in Colombia. EURO XXI in Iceland: 21st European Conference on Operational Research, Reykjavik (Island). 2006.

Representación del concepto de administración: una exploración en profesionales colombianos. Encuentro Internacional en Administración. Cali, Colombia. 2007

Optimizacion of the colombian pharmaceutical supply chain including transaction cost. Euro XXI in Iceland: 21st European Conference on Operational Research, Reykjavik (Island). 2006.

Planeación estratégica y táctica de una cadena de abastecimiento doméstica para la erradicación de minas antipersonales mediante robots In: XIII CLAIO, Montevideo (Uruguay). 2006.

Optimization model to planning of supply chain on a palm oil plantation. Sixteen Annual Conference of POMS - OM Frontiers: Winds of Change. Chicago (USA). 2005

Modelación matemática de una cadena de abastecimiento en el sector agroindustrial colombiano: Palma Africana. XI ELAVIO Latin American Summer Workshop on Operations Research. Villa de Leyva (Colombia). 2005.

SMAA y Análisis Discriminante Múltiple: aplicaciones al análisis de los límites entre EPS e IPS de III nivel en Bogotá. XV Simposio de Estadística. Universidad Nacional de Colombia. Paipa, 2005.

Análisis del sector generador de energía eléctrica en Colombia (año 2001). XV Simposio Nacional de Estadística. Universidad Nacional de Colombia. Bogotá, 2005.

Determinación de la carga física y el consumo de oxígeno en conductores de carga y pasajeros en la ciudad de Bogotá. VIII Congreso La Investigación en la Pontificia Universidad Javeriana. Bogotá (Colombia). 2005.

Intercambio de Servicio de Consulta Externa en Hospitales de Bogotá, Colombia. Management, Knowledge and Flexibility. Iberoamerican Academy of Management 4th International Conference. Lisboa (Portugal). 2005

Una aplicación DEA al análisis del sector generador de energía eléctrica en Colombia. XI ELAVIO Latin American Summer Workshop on Operations Research. Villa de Leyva (Colombia). 2005.

Formas de CONTRATACIÓN de los servicios de urgencias: una APROXIMACIÓN desde la economía de los costos de transacción. III Congreso Colombiano y I Encuentro Andino de investigación de operaciones. Cartagena (Colombia). 2004.

Localización óptima multipropósito de instalaciones bajo incertidumbre. III Congreso Colombiano y I Encuentro Andino de investigación de operaciones. Cartagena (Colombia). 2004.
Determination of the Manual Material Handling Capabilities for Workers in Colombia. ISOES - Conference Proceedings entitled “Quality of Work and Products in Enterprises of the Future”. Munich (Germany). 2003.
Statistical analysis of the nature of Colombian Gross National Product. Simposio en Investigación Operativa. Buenos Aires (Argentina). 2003.
Measuring the relative efficiency of electric power generating agents in colombia using data envelopment analyses analices. Joint International Meeting IST. Istanbul (Turkey). 2003.
Differences between Anthropometrics of Workers and College Students in selected Measurements. XVII Annual Conference de la International Society for Ergonomics and Safety (ISOES). Munich (Germany) 2003.
Measuring the relative efficiency of electric power generating agents in Colombia. Simposio en Investigación Operativa SIO'2003. Buenos Aires.(Argentina).2003.
Approximation to a model of optimal water flow dispatch in an aqueduct network. Simposio en Investigación Operativa SIO'2003. Buenos Aires (Argentina). 2003.
Análisis de los Componentes del PIB Colombiano. XII Congreso de Colombiano de Estadística, Simposio Colombiano de Procesos Estocásticos. Universidad Nacional de Colombia. Bogotá (Colombia).2002.
Análisis de los componentes del Pib Colombiano (versión 1). XII Congreso de Estadística, Simposio Colombiano de Procesos Estocásticos. Bogotá (Colombia). 2002.
Hypothetic optimization model of supply chain on a palm oil plantation. International conference on industrial logistics. Montevideo: International Centre for innovation and Industrial Logistics (ICIIL), 2005. p.193 – 202.

Field of Study

Optimization, Statistics, Applied Mathematical, Logistics, Production, Decision Theory, Supply Chain Management.

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RESEARCH OBJECTIVES

The current research objectives can be summarized as follows:

1. Development of adequate mathematical procedures capable of dealing with particular supply chain optimization problems.
2. Development of a methodology that allows to integrate cardinal and ordinal criteria in stochastic optimization contexts.
3. Application of the developed methodology to supply chain practical cases.

ABSTRACT AND RESEARCH ORGANIZATION

The present doctoral dissertation introduces a series of contributions to current optimization and decision problems, each of them within a single chapter issuing an article on the topic, and including its corresponding literature review, study cases, and associated research perspectives. Chapter one presents a mathematical model and a solution procedure for an african palm oil sector's supply chain, dealing with fruit collection, raw material transport from collection zones to stock centres, and extraction of red oil and other primary derivates. The dynamic model developed takes into account particular plantation conditions and production features, of which access roads to collection zones and specific harvesting conditions are respective examples in the current case. The paper presents a solution procedure based on commercial software, together with a complete sensibility analysis of the most outstanding functioning conditions of the supply chain.

Chapter two presents a mathematical model, two solution procedures and a sensibility analysis supporting the strategic and tactical decision making process of an anti-personal mine robotic erradication system's supply chain. Strategic decision making includes production and distribution infrastructure definition, factory location, and supply and distribution channel selection. The two decision types are integrated in a single MIP model (which is an aproximation of a more complex stochastic MNLIP), solved by procedures based on commercial optimization software.

Chapter 3 issues a study on transaction costs resulting from commercial relationships between Health Insurance Companies[1] and Health Service Providers[2] in rendering the external consultation services commanded by the Solidarity and Social Security Health

[1] These companies are locally known as "Empresas Promotoras de Salud", which means "Health Promoting Companies", and gives raise to their abbreviation as EPSs.
[2] These companies are locally known as "Instituciones Prestadoras de Servicios (IPSs)", which means "Health Providing Institutions".

General System (SSSHGS)[3] in Bogotá, Colombia. In order to obtain the necessary information for the analysis, a survey was conducted on levels 3 and 4 IPSs, which hold the largest and more complex service offers. The information was analyzed by means of Discriminant Multivariate Analysis (DMA) and a Deterministic version of Stochastic Multicriteria Acceptability Analysis (SMAA). As a result, a complete analysis was obtained, not only allowing to determine the most efficient governance forms at reducing the transaction costs between the two mentioned agent types, but also the reasons why they are established.

Finally, chapter 4 introduces the new Integral Analysis Method (IAM), presenting both its theoretical background and its practical application to a location problem. This methodology integrates cardinal and ordinal aspects of combinatorial stochastic optimization problems in four stages: problem definition, cardinal analysis, ordinal analysis and integration analysis. Integrating concepts from SMAA, Monte Carlo Simulation, Optimization Techniques and Probability Elements, IAM was used to determine an optimal location for a Colombian coffee marketing company.

[3] "Sistema general de Solidaridad y Seguridad Social en Salud", stands for its spanish name.

INTRODUCTION AND CONCEPTUAL APPROACH

Advances in optimization have allowed the modelling of a great number of problems, which have been “solved” with the aid of new computational advances that include mathematical solution procedures capable of dealing with cardinal variables. The solution procedures include algorithms to solve non – linear, integer, combinatorial, stochastic, global, and multiobjective problems, which have succeeded in small and medium optimization instances. Exceptions are the linear, quadratic, integer and combinatorial problems with special structures, which can be solved efficiently in large instances. On the other hand, techniques that allow approximate solutions are now having relevant success for integer, combinatorial, multiobjective, non – linear and global problems. Among these techniques there are heuristic, metaheuristic and hybrid ones (those that combine algorithms and heuristics). But despite such advances, it has not yet been possible to develop any technique that is capable of handling qualitative aspects in optimization problems. In sum, it can be said that in many cases, the currently existing procedures do not allow finding solutions that are more in accordance to reality, due to epistemologic and technical limitations that make it difficult to treat both quantitative and qualitative aspects at the same time in these decision contexts. In order to work out such solutions, an Integral Analysis Method (IAM) is developed in chapter 4.

Practical Application: Supply chains

The outset of the supply chain concept and its practical applications appeared in the 80’s, not only as a response to the globalization process, which germinated by the time, but also as a consequence of the apparent impossibility that single agents would find to increase their competitiveness and participation in the market by themselves [Johnson et al., 1999]. In this sense, various authors [Giannakis and Croom, 2004; Lummus and Vokurka, 1999] have established that current competition does not actually take place among firms, but among supply chains.

The need to increase collaborative efforts among different agents, experimented by the industrial sector [Porter, 1987], along with an inefficient answer on the part of the academic community, brought up an abundant conceptual proliferation and non-standardized literature. Such proliferation prevented faster theoretical developments in supply chain management theory, which was only later incipiently conceived by the pioneer work of Paulraj [2002]. Such non-standardization has taken place at fundamental conceptual levels, including for example, discrepancies in the very definition of what a supply chain is, coming from a variety of literature sources ranging from APICS dictionary, the Supply Chain Council, the Institute for Supply Chain Management and the Global Supply Chain Forum, to those provided by different practitioners and theorists on this issue.

As a result, the supply chain concept has been continuously changing since its inception, from the initial thought just regarding material control [McKone-Sweet et al., 2005], to a variety of proposals currently in use [Lambert et al., 2005]. These proposals conceive the supply chain concept as a series of activities, from raw material to final consumer stages, involving information and resource flows [Brennan, 1998, Lambert et al, 2005], and entailing several necessary aspects, like demand management, suppliers, supply orders, logistics, inventory, and manufacturing planning [Brennan 1998; Quinn, 1997; Lummus and Vokurka 1999]. Besides these aspects, Lambert et al. [1988] have included some additional items like customer relationship management, customer service, manufacturing development and customization. To sum it up, supply chains can be said to imply a multi-organizational effort to manufacture and place goods, from the supplier's supplier to the customer's customer. That is, all activities involved in getting a product to its final consumer, including raw material and part sources, manufacturing and assembly, storage and stock monitoring, order reception and shipment management, distribution, delivery, and necessary information systems to control it all [Tan, 2001]. Notwithstanding, as will be shown next, not all of these aspects have been dealt with in the supply chain literature.

Supply chain optimization is a widely developed topic, as it results from the variety and abundance of works in this field, some of which are referred in the literature reviews here cited [Aikens, 1985; Cohen and Lee, 1988; Bhatnagar et al., 1993; Geoffrion and Powers, 1995; Thomas and Griffin, 1996; Vidal and Goetschalckx, 1997; Tsay, 1999 and Goetschalckx et al., 2002], and have led to relevant considerations in supply chain decision making, which have been recently included by Paulraj [2002] within the development of a theoretical framework on the topic.

Two types of decision making can be found concerning supply chains: strategic and tactical, respectively dealing with long and medium term actions [Shapiro, 2001; Harrison, et al., 2003]. Strategic decisions are the most important ones, since they have a stronger impact on supply chain financial operation and viability [Shapiro, 2001; Harrison, et al., 2003]. Their optimization has allowed a 10% average cost reduction, ranging from 5% to 60% in some cases; while service times have been reduced by 25% to 75%, averaging 30%. Such improvements have allowed substantial increases in manufacturing throughput, reliability, and customer satisfaction [Harrison, et al., 2003]. Strategic decisions in optimization contexts have to do with location and capacity of manufacturing plants and distribution centers, procurement channels, suppliers, and logistic considerations about distribution [Harrison, et al., 2003].

On the other hand, optimum tactical and operational decisions in the supply chain are associated to a variety of items, like lead time fulfillment, bill of materials, logistic break – up, issues concerning international supply chains, distribution and manufacturing aspects such as scale economies, and the establishing of dynamic and static inventories and appropriate raw material and product flows in multi – stage supply chains [Harrison, et al., 2003]. As a pioneer practical application, chapter one presents the tactical modelling of an African palm oil sector's supply chain, issuing some frequently omitted aspects in the literature, like periodical programming of the collection and delivery fleet, or production set-up.

In spite of the advances in strategic and tactical decision making optimization, only few works have integrated both types of decision within a single model. Such is the scope of the paper presented in chapter two, in dealing with an antipersonal mine erradication system's supply chain.

Supply Chain Governance Forms

A series of different standpoints, namely strategic fields [Williamson, 1991], marketing [Dwyer et al., 1987], and supply chain management [Grover and Malhotra, 2003] have clearly recognized how the competitive development of organizations is strongly affected by the way they interact to exchange goods and services. In this sense, the supply chain structure has a two-fold effect, comprising both cost reduction [Brennan, 1998; Mckone-Sweet et al., 2005] and generation of added value [Mckone-Sweet et al., 2005].

Linked to the globalization process and to new developments in computer technology and telecommunications, and with the consequent competitiveness intensification, important changes have emerged for supply chains [Lambert et al., 2005]. One of the most important has to do with the way in which economic agents should deal with one another in order to minimize their costs. On the one hand, a vertical disintegration process, encouraged by the need of reducing operational risks has been taking place [Jones et al., 1997; Lummus and Vokurka, 1999], therefore concentrating organizational efforts in the development of central competences [Prahalad and Hamel, 1990]. However, such disintegrated structure has been experimented, for example, in the exchange with intermediate goods and logistic service suppliers with whom marketing relationships are not clearly established, but (with whom) formalization becomes imperative, consequently determining the cooperation relationship to be preferred as a governance form [Heide, 1994], [Shin et al., 2000]. All these factors have rendered complex exchange relationships [Dwyer et al., 1987], and a high interpenetration degree among different agents in the chain [Heide, 1994], therefore allowing different governance forms to coexist.

A governance form is defined as the institutional framework in which contracts support the transaction of goods and services between agents [Palay, 1984]. The different governance forms that can be found in supply chains are: vertical integration [Kim and Frazier, 1996], several agreement types on bilateral cooperation [Arzt and Norman, 2002; Dwyer et al, 1987, Heide, 1994; O'Toole and Donaldson, 2000], supply networks [Moriarty and Moran, 1990], and market forms [Artz and Norman, 2002].

Although decisions that are only based on operational costs are known not to allow an overall estimation of supply chain costs (which should also include transaction costs [Coase, 1937; and Williamson, 1975, 1985, 1991, 1993]), the optimization techniques that support the supply chain decision making process have been mainly focused on financial measurements of performance [Beamon, 1998], despite the strategic and tactical importance of supply chain governance form optimization, which has only recently been approached [Tsay, 1999] by works related to contractual aspects [Weng, 1995; Gu, 2001]. Governance forms appear then as a tacit deficiency of supply chain optimization literature, and deserve to be considered as a fruitful and relevant research perspective [Paulraj, 2002], [Grover and Malhotra, 2003]. For this reason, chapter three presents a pilot test developed to identify the most efficient governance forms at reducing transaction costs in a specific echelon of the pharmaceutical supply chain in Bogotá.

CHAPTER ONE

Send to Applied Mathematical Modelling

Status: Second review

Tactical and operative optimization of the supply chain in the oil palm industry *

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Abstract

This paper shows a dynamic mathematical model of the supply chain for the harvest and oil extraction from oil palm. The mathematical programming model developed has nonlinear and mixed integer features both in the objective function and the constraints, implying a NP-hard problem. In the solution process, the nonlinear nature of the problem is treated, redefining adequately some original variables and modifying certain constraints; as result, an equivalent MIP model is obtained. The model was validated using an experiment based in computational simulations.

Key words: *Mathematical programming applications, integer programming, linear programming, logistics.*

1.1. Introduction

The plantation where the supply chain actually takes place is divided into sections which are made up of land plots aligned by furrows sown at appropriate distances so as to leave the necessary space for plants to grow and to facilitate fruit harvest. Harvest is organized in groups of workers who load the wheelbarrows; these are pulled by animals force through rough and difficult-to-transit paths. The various groups of workers are responsible for harvesting fruit in a pre-established number of land plots; they must left their daily load at internal stockpiling centers (hereinafter referred to as CAIs) located on

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the access roads. On the other hand, the harvest zone allotted to each group of workers must be previously determined per each production cycle.

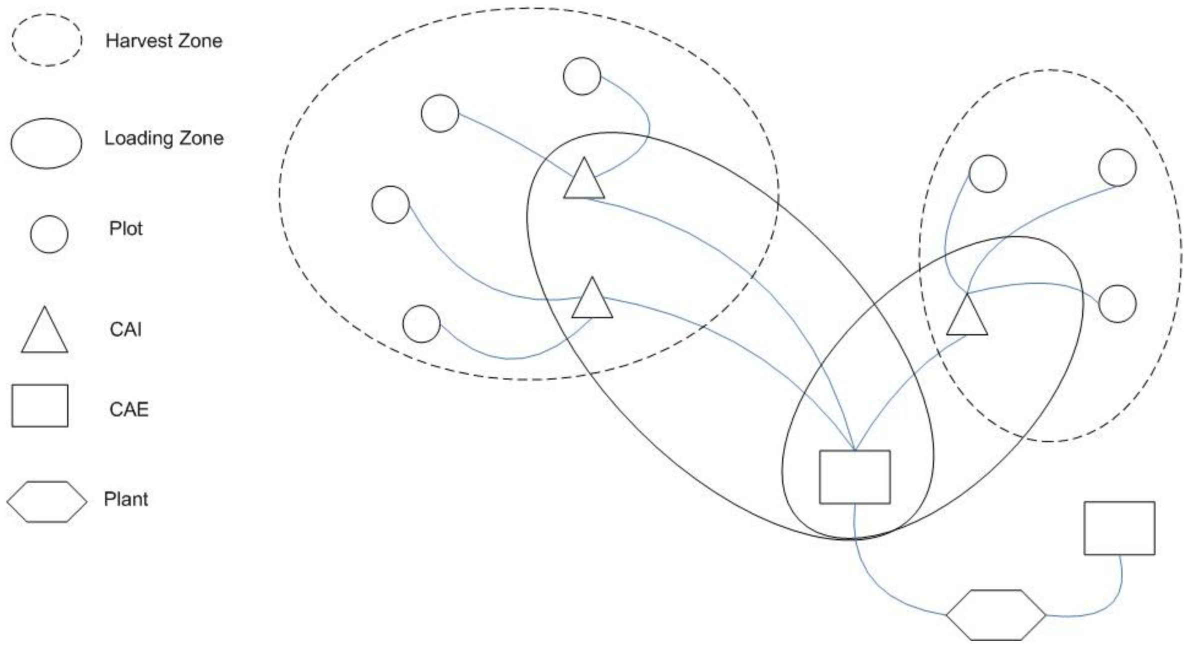

Figure 1.1. Supply Chain Scheme

The road network is divided into zones which are passed through by truck-type vehicles in which the fruit are taken from CAIs to larger external stockpiling centers (hereinafter referred to as CAEs), located on various road intersections. One important consideration for the vehicles used is that these guarantee the load security under difficult circumstances: road, weather and geographical conditions. On the other hand, plantations are connected to main roads for bulk transportation purposes from CAEs to processing plants, which represents a final transport echelon. Vehicles running through this echelon must comply with certain technical requirements concerning capacity and speed. The whole process is supported by equipment used for lifting the fruit from the floor in stockpiling centers and loading it into vehicles; this task can be performed by attaching certain devices to the vehicles or independently by cranes or forklift trucks.

The throughput capacity of the harvest plots (CAI's) is concretely defined by a multiple of the throughput capacity of the supplying trucks so that these vehicles exclusively perform trips between the CAI's and the CAE which is allotted to the harvest zone, without having to approach other CAI's in order to fill their maximum capacity. Thus, by cutting down the trip length, the most efficient flow of prime material is achieved at this echelon of the supply chain.

Unlike the fruit picking itself, which is carried out in a single-step activity, the transport of the crop is divided into two stages: the first consists of the hauling between the CAI's and the CAE's, the second between the CAE's and the oil extraction plant. Both require a separated organizational scheme. The performance at each echelon is determined by the actual throughput capacity of the trucks, be they company owned or subcontracted. The way of assigning the real hauling task for each kind of vehicle varies, because the reliability on subcontracted trucks depends on their lower availability, since every horizon planning anew the equal conditions for each cooperative have to be established due to the fact, that the productivity of each lot differs yearly with the age of trees. Consequently, the company-owned trucks are assigned to the areas with less prospected productivity. As becomes obvious, the procurement of work force, animals, and required vehicles has to be ascertained previously to each harvest season. This includes as well the computation of trips necessary to be carried out in order to satisfy the balance between the expected supply and demand. In the Figure 1.1 the graphical presentation of the supply chain under scrutiny is showed.

As a preventive measure for assuring the continuity of the productive process, it must begin only when the raw material in stock at the plant has reached a pre-established minimum amount. This measure is useful to avoid losses caused by over-costs generated by interruptions unforeseen in the productive system.

The production involved in the extraction process includes red oil obtained from the fruit flesh, as well as palm oil and palm pulp obtained from the fruit bone by a pressing process. Other products, such as fibber and husk, are obtained and used as fuel and fertilizers. These products are then stored and finally sold or consumed in the productive process.

During the process, raw material inventories are generated in the stockpiling centers, and in the warehouses where raw material, and finished products are kept in stock, bounded by their related throughput capacity. Inventories force administrators (particularly in the case of raw materials) to adopt preventive measures to avoid perishing of crops. In order to embody this consideration into the development of systematization whose product is this article, the timing can be tightly linked to time span which the perishable product allows, because due to the periodicity of the productive cycle of the oil palm and because of the loss of oil quality caused by fruit over ripeness once the harvesting time has passed, land plots in their productive time should be totally harvested at the end of productive cycle.

Some aspects, such as provision capacity and uncertainty of demand are irrelevant in this supply chain, because it is always possible to have well-adjusted production curves based on the age of the land plot, and because demand is usually guaranteed by the market that buys all available production, which late on is sold to refineries (an echelon which is not being investigated in this article). However, more general considerations can be taken into account in the latter case as new possible applications of the research.

In order to rationalize production, oil producing companies have opted for different forms of work organization that foster the intervention of third parties (out sourcing) in the process. A frequently used organizational form leaves harvest and transportation tasks to cooperatives subcontracted. Another reason for low competitiveness is the almost total lack of sophisticated technology for decisions making techniques that would optimize raw material and product flow in the chain and minimize the costs involved in harvest, transport and production. In summary, the logistic and production operations in the palm oil industry are likely to be improved because of the system’s complexity and the little support available for the decision-making processes that hamper planners' tasks.

This research project emerged as one of the Government's measures to improve oil palm agricultural industry competitiveness. The work presented here includes a description of the characteristics of the oil palm supply chain; based on the analysis of this chain, a model for the harvest and oil extraction echelons of the supply chain is presented, which can be reproduced due to the similar production characteristics shared by other agricultural industries [FAO, 2004].

1.2. Literature review

One first review was developed by Aikens (1985). The author offers a description of the relevant aspects on supply chain modelling of single echelon systems with deterministic demand. The fundamental tactical aspects were associated with distribution of raw materials and final products. The size of the problems was limited by the absence of a computationally adequate MIP optimizer. On the one hand, as was indicated by Aikens, dynamic modelling aspects and handling of inventories associated to an agent were developed [Cohen and Lee, 1988]. A later development is focused towards a better coordination of the logistics operations between the different stages within the supply chain (procurement, production and distribution), a special attention has to be drawn to the publications by Thomas and Griffin (1996). The considered aspects included: capacities of the procurement and distribution channels, and bill of materials. With regard to the solution heuristic procedures supported in commercial software were developed [Goetschalckx et al., 2002], that resulted in satisfactory practical performances, which is supported by [Vidal and Goetschalckx, 1997]. Finally, Eskigun et al. (2005) take into account the constraints in transportation capacity imposed by a limited number of vehicles in distribution centers, which are sent from production plants to one single distribution center in a particular period of time. This work is an expansion of the one carried out by Eskigun et al. (2001).

Some of the work done on the application of mathematical modeling in agro-industrial supply chains includes that of López et al. (2001), who propose a solution to the problem of high transportation costs for sugar cane grown in different remote fields and transported to a central sugar-processing plant. Constraints include the need for steady central supply, the means used in harvesting, the different types of transportation, and the supply routes; sugar cane must be taken first to stockpile centers and transported to the processing plant by train. Finally, Villegas, et al. [2006] introduce a model of the coffee supply chain in Colombia whose objectives are to minimize costs and to maximize service level, and involve distribution issues, similar to those being considered in this article.

1.3. The model

In order to present the MINLP and MIP models, a consistent notation is presented as the aspects of the supply chain are introduced.

Aspects taken into account

The aspects considered in the model are here treated in detail, as shown next:

Supply available in the planning horizon

Depending on the planning horizon, the harvest operation can be carried out totally or partially. In the present case the situation is modelled by means of an inequality, which can eventually be changed for an equality if the planning horizon coincides with the critical harvesting period, in order to guarantee the quality of the product.

Indexes and Sets:

i : Land plots index, where $i \in \Omega$

t : Planning horizon index, where $t \in T$

$\Gamma(i)$: Internal stockpiling centers set supplied by land plot i

Parameters:

o_i^t : Supply of raw material at land plot i in time period t. (input quantity / time period t).

Variables:

X_{ij}^t : Raw material transported between land plot i and storage deposit j in time period t. (weight or volume quantity / time period t).

Constraint:

$$\sum_{t \in T} \sum_{j \in \Gamma(i)} X_{ij}^t \leq \sum_{t \in T} o_i^t \quad i \in \Omega \tag{1.1}$$

Mass balance

The model is being conceived as a mass flow through a conservative multi-period network which begins in the plantation and ends with the end product. Within the span between harvesting plots and the production plant, stock surveillance of raw material and products are being carried out, since the conditions of supply and demand influence considerably the flow of raw material in the multi periodical net. The purpose of mass balance constraints is to guarantee a conservative flow in the supply chain network. Constraints modulate decisions concerning the size of inventories in stockpiling centers and plant warehouses, as well as the flow through transport and harvest zones. The accumulated stock of each product in a time period is equal to that product's inventory in the previous time period plus production minus demand during the period. On the other hand the stock of raw material in a plant warehouse in a time period is equal to its inventory in the previous time period, plus the raw material received, minus the raw material used in production in the next time period. The equations representing these relations are the following:

Indexes and Sets:

j : index of internal stockpiling centers, where $j \in \Gamma$

k : index of external stockpiling centers, where $k \in \Theta$

p : index of products, where $p \in P$

Parameters:

$d_p^{\,t}$: Estimated demand of product *p* in time period *t*. (quantity of product *p* / time period *t*).

$rend_p$: Quantity of product *p* / Quantity of raw material. (percentage / product).

Variables:

$I_{▫}^{t}$: Raw material inventory at storage deposit ▫ in time period *t, w*here ▫ Є (*Γ U Θ)*. (weight or volume unit / time period *t*).

JM^t : Raw material inventory at storage deposit of *plant* in time period *t*. (weight or volume unit / time period *t*).

$JP_p^{\,t}$: Product *p* inventory in plant warehouse in time period *t*. (product *p* units / time period *t*)

MP^t : Raw material used as production input in time period *t.* (weight or volume quantity / time period *t*).

$X_{jk}^{\,t}$: Raw material transported between storage deposit *j* and *k* in time period *t*. (weight or volume quantity / time period *t*).

Y_k^t : Raw material transported between CAE *k* and plant in time period *t*. (weight or volume quantity / time period *t*).

$Z_p^{\,t}$: Product *p* produced in time period *t.* (quantity of product *p* / time period *t*).

Constraints:

Mass balance of raw material inventory at plant in the time period:

$$JM^{t} = JM^{t-1} + \sum_{k} Y_k^{\;t} - MP^{t+1} \quad t \in T \tag{1.2}$$

Mass balance of raw material inventory at internal stockpiling center:

$$I_j^{\;t} = I_j^{\;t-1} + \sum_{i \in \Omega(j)} X_{ij}^{t} - \sum_{k \in \Theta(j)} X_{jk}^{t} \quad j \in \Gamma, t \in T \tag{1.3}$$

Mass balance of raw material inventory at external stockpiling center:

$$I_k^{\,t} = I_k^{\,t-1} + \sum_{j \in \Gamma(k)} X_{jk}^t - Y_k^{\,t} \quad k \in \Theta, t \in T \tag{1.4}$$

Mass balance of a product inventory in the planning horizon:

$$JP_p^t = JP_p^{\,t-1} + Z_p^t - d_p^t \quad p \in P, t \in T \tag{1.5}$$

Production

Indexes and parameters:

q_p : Quantity of product *p* / Quantity of raw material. (percentage).

Constraint:

$$Z_p^t = q_p MP^t \quad p \in P, t \in T \tag{1.6}$$

Capacity

As can be seen further below, the flows and stocks are determined by the parameters of performance and the throughput capacity of each stock. The constraints which occur in this process are the following:

Indexes and parameters:

c_p : Capacity to produce product *p*. (weight or volume units of product *p* / time period).

$f_{▫}$: Capacity to store raw material at storage deposit type ▫, where ▫ $\in$ *(Γ U Θ)*. (weight or volume units / storage deposit).

u : Raw material stock capacity of plant warehouse. (weight or volume units).

Constraint:

Plant production capacity:

$$Z_p^t \le c_p \quad p \in P, t \in T \tag{1.7}$$

Raw material stock capacity of plant warehouse:

$$JM^t \leq u \quad t \in T \tag{1.8}$$

Raw material inventory capacity at stockpiling centers:

$$I_\circ^t \leq f_\circ \quad \circ \in (\Gamma \cup \Theta), t \in T \tag{1.9}$$

Distribution capacity

The quantity of raw material transported per echelon in each time period is determined by the loading capacity of each type of vehicle used, and the number of trips made by them in the planning horizon; where both vehicles and number of trips are bounded. The bounds of trip numbers by the vehicles in each echelon of harvesting and transportation represent average values obtained by experience and which depend on the age of the plantation the type of vehicle used, load safety and soil conditions in the zone. It must be highlighted, that the entire character of the issue depends on the parameter of throughput (load/speed) capacity of the trucks. The pertinent equations to represent this are the following:

Indexes and Sets:

A : Edges set of the supply chain network. The set A is composed by the three types of edges associated to the following pairwise sets : *(Ώ, Γ)U(Γ, Θ)U(Θ, plant).*

v : Vehicle property index, where $v \in \Xi$.

Parameters:

$b_{▫▪}^{v}$: Load capacity of type of transport v used between storage deposit ▫ and ▪, where *(▫,▪) Є ((Ώ, Γ)U(Γ, Θ))*. (weight or volume units / type of vehicle).

b_k^v : Load capacity of type of transport v used between storage deposit k and plant. (weight or volume units / type of vehicle).

$h_{▫▪}^{v}$: Maximum number of possible trips that a type of transport v can make between storage deposit ▫ and ▪ in one time period, where *(▫,▪) Є ((Ώ, Γ)U(Γ, Θ))*. (trips / time period).

h_k^v : Maximum number of possible trips that a type of transport v can make between CAE k and plant. (trips / time period).

Variables:

$L_{▫▪}^{vt}$: Number of vehicles type v used for transportation between storage deposit ▫ and ▪ in the time period t, where $(▫,▪)$ Є $((\Omega, \Gamma)U(\Gamma, \Theta))$. (vehicles / time period).

L_k^{vt} : Number of vehicles type v used for transportation between storage deposit k and *plant* in the time period t. (vehicles / time period).

$N_{▫▪}^{vt}$: Number of trips made by transportation vehicle type v between storage deposit ▫ and ▪ in the time period t , where $(▫,▪)$ Є $((\Omega, \Gamma)U(\Gamma, \Theta))$. (trips / time period).

N_k^{vt} : Number of trips made by transportation vehicle type v between CAE k and plant in the time period t. (trips / time period).

Constraints:

Maximum number of trips by echelon:

$$N_{\circ\bullet}^{vt} \le h_{\circ\bullet}^{v} \quad (\circ,\bullet) \in A, v \in \Xi, t \in T \tag{1.10}$$

Quantity of raw material harvested and transported between stockpiling centers:

$$X_{\circ\bullet}^{t} = \sum_{v \in \Xi} b_{\circ\bullet}^{v} N_{\circ\bullet}^{vt} L_{\circ\bullet}^{vt} \quad (\circ,\bullet) \in A, t \in T \tag{1.11}$$

Maximum number of trips between external stockpiling centers and plant:

$$N_k^{vt} \le h_k^{v} \quad k \in \Theta, v \in \Xi, t \in T \tag{1.12}$$

Quantity of raw material transported between external stockpiling centers and plant:

$$Y_k^{t} = \sum_{v \in \Xi} b_k^{v} N_k^{vt} M_k^{vt} \quad k \in \Theta, t \in T \tag{1.13}$$

Infrastructure Distribution

The corresponding bound for the vehicle fleet assigned to any given harvesting zone and transportation are, in the case of outsourcing, previously defined through the conditions of the contract agreed on with the cooperatives. As for the company-owned vehicles, this depends on the availability of trucks in the respective harvesting zone, which are determined by the by the transport operation projections and the geographical distances where they are located in the moment of planning:

Indexes and Sets:

r : Harvest Zone index, where $r \in R$

s : Index of transportation Zone between Stockpiling Centers, where $s \in S$

Parameters:

$m_{\square}^{v}$: Maximum number available of vehicles type v at the zone type ▫ in one given time period, where ▫ $\in$ (R, S, Θ) (units / time period)

Variables:

$M_{\square}^{vt}$: Number of vehicles type v used at transportation zone type ▫ in time period t, where ▫ $\in$ (R, S, Θ). (units / time period)

Constraints:

Number of work teams per harvest zone:

$$M_r^{vt} = \sum_{(i,j)\in r} L_{ij}^{vt} \quad r \in R, v \in \Xi\, t \in T \tag{1.14}$$

Maximum number of harvest work teams:

$$\sum_{r\in R} M_r^{vt} \le m_r^{v} \quad r \in R, v \in \Xi, t \in T \tag{1.15}$$

Number of vehicles type v per zone of transportation between stockpiling centers:

$$M_s^{vt} = \sum_{j,k)\in s} L_{jk}^{vt} \quad s \in S, v \in \Xi, t \in T \tag{1.16}$$

Maximum number of vehicles type v for transportation zone:

$$\sum_{s \in S} M_s^{vt} \le m_s^v \quad s \in S, v \in \Xi, t \in T \tag{1.17}$$

Maximum number of vehicles type v used between external stockpiling centers and plant:

$$\sum_{k \in K} L_k^{vt} \le m_k^v \quad k \in K, v \in \Xi, t \in T \tag{1.18}$$

Demand

Production in a particular time period plus the input in the previous one must satisfy al least the demand in that period.

Constraint:

$$JP_p^{t-1} + Z_p^t \ge d_p^t \quad p \in P, t \in T \tag{1.19}$$

Set up of production

For the production process to start there must be a minimum stock of inventory that guarantees the continuity of plant production. In this way, interruptions in the production process are avoided as well as their negative economic effects caused by the lack of available raw material. This situation is modeled with the aid of binary variables that are only activated (status = 1) if the minimum levels of inventory in the time period are satisfied.

Parameters:

BIG : Positive number large enough to model production set-up

Π : Minimum raw material inventory at storage deposit of plant required to start production (weight or volume units)

ε : Positive number small enough to model production set-up

Variables:

$$w^t = \begin{cases} 1 & \text{If the level of raw material exceed the minimun stock level in the period } t \\ 0 & \text{Otherwise} \end{cases}$$

Constraint:

$$(BIG)w^t \geq (JM^t - \pi) + \varepsilon \quad t \in T \tag{1.20}$$

Bounds of decision variables

$$\begin{aligned}
&I_{\circ}^t \geq 0 \quad \circ \in (\Gamma U\, \Theta),\, t \in T \\
&JM^t \geq 0 \quad t \in T \\
&JP_p^t \geq 0 \quad p \in P, t \in T \\
&L_{\circ\bullet}^{vt} \geq 0 \quad (\circ,\bullet) \in A, v \in \Xi, t \in T \text{ and integer} \\
&L_k^{vt} \geq 0 \quad v \in \Xi, k \in \Theta, t \in T \text{ and integer} \\
&M_{\circ}^{vt} \geq 0 \quad v \in \Xi, \circ \in (R\, U\, S), t \in T \text{ and integer} \\
&N_{\circ\bullet}^{vt} \geq 0 \quad (\circ,\bullet) \in A, v \in \Xi, t \in T \text{ and integer} \\
&N_k^{vt} \geq 0 \quad k \in \Theta, v \in \Xi, t \in T \text{ and integer} \\
&MP^t \geq 0 \quad t \in T \\
&X_{\circ\bullet}^t \geq 0 \quad (\circ,\bullet) \in A, t \in T \\
&Y_k^t \geq 0 \quad k \in \Theta, t \in T \\
&Z_p^t \geq 0 \quad p \in P, t \in T
\end{aligned} \tag{1.21}$$

Objective function

Costs:

$CR_{\square\blacksquare}^{v}$: Lifting and load cost per unit between storage deposit ▫ and ▪ in one given time period through type of transport v, where $(\square,\blacksquare) \in ((\Omega, \Gamma) U(\Gamma, \Theta))$. ($ / weight or volume unit of raw material).

CP_p : Production cost per unit of product p. (\$ / unit of product p).

$CC_{▫▪}^{v}$: Transportation cost per trip between storage deposit ▫ and ▪ in one given time period through type of transport v, where $(▫,▪) \in ((\Omega, \Gamma) U (\Gamma, \Theta))$. (\$ / weight or volume unit of raw material).

CC_k^{v} : Transportation cost per trip between storage deposit CAE k and *plant* in one given time period through type of transport v. (\$ / weight or volume unit of input).

$CI_{▫}$: Inventory cost per unit of raw material at storage deposit ▫ per time period, where ▫ $\in (\Omega, \Gamma, \Theta)$. (\$ / unit of raw material).

CIP_p : Inventory cost per unit of finished product p in plant warehouse. (\$ / unit of product p).

$CF_{▫}^{v}$: Fixed cost of type of transport v at zone ▫ in one time period, where ▫ $\in (R, S, \Theta)$. (\$ / team in planning horizon).

CS : Set-up cost of production

$$MIN{:}\sum_t \sum_p CP_p Z_p^t + \sum_t \sum_{i,j\in A} \sum_{v\in \Xi} CR_{ij} X_{ij}^{vt} + \sum_t \sum_{j,k\in A} \sum_{v\in \Xi} CC_{jk}^{v} b_j^{v} N_{jk}^{vt} L_{jk}^{vt} + \sum_t \sum_{k\in\Theta} \sum_{v\in \Xi} CC_k^{v} b_k^{v} N_k^{t} L_k^{t}$$
$$+ \sum_t (CI) JM^{t} + \sum_t \sum_{\circ\in(\Gamma U \Theta)} (CI) I_{\circ}^{t} + \sum_t \sum_p CIP_p JP_p^t + \sum_t \sum_{\circ\in(R U S)} \sum_{v\in\Xi} CF_{\circ} M_{\circ}^{vt} + \sum_t \sum_{k\in\Theta} \sum_{v\in\Xi} CF_k L_k^{vt} + \sum_t (CS) w^t \tag{1.22}$$

The objective here is to minimize the operation costs of harvesting and extracting oil palm and products, taking into account the conditions already mentioned. The costs presented in equation (1.22) represent respectively: production (*C1*), load and lifting raw material inside land plots and CAIs (*C2*), load and lifting and transporting raw material between stockpiling centers (*C3*), load and lifting and transporting raw material between CAEs and plant (*C4*), raw material inventory in plant (*C5*), raw material inventory at stockpiling centers (*C6*), product inventory in plant (*C7*), fixed cost at harvest and internal loading zone (*C8A, C8B*), fixed cost at external loading zone (*C9*), production set-up (*C10*).

1.4. Solution Procedure

The model here proposed is a nonlinear, mixed integer mathematical programming equivalent to a MIP problem using necessary modifications. The process begins with the transformation of variables in order to eliminate non-linearity:

Transformation of variables

What follows is a description of the transformations made to overcome the nonlinear nature of the problem.

$$\alpha_{\circ\bullet}^{vt} = N_{\circ\bullet}^{vt} L_{\circ\bullet}^{vt} \quad (\circ,\bullet) \in A, v \in \Xi, t \in T \tag{1.23}$$

$$\beta_k^{vt} = N_k^{vt} L_k^{vt} \quad k \in \Theta, v \in \Xi, t \in T \tag{1.24}$$

The equation (1.23) represents the number of trips made between the plots and the CAIs, and the number of transportation trips made between CAIs and CAEs. On the other hand the equation (1.24) describes the number of transportation trips completed between CAEs and the plant.

Substitution of variables and rounding up and modification of constraints

The two new variables are substituted in the objective function. Furthermore, the variable, defined by equation (1.23) is replaced in equation (1.11), and likewise, the variable resulting in equation (1.24) is transferred to equation (1.13). On the other side, these two new variables are redefined and rounded up using the procedure proposed by Chvátal (1973) – Gomory (1958) which leads to modifying equations (1.10) and (1.12):

Number of trips for harvesting and between stockpiling centers – equation 1.10 -:

The number of trips made by harvesting teams in a particular time period between each plot-CAI echelon cannot exceed the maximum number established.

$$\alpha_{\circ\bullet}^{vt} \leq \lfloor h_{\circ\bullet}^{v} \rfloor L_{\circ\bullet}^{vt} \quad (\circ,\bullet) \in A, v \in \Xi, t \in T \tag{1.25}$$

where $\lfloor \circ \rfloor$ represents the highest full figure less or equal to the parameter. In order to continue the procedure followed so far, equation (1.25) is modified. The procedure replaces the inequality with an equality, including an additional integer variable and define the bounds of it, as shown next:

$$\alpha_{\circ\bullet}^{vt} = \lfloor h_{\circ\bullet}^{v} \rfloor L_{\circ\bullet}^{vt} - \delta_{\circ\bullet}^{vt} \quad (\circ,\bullet) \in A,\ v \in \Xi,\ t \in T \tag{1.26}$$

Number of trips necessary for transportation between CAEs and plant -equation 1.12-: Following the same procedure we obtain the expressions, as shown below:

$$\beta_{k}^{vt} = \lfloor h_{k}^{v} \rfloor L_{k}^{vt} - \delta_{k}^{vt} \quad k \in \Theta, v \in \Xi, t \in T \tag{1.27}$$

Bounds of decision variables:

$$\begin{aligned}
&\alpha_{\circ\bullet}^{vt} \geq 0 \quad (\circ,\bullet) \in A, v \in \Xi, t \in T \textit{ and integer} \\
&\delta_{\circ\bullet}^{vt} \geq 0 \quad (\circ,\bullet) \in A, v \in \Xi, t \in T \textit{ and integer} \\
&\beta_{k}^{vt} \geq 0 \quad k \in \Theta, v \in \Xi, t \in T \textit{ and integer} \\
&\delta_{k}^{vt} \geq 0 \quad k \in \Theta, v \in \Xi, t \in T \textit{ and integer}
\end{aligned} \tag{1.28}$$

The resulting model is made up of equations (1.1) a (1.9), (1.14) a (1.22), equations (1.11) and (1.13) as modified by the solution procedure, equations (1.26) and (1.27) suggested by the same procedure; and the bounds and their integer or linear condition associated to the decision variables.

1.5. Sensibility analysis

The supply chain network (which is similar to the one shown in Figure 1.1) is constituted by: eight harvest zones, each of them made up of three to five plots and one CAI; five loading zones, each of which allows one to five CAIs and one CAE; and finally one production plant. In the harvest zones the number of trips per day ranges from four to nine; between stockpiling centers from four to eight, and between CAEs and the plant, from three to eight. The seven periods studied correspond to a week. Given that the studied network constitutes a considerable part of the entire network of the company, the obtained results can significantly aid in the decision making process of the whole supply chain.

The parameters under study were: loading capacity of a typical work team in the harvest zones; loading capacity of the company owned vehicles used between stockpiling centers; and of those used between CAEs and the plant; and finally, production capacity and raw material set up inventory stock size. The conducted analyses show the changes in the parameters in the directly related costs.

The process of the sensibility analysis implied changing one or two parameters at most, which are indicated in each case. The offer equation was fixed as an equality (equation 1) and the inventories of the initial and final periods were fixed in 0. The majority of the constraints contemplated in the model were included, except for those that correspond to the bounds of the number of vehicles in the harvest and transportation zones (equations 1.15, 1.17 and 1.18). Such procedure takes as an intention to eventually adopt a single operation system that is capable of rendering a more efficient functioning. The situation does not suggest unfeasibility because, given the fact that we are dealing with just a fraction of the network, the solutions can be considered to be optimal, since it is always possible to satisfy the corresponding number of vehicles.

The different scenarios of the model were executed with the aid of a LINGO 10 commercial software package in a 256 MB RAM portable PC with Pentium 3 CELERON CPU and Windows XP operating system. The integer and linear optimization gaps were respectively 8*10-5 and 5*10-7. The model comprises 1540 constraints and 10303 variables of which 7903 are integer, and seven are binary; the rest of them being linear.

Analysis of harvesting capacity:

The sensibility analysis of the harvesting capacity studies the behaviour of the fixed and variable costs of a significant part of the supply chain, along a series of different scenarios previously defined by the decision makers, who considered the possible changes in the parameters: maximum number of trips in each harvest zone; loading capacity of the harvesting work team; type of animal used for the harvest (in the present case two types of draught animals were studied, namely mule (type 1) and buffalo (type 2)); and finally, the associate unitary fixed cost of the combinations of these four parameters, which takes into account different mechanical versions of the animal drawn wheelbarrow and its maintenance. The treatment of the parameter "animal type" was mutually exclusive, that is to say, the decision makers wanted the two possibilities to be studied independently, and that no combinations were accepted between them.

The treatment of the parameters used in this analysis expresses the conditions and the changes simulated by the model upon the current situation of the system, which is given by the second scenario (number 2) in Table 1.1. Among such conditions we have ordinal ones (animal type) and absolute cardinal ones (load capacity (b_{ij}), that appears explicitly in tons). Similarly, the simulated changes include relative absolute ones (in the maximum number of trips carried out between the plots and CAI associated to each harvest zone (h_{ij})) as well as percentage changes (in the case of the fixed unitary cost (CF_i)).

Table 1.1: Different possible scenarios of the harvesting stage

Scenario	*Type*	h_{ij}	b_{ij}	$\%CF_i$	*%C8A*	*CPU Time*
1	1	0	0.3	-14.29	22.6	120
2	1	0	0.4	0	0	95
3	1	0	0.5	14.29	-3.98	101
4	1	1	0.3	28.57	172.83	112
5	1	1	0.4	42.86	29.52	100
6	1	2	0.3	100	108.48	53
7	1	2	0.4	142.86	91.71	80

8	2	0	0.7	14.29	-28.09	98
9	2	0	0.8	42.86	-22.96	40
10	2	0	0.9	71.43	-17.52	77
11	2	0	1	100	-17.93	24
12	2	1	0.7	114.29	27.29	66
13	2	1	0.8	142.86	13.89	22
14	2	1	0.9	171.43	30.54	90
15	2	2	0.7	214.29	84.41	87
16	2	2	0.8	242.86	42.03	34

No changes were attributed by the model to the harvesting variable total cost (*C2*), because the variable unitary cost (CR_{ij}) is established every year in agreement with the syndicate, in terms of the gathered ton. In consequence, its value remains constant in any possible scenario under analysis. That is the reason why the total harvesting cost is not shown in Table 1.1. In this case, the variable that actually supports the decision making process is the value of the total fixed cost (*C8A*). As it can be established from the analysis, the best scenarios are related to the buffalo drawn wheelbarrow proposal, especially when no harvesting work team current speed increasing changes are undergone by the wheelbarrow. This condition contrasts with the current one, that establishes the use of mules.

Analysis of transporting capacity between stockpiling centers:

This particular analysis studies the percentage changes in the variable and fixed costs resulting from the operation of the vehicles between stockpiling centers in the transportation zones, as far as they are induced by percentage changes in the througput capacity of the typical company owned truck (b_{jk}). The specifically studied costs are not only the total ones (*C3* and *C8B*) but their components too, here discriminated as those resulting from the operation of the company owned truck fleet (*C3P* and *C8BP*) and of the subcontracted one (*C3T* and *C8BT*). The variable costs mainly result from raw material gathering and fuel supply for the vehicles; whereas the fixed costs result from vehicle maintenance and insurances. The current condition can be observed in scenario 6 of Table 1.2, together with the rest of the studied scenarios.

Table 1.2: Scenarios of the transportation stage between stockpiling centers

Scenario	b_{jk}	*%C3P*	*%C8BP*	*%C3T*	*%C8BT*	*%C3*	*%C8B*	*CPU Time*
1	0.5	0	0.3	0	0	0	0	44
2	0.6	0	0.4	0	0	0	0	30
3	0.7	0	0.5	0	0	0	0	14
4	0.8	0	0.3	0	0	0	0	14
5	0.9	0	0.4	0	0	0	0	48
6	1	40	0.3	-5.13	-5.56	7.69	0	14
7	1.1	340.19	0.4	-46.69	-58.89	62.34	-5.56	208
8	1.2	428	0.7	-67.95	-90.24	69.23	-16.62	80
9	1.3	441.57	0.8	-73	-92.61	68.53	-16.7	117
10	1.4	451.57	0.9	-81.56	-96.61	63.17	-17.25	110
11	1.5	520	1	-100	-100	66.67	-19.44	184
12	2	600	0.7	-100	-100	92.31	-22.22	76

In order to obtain a clearer analysis of the behaviour of the costs in face of changes in transporting capacity, the following three figures are used. As for the variable costs, Table 1.2 shows how the total variable costs increase together with the capacity of the company owned vehicle. Their biggest percentage change can be observed when the capacity of the vehicle increases by 10 % above the current condition. This situation tends to appear when the modelled operation mode determines the company's truck fleet to dominate over the subcontracted one, as it can be clearly seen in Figure 1.2. The same figure allows to see how if the capacity of the company owned vehicle falls ten percent (or more) below the current condition, then the distribution can only be carried out on a single mode of operation, which is in this case the subcontracted vehicle one. The opposite situation turns out when the capacity of the vehicle increases by more than 50 % over the current condition.

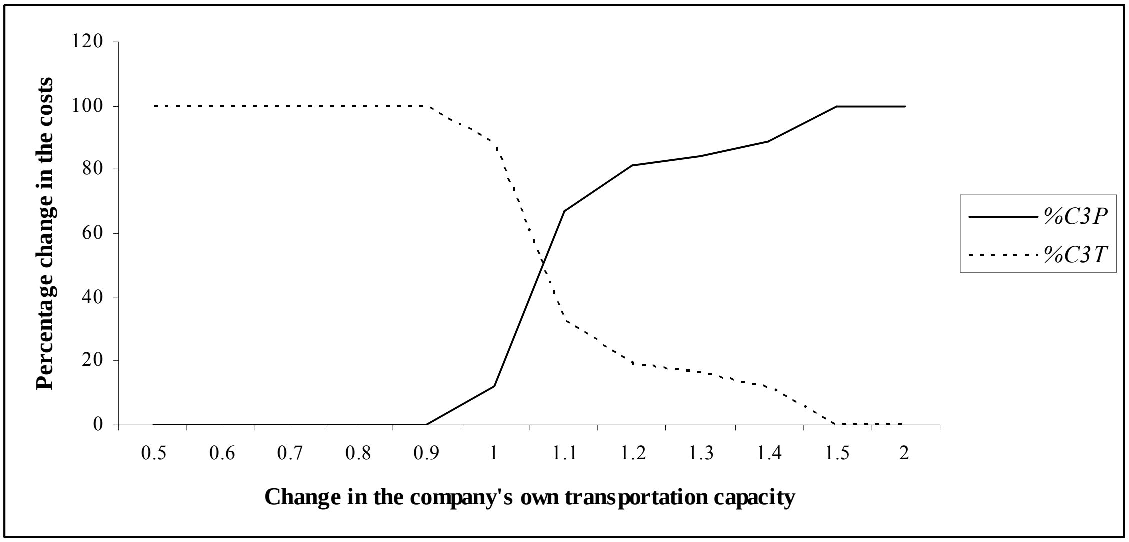

Figure 1.2. Minimum variable costs of transportation between stockpiling centers, according to transport type

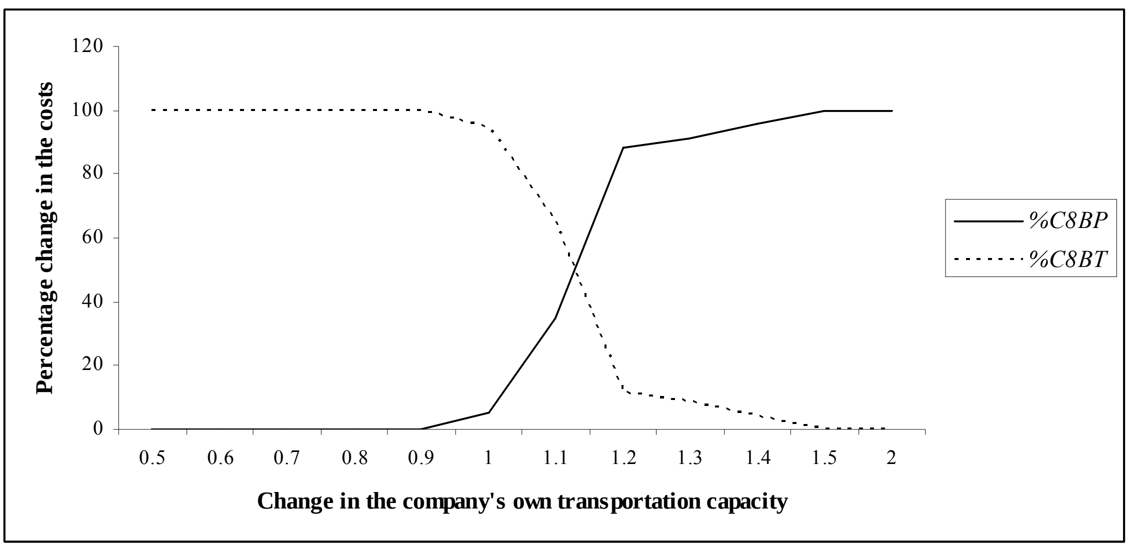

Figure 1.3. Minimum fixed costs of transportation between stockpiling centers, according to transport type

The analysis of the fixed costs is supported on Table 1.2 and Figure 1.3. The behavior of the fixed total costs is in opposition to that of the variable total costs, as far as the former decrease when the capacity of the company owned vehicles increases, although such percentage changes are not as big as those of the variable costs. However, the more remarkable variations in the fixed costs take place under similar conditions to those of the variable ones. In sum, it can be said that fixed and variable costs present a similar behavior at this distribution stage.

The following analysis compares the percentage of participation of the fixed and variable costs in the transportation final costs of this stage. Figure 1.4 shows how the fixed costs respond for more than 90 % of the costs of the transportation stage. This explains why the variable costs increase together with the capacity of the company owned vehicles, which is due to the fact that the decrease in the fixed costs counterbalances the increase in the variable costs, therefore determining an overall decrease of the total costs at this transportation stage.

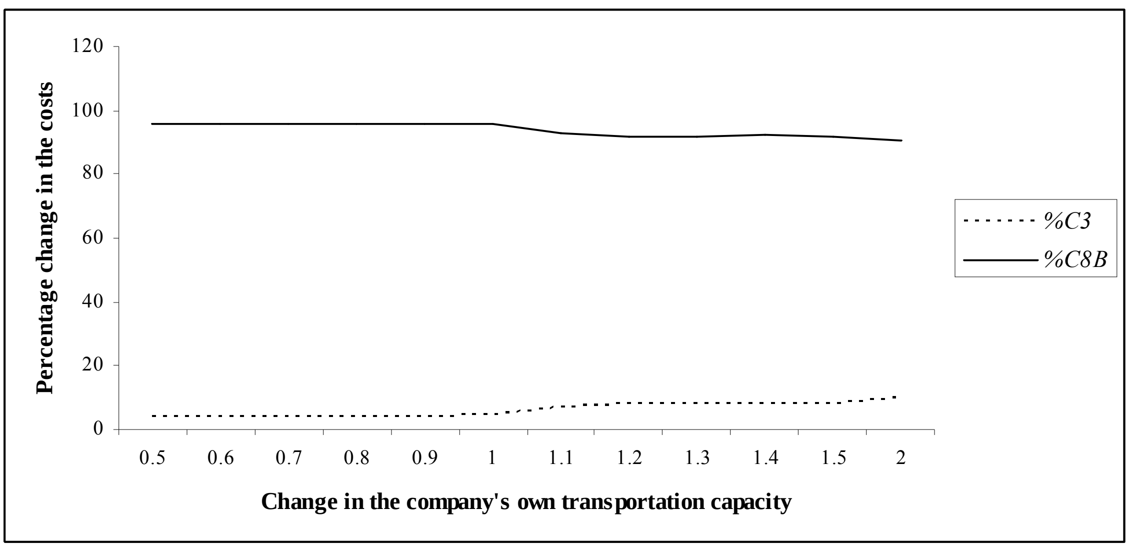

Figure 1.4. Minimum costs of transportation between stockpiling centers, according to cost type

Analysis of transporting capacity between CAEs and the plant:

This specific analysis studies the percentage changes in the costs of transport operations between CAEs and the factory, as a consequence of percentage changes in the througput capacity of the company owned trucks (b_k). The studied costs include both the variable and fixed total costs (*C4* and *C9*) and their discriminated components *C4P* and *C9P* for the proper operation, and *C4T* and *C9T* for the subcontracted operation. Given that the company owned vehicles are provided with load lifting devices, the variable costs at this transportation stage correspond to those of refueling, whereas the fixed costs mainly result from vehicle maintenance and insurances. The different studied scenarios are shown in Table 1.3, where the current operation corresponds to number 6.

Table 1.3: Scenarios of the transportation stage between CAEs and the plant

Scenario	b_k	*%C4P*	*%C9P*	*%C4T*	*%C9T*	*%C4*	*%C9*	*CPU Time*
1	0	0	0	0	0	0	0	95
2	0.2	90	42.86	-4.48	-60	24.74	-5.66	128
3	0.4	190	60.71	-42.54	-84	29.38	-7.55	78
4	0.6	22.5	73.21	-100	-100	-62.11	-8.49	240
5	0.8	10	71.43	-100	-100	-65.98	-9.43	61
6	1	0	0	-100	-100	-69.07	-47.17	65
7	1.2	-7.5	0	-100	-100	-71.39	-47.17	191
8	1.4	-17.5	-14.29	-100	-100	-74.48	-54.72	98
9	1.6	-25	-21.43	-100	-100	-76.8	-58.49	130
10	1.8	-25	-25	-100	-100	-76.8	-60.38	190
11	2	-30	-26.79	-100	-100	-78.35	-61.32	93
12	3	-50	-28.57	-100	-100	-84.54	-62.26	120

The analysis of the transportation costs at this stage is supported on the same three types of diagrams used in the previous stage. As it can be seen in the table above, the variable total costs reach a maximum when the capacity of the company owned vehicles is 60 % of the current one. The biggest percentage decrease occurs when the capacity of the vehicle is 40% lower than the current condition, which happens when the transport is totally done by the proper fleet (see Figure 1.5). The figure also allows to see that for the transport to be carried out with a major participation of the subcontracted fleet, the current capacity of the vehicle has to be reduced in more than 80 %.

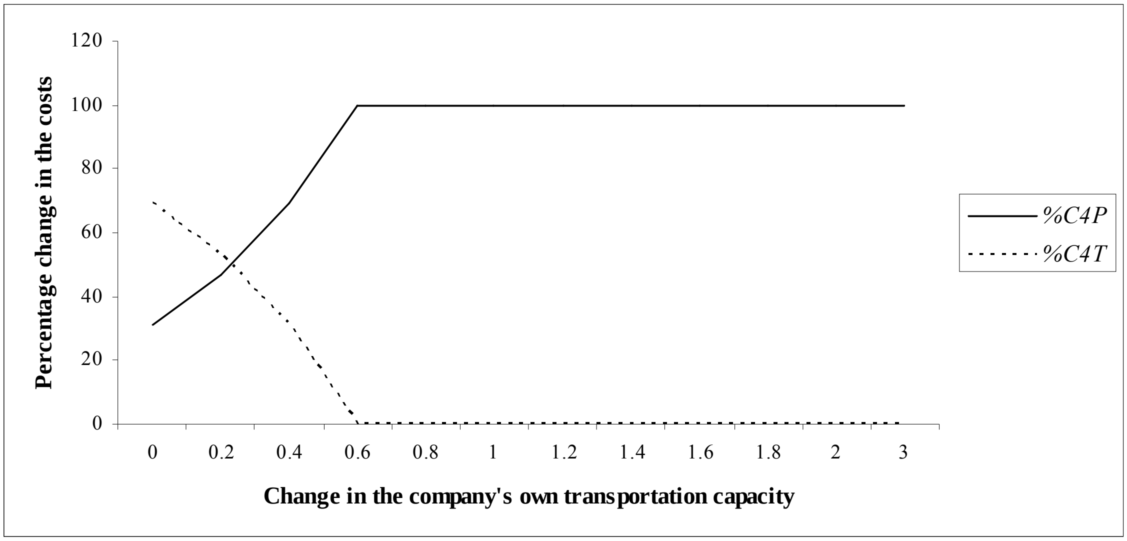

Figure 1.5. Minimum variable costs of transportation between CAEs and the plant, according to transport type

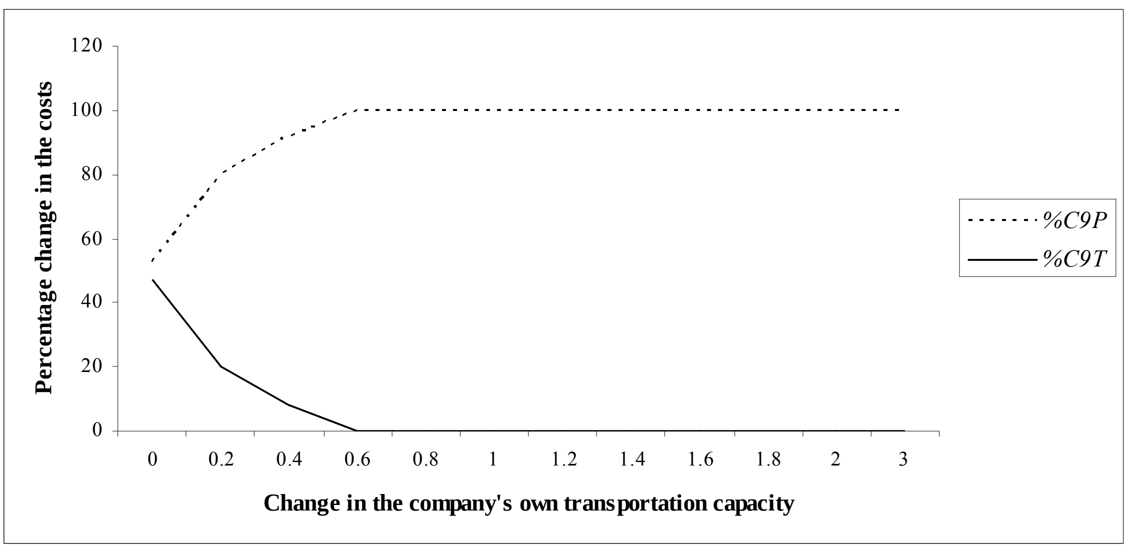

Figure 1.6. Minimal fixed costs of transport between CAEs and the plant, according to transport type

The analysis of the fixed costs is supported on Table 1.3 and Figure 1.6. The fixed total costs decline as the capacity of the company owned vehicles raises. Nevertheless, the percentage changes are not as big as those of the variable costs. Without restricting the number of vehicles of either transport fleet, the current operation should be carried out by the company's one. The model predicts indeed, that such operating conditions allow to reach capacities that are 40% above the current functioning. For capacity decrease values that are close to 100% below those of the scenario of reference, the two components of the fixed total costs of the transport operation at this stage show similar participation percentages.

Figure 1.7 shows the percentage of participation of the fixed and variable costs in the total transport cost at this stage. Just as in the previous stage, the fixed costs constitute more than 90% of the total.

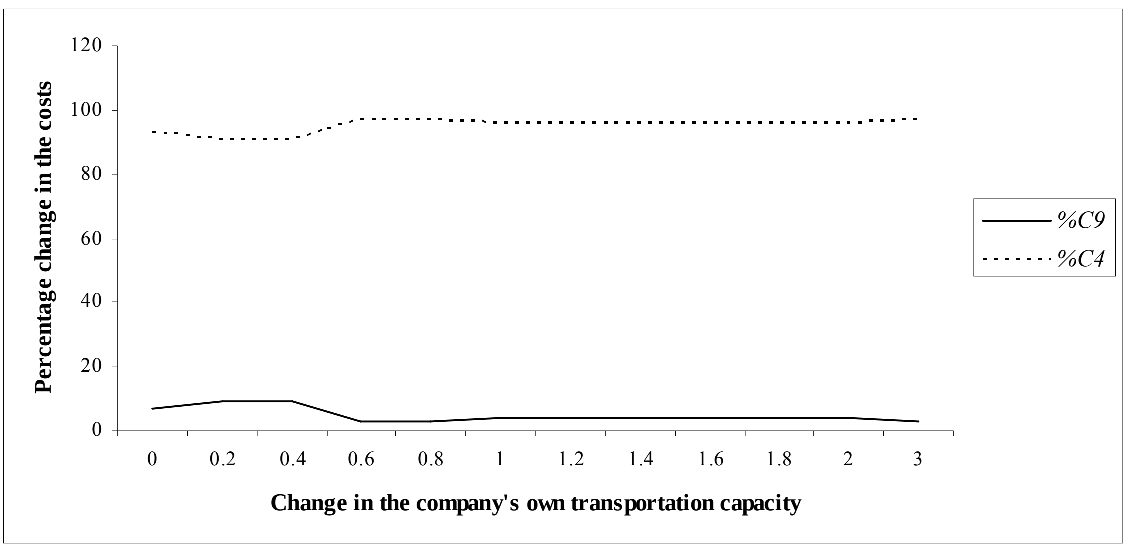

Figure 1.7. Minimum transport costs between CAEs and the plant, according to cost type

Analysis of production and set-up capacity:

Twelve different scenarios were simulated in each of the two analyses. Given that the sensibility analysis was limited to just a fraction of the network, and taking the current capacity as a referential frame, the study of the production (set-up) capacity only reveals unfeasibility in those scenarios that suffer reductions below 85 % (30 %) of the current capacity. The analysis allows to establish that production (set-up) costs do not vary as a result of changes in production capacity; the only cost that exhibits certain variability is the raw material inventory cost, which diminishes (increases) linearly as the manufacturing capacity increases.

Cost structure of the supply chain:

The final part of the sensibility analysis presents a preliminary approach to the structure of the most significant costs of the supply chain. Table 1.4 shows the proportion of the costs and the variation coefficient, with regards to the average of the 64 different scenarios studied in the analysis.

Table 1.4: Main features of the costs studied in the supply chain

Cost component	*C1*	*C10*	*C4*	*C9*	*C3*	*C8B*	*C2*	*C8A*
% of participation	0.054	0.023	0.01	0.15	0.004	0.078	0.141	0.541
Variation coeficient	0	0	0.272	0.102	0.853	0.403	0	0.417

According to the table, the highest costs of the chain are those related to the harvesting stage: fixed cost at harvest zone (*C8A*); raw material lifting and loading inside land plots and CAIs (*C2*); and the loading cost at the external (loading) zone (*C9*). As it has been previously deduced, the fixed costs are dominant in the structure of the supply chain of INDUPALMA. With respect to cost changeability, high variation coefficients can be found in those costs regarding raw material loading, lifting and transport between stockpiling centers (*C3*), as well as in the fixed cost at the harvest zone (*C8A*) and in the fixed cost at the internal loading zone (*C8B*).

1.6. Conclusions and further research

This paper presents a dynamic and innovative mathematical programming for tactical and operational planning in the supply chain involving oil palm fruit harvesting and the extraction of products. The model proposed minimizes the fixed costs of the logistic infrastructure, as well as the variable costs of raw-material inventories, loading and lifting, transportation and harvesting, and the extraction of derived products. The dynamic network flow model also illustrates the particular conditions of the supply chain, thus facilitating decision-making processes concerning the number of work teams necessary for fruit harvesting in the harvest zones, the number of vehicles required to transport the raw material from CAIs to CAEs and from CAEs to the plant, and the setup status of production in each moment of the planning horizon.

The particular conditions of the supply chain imply certain constraints in production, harvesting, transportation and storage capacity; mass balance; maximum and minimum bounds in the decision variables in each time period, and finally, a minimum stock to keep the production system working. The solution proposed involves streamlining the problem through a convenient transformation of variables.

The most significant contribution of the work here presented is the clear identification of the number of harvest and transportation vehicles involved in the supply chain, and the conditions for task organization.

Finally, and considering the hardware tool used, it can be said that CPU times showed reasonable results

New research possibilities opened up by this work include further analysis of the conditions under which tasks must be organized based on the theory of transaction costs, and the inclusion of the refining stage in the process.

1.7. References

Aikens, C.H. (1985), Facility location models for distribution planning. European Journal of Operational Research. 22 263-279.

Chvátal, V. (1973), Edmonds Polytopes and a hierarchy of combinatorial problems, Discrete Mathematics 4 (305-337.

Cohen, M.A., Lee, H.L. (1988), Strategic analysis of integrated production-distribution systems: Models and methods. Operations Research 36 216-228.

Eskigun, E., Uzsoy, R., Preckel, P.V., Beaujon, G. Krishnan, S. (2005), Outbound supply chain network design with mode selection, lead times and capacitated vehicle distribution centers. European Journal of Operational Research. 165 182-206.

Eskigun, E., Beaujon, G., Krishnan, S., Uzsoy, R., Preckel, P.V. (2001), General Motors onbutbound supply chain network design with uncapacitated vehicle distribution centers, Research Report, General Motors Research and Development Center, 15 December.

FAO. Organización de las Naciones Unidas para la agricultura y alimentación. 2004.

Goetschalckx M., Vidal C.J., Dogan K. (2002), Modeling and design of global logistic system: A review of integrated strategic and tactical models and design algorithms. European Journal of Operational Research 143 (1) 1-18.

Gomory, R.E. (1958), Outline of an algorithm for integer solutions to linear programs, Bulletin of the American Mathematical Society 64 275 – 278.

López, M,E., Fernández, S.M., Plá, L.M. (2001), El problema de transporte de la caña de azúcar. Reporte de Investigación. Universidad de Holguín. Cuba.

Thomas, D., Griffin, M.C. (1996), Coordinate supply chain management. European Journal of Operational Research 94 1-15.

Vidal C.J., Goetschalckx M. (1997), Strategic production-distribution models: A critical review with emphasis on global supply chain models. European Journal of Operational Research 98 1-18.

Villegas, J. G., Palacios, F., Medaglia, A.L. (2006), Solution methods for the bi-objective (cost-coverage) unconstrained facility location problem with an illustrative example, forthcoming in Annals of Operations Research.

CHAPTER TWO

Send to Applied Mathematical Modelling

Status: First review

Planning of a Supply Chain for Anti-Personal Landmine disposal by means of Robots *

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Fernando Palacios Gómez **

Julián Arturo Aráoz Durand***

Abstract

The current paper presents a Mixed-Integer-Linear Programming Model (MIP) which incorporates strategic and tactical management decisions into the supply chain of an anti-personal landmine robotic detection and disposal system. Originally based on a mixed-integer-non-linear programming model (MINLP) with stochastic elements, of which it is an approximation, the MIP model is obtained by means of two solution procedures that include redefining variables, treating stochastic and non-linear constraints, and incorporating valid constraints. Finally, a sensibility analysis of the parameters of the MIP model is presented.

Keywords: *mathematical programming applications, integer programming, non-linear programming, logistics, supply chain, robots, anti-personal landmines*

2.1. Introduction

The UN ban on the use of anti-personal landmines as war material (justified by their devastating impact on the world population, specially civilians who are not involved in the conflicts) materialised in the 1997 Ottawa Convention, which endeavoured to find an unanimous agreement on the establishment of observation centres for the surveillance over the de-mining of contaminated territories, the promotion of necessary measures for their disposal, the ban on their production and use as well as the destruction of all existing arsenals [Landmine Monitor Reports, 2003].

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Mine-laying is a common practice in war conflicts due to the low cost and simplicity of construction of anti-personal mines (at least in low sophisticated devices).

In army operations mines are used in a variety of ways: to block the advance of the enemy into specific areas, or to lead them into certain other ones where they can be more effectively attacked; to obstruct their movements during attacks; to prevent them from using resources in areas that will be abandoned (natural resources, facilities, equipment, communication routes, etc.); to reinforce natural or artificial obstacles; to prevent enemy retreat or to facilitate one's own, and to get in the way of the enemy's logistic support.

Mines have meant another issue in the horror of war because of the damage they cause to civilians. The main reasons are, on the one hand, that landmine laying and clearance dynamics is hardly predictable and carelessly registered, and therefore impossible to analyse. On the other hand, partial mine-clearing of fields, also known in the military jargon as 'gap opening', is a general practice.

The consequences of mine explosions are burns, multiple wounds and infections caused by splinters. Wounds may have deadly consequences due to the impact of the explosion itself or to the evolution of the injures received. Besides, there is constant fear amongst the affected population because of the risk of injure they are permanently exposed to.

The 2003 annual mine report informed that, by 2002, anti-personal mines had already killed 300.000 people around the world. The number of mutilated people in Angola is said to be around 20.000 according to the United Nations, and 70.000 according to "Doctors without Borders". For a 10 million people population, the rate could go from 1 out of 500 inhabitants, to 1 out of 145. In Somalia, the approximate rate is 1 out of 650, and in Cambodia, 1 out of 234. In Colombia, the number increased from 216 injured inhabitants in 2001 to 530 in 2002, between January and April of 2003, 151, and 100 0 casualties and wounded people were reported in average and the following years.

The Red Cross International Committee (RCIC) estimates that 800 people are killed by mines every month (26 a day), while figures from the U.S. Department of State talk about 26.000 casualties and wounded people every year (72 per day). According to estimations published in IDOC Internazionale, for each victim surviving to a mine explosion, two people have died. In some countries, 75% of the survivors require amputations.

Figures are difficult to calculate since most highly-mined countries (with a recently ended conflict or still in conflict) lack the necessary infrastructure to transport and look after the victims on time.

According to “Physicians for Human Rights” (PHR), a full recovering medical treatment costs between US$3.000 and US$5.000, while the equipment needed by a child victim to walk again is priced above US$3.000.

The traditional landmine detection procedure on a land strip that has been classified as contaminated by mines is first carried out remotely by causing explosions, either by grenades dropped from aircraft or helicopters, by impacts of artillery shells, or with special vehicles that detonate landmines by direct contact. In a second step, specialized personnel are sent in order to detect remaining mines with hand held devices. Given the many types of mines and the mechanisms used to hide them, it becomes clear that this procedure is far from being efficient, cost saving, safe or environmentally sustainable.

As a result of advances in robot technology, the latter has emerged as a viable innovative option for landmine detection and disposal. Although these developments do not allow large scale applications, it becomes clear that this procedure will enhance safety for specialised personnel, and is much more environmentally friendly when compared to other procedures currently in use.

Considering the future viability of this option, a mathematical programming model to design supply chains for landmine disposal might probably become a sine qua non. The model would have to encompass technical robot requirements, as well as relevant production and logistic considerations. Such is the scope of the current paper.

2.2. Background

The following review focuses on some topics generally considered as relevant for strategic and tactical decision making in supply chains that have additionally been treated by means of mathematical programming models.

Among the first literature reviews on the topic, the one published by Aikens (1985) makes a description of the most relevant aspects of supply chain modelling for single echelon systems with deterministic demand. The fundamental aspects were associated to facilities location in plants and distribution centres (DCs), as well as raw material and final product distribution. The problem size was then limited by the absence of a computationally adequate MIP optimiser.

The evolution of supply chain research has spread out in several directions since then. In the first place, as properly indicated by the above mentioned author, towards dynamic modelling considerations and handling of inventories associated with one agent [Cohen and Lee, 1988]; in the second place, looking forward to some greater satisfaction of the final consumer [Arntzen et al., 1995]; in the third place, towards the development of distribution systems [Geoffrion and Powers, 1995]; and last, seeking for a better co-ordination of logistic operations in different stages of the supply chain (procurement, production and distribution) [Thomas and Griffin, 1996]. The aspects considered by these authors included: lead times, procurement and distribution channel capacity, scale economies and bill of materials, among others. Towards the end of the twentieth century, due to increased pressures caused by the internationalisation of economy, and taking in new developments in computational processing, the characterization of the global supply chain concept was consolidated by Vidal and Goetschalckx (1997). After a short time, new aspects like reliability, inventories [Vidal and Goetschalckx, 2001] and uncertain demand had to be considered. In order to solvethese new aspects, optimisation and heuristic procedures supported by commercial software were developed by Goetschalckx et al. (2002), resulting in satisfactory practical results [Vidal and Goetschalckx, 1997]. Although some recent study topics on supply chains have included uncertainty in the demand [Gupta and Maranas, 2003; Chen and Lee, 2004], no research on specific supply chain design has been publishedso far. Such is the topic of the current document, which boasts an incorporation of strategic and tactical aspects in both static and dynamic contexts, including particular infrastructure and logistics considerations about distribution and production, together with some other important items like reliability of procurement channels, factory location, and stochastic demand. Summarising, the paper presents a model, a solution procedure and a sensibility analysis, applied to a particular example. In order to explain the model, each of the aspects it deals with is presented in both conceptual and mathematical contexts.

2.3. The Model

Although more complex, supply chain models integrating strategic and tactical decisions are known to allow closer approximations to reality than those only linked to either type of decision [Goetschalckx et al., 2002]. In fact, the medium scale optimisation instances found in the realm of this particular case make it advisable to apply the former model type. In order to introduce the MINLP and MIP models, a consistent notation is presented as the different aspects of the supply chain are introduced.

Aspects taken into account

The different aspects considered in the model are treated in detail in the following sections.

Procurement reliability

A very important consideration in supply chain strategic management has to do with channel selection, not only because it involves raw material and supply costs, but procurement lead times and raw material quality too, which all come up as reliability requirements in the production stage. Special attention was given in this paper to the proposals of Vidal and Goetschalckx (2001), who used binary variables to model procurement channel reliability constraints, and then applied them as relevant choosing criteria.

Sets

AIP(i,p) : raw material used up by supplier i in product p

IJ(j) : plant j suppliers

J : plant locations

PJ(j) : robot types made in factory j

Parameters

$PROB_{ij}^{a}$= reliability of the supply channel that links supplier i with plant j through raw material a (percentage).

PRO_{j}^{p}= reliability goal in the production of robot type p at plant j (percentage)

Variables

$$v_{ij}^{a} = \begin{cases} 1 & \text{if supplier } i \text{ } \textit{provides} \text{ plant } j \text{ with raw material } a \\ 0 & \text{otherwise} \end{cases}$$

Expression for supply channel choice reliability:

$$\prod_{i \in IJ(j)} \prod_{a \in AIP(i,p)} \left(PROB_{ij}^{a} \right)^{V_{ij}^{a}} \geq PRO_{j}^{p} \qquad j \in J, p \in PA(j) \tag{2.1}$$

Reliability is modelled through the supply compliance percentage required by the factories for each raw material, which can be obtained by means of a feasible combination of their suppliers' reliability percentage measurements.

Bill of Materials (BOM)

The bill of materials constraint has a twofold function in the model, both linking the procurement and distribution stages (between plants and DZs), and quantifying the raw material amounts required to satisfy the demand. Given the importance of these two aspects, this constraint becomes particularly necessary when choosing suppliers and procurement channels in the planning horizon.

Sets

A : raw material

$PA(a)$: robot types using raw material type a

RIJ : supply network made up of logistic links between suppliers and plants

RJK : supply network composed of logistic links between plants and DCs

Parameters

q^{ap} = amount of type a raw material used for the construction of one type p robot (resource units / robot)

Variables

x_{jk}^{p} = average periodic amount of type p robots delivered from plant j to DZ k in the planning horizon (units / planning horizon)

s_{ij}^{a}= average periodic amount of raw material type a provided by supplier i to production plant j in the planning horizon (units / planning horizon)

Expression for BOM: The proposal includes a constraint for each factory - raw material combination required.

$$\sum_{(i,j)\in RIJ} s_{ij}^{a} = \sum_{p\in PA(a)} \sum_{(j,k)\in RJK} q^{ap} x_{jk}^{p} \qquad j \in J, a \in A \tag{2.2}$$

Allocation of DCs regarding one singular supply source

The geographical location of production plants and distribution centres depends on the particular operational conditions of the army. A national army generally consists of divisions that are themselves composed of brigades, which are in turn subdivided into battalions that can have assigned special tasks like engineering, cavalry, artillery, infantry, special forces, etc. Yet, the division commanding tasks are assigned to higher level battalions, namely the division ones. To avoid overlapping of competencies, each brigade has its assigned territory. In this manner, the security and efficiency of army operations and the monopoly of war material are safeguarded.

Consequently, any decision making endeavours to outline the location of production plants within division battalions, and their associated DCs in brigade battalions. Additionally, for army operation security reasons, each DC is responsible for the de-mining of just one DZ. In modelling this aspect, Geoffrion and Grave's (1974) proposal has been used as a referential milestone, as far as it links the aggregate demand of each DZ to a single procurement source. This constraint is particularly relevant due to the aforementioned army hierarchy. The correspondent expressions are shown below:

Sets

JK(k) : DZs supplied by facility *k*

K : demand zones

Variables

$$B_{jk} = \begin{cases} 1 & \text{if plant } j \text{ supplies DZ } k \\ 0 & \text{otherwise} \end{cases}$$

Expression for single supply source selection

$$\sum_{j \in JK(k)} B_{jk} = 1 \qquad k \in K \tag{2.3}$$

Integration of production, distribution and allocation stages

The construction of a robot is typically modular, and it is foreseeable that the main production activities (assembly or manufacture) are carried out in factories, whereas the repairing activities are restricted to distribution centers (DCs). However, the constraint presented here is not only to aim these simple tasks, but also the production of new (or innovative) robot components. Additionally, in the tactical aspect, the model defines robot production and distribution for each planning period.

In proposing these constraints we seek to establish a cross link between the strategic and tactical decisions of the chain. In regards to the former ones, the average aggregate distribution from plants and DCs is linked to the production periods in the factories, in order to correctly choose their relative location and assignment. Division and brigade battalions are usually lodged in strongly guarded locations and have various means of transportation among which their habitually well maintained roads are the most common.

Sets

PJK(j,k) : robot types sent from factory *j* to DZ *k*

PK(k) : robot types sent to DZ *k*

T : periods

Parameters

N = number of periods.

Variables

d_k^p = average periodic amount of type *p* robots used at DZ *k* in the planning horizon (units/period)

y_{kt}^p = amount of type *p* robots delivered at DZ *k* during period *t* (units / period)

Expression for unique permissible production and distribution source choice for a DC:

$$x_{jk}^p = B_{jk}\, d_k^p \qquad (j,k) \in RJK,\ p \in PJK(j,k) \tag{2.4}$$

Expression for link between both average periodical production and periodical production, delivered at a DZ:

$$\sum_{t \in T} y_{kt}^p = N\, d_k^p \qquad k \in K, p \in PK(k) \tag{2.5}$$

Note that both sides of the balance equation show the aggregated amount of robots at DZs.

Selection of procurement channels and location of factories

Procurement and location are core decisions in logistics, due to their associated strategic and tactical potential costs along the entire planning horizon. In addition, each supplier bases his calculations on a minimum offer, which depends on his procurement policies and on a maximum supply bound which in turn relates to his production capacity. Consequently, the suggested model includes throughput capacity constraints for each supply channel and production plant.

Sets

AIJ(i,j) : raw material types provided by supplier *i* at plant *j*

JI(i) : plants provided by supplier *i*

KJ(j) : DZs supplied by factory *j*

Parameters

CAP_j^p = periodic production capacity of plant *j* for manufacturing type *p* robot, in the planning horizon (units / period)

O^p = capacity fraction used in the production of type *p* robots (resource units / robot)

$SMAX_i^a$ = maximum periodic amount of type *a* raw material provided by supplier *i* in the planning horizon (units of raw material / period)

$SMIN_i^a$ = minimum periodic amount of type *a* raw material provided by supplier *i* in the planning horizon (units of raw material / period)

Variables

$$A_j = \begin{cases} 1 & \text{if the plant is located in } j \\ 0 & \text{otherwise} \end{cases}$$

Logical expression linking suppliers to plants, which becomes necessary because a procurement channel can only be selected if its supplied plant location is selected too.

$$v_{ij}^a \le A_j \qquad j \in J,\ i \in IJ(j),\ a \in AIJ(i,j) \tag{2.6}$$

Expressions for procurement capacity:

$$SMIN_i^a v_{ij}^a \leq s_{ij}^a \leq SMAX_i^a v_{ij}^a \qquad i \in I,\ j \in JI(i),\ a \in AIJ(i,j) \tag{2.7}$$

Raw material flow from suppliers to factories depends on procurement channel reliability. The left (right) side of the above constraint allows to model minimum (maximum) procurement conditions, traditionally imposed by some suppliers, deriving from their production and logistic inflow capacity.

Expressions for production capacity:

$$\sum_{k \in KJ(j)} O^p y_{kt}^p \leq CAP_j^p A_j \qquad j \in J,\ t \in T,\ p \in PJ(j) \tag{2.8}$$

Robot production is bounded by factory capacity, which can be feasible, and consequently positive, only if factory location is also feasible.

Scale economies

Operation levels define production and distribution (from plants to DZs) scale economies in each time period, a relation that can be modelled through mathematical programming, by defining the production and distribution range sizes for which a related differential cost has been established. The average unitary cost decreases gradually along ranges, up to the point where the capacity is saturated. From then on, an increase can be observed as the demand grows beyond the available capacity and has to be satisfied either by outsourcing or reinvestment. Scale economies have been considered in this article because of their relevance to the design of the supply chain.

Sets

E(p) : type *p* robot production scales

Parameters

$GMAX_k^{pe}$ = maximum production bound for type *p* robots delivered at DZ *k* in operation scale *e* (robot units / period)

$GMIN_k^{pe}$ = minimum production bound for type p robots delivered at DZ k in operation scale e (robot units / time period)

Variables

y_{kt}^{pe} = type p robots delivered at DZ k in operation scale e during period t (units / period)

$$w_t^{pe} = \begin{cases} 1 & \text{if product } p \text{ is produced in operation scale } e \text{ during period } t \\ 0 & \text{otherwise} \end{cases}$$

Expression for operation scale: the number of robots distributed during a given time period must have been produced in any of such period's production scales.

$$y_{kt}^{p} = \sum_{e \in E(p)} y_{kt}^{pe} \qquad k \in K, t \in T, p \in PK(k) \tag{2.9}$$

Logical expression for operation scales: one only robot production scale at the most, can be activated in a given time period.

$$\sum_{e \in E(p)} w_t^{pe} \leq 1 \qquad t \in T, p \in PK(k) \tag{2.10}$$

Expression for operation scale bounds: in order to match periodical robot production to its corresponding scale, the following constraint is used:

$$(GMIN_k^{pe})w_t^{pe} \leq y_{kt}^{pe} \leq (GMAX_k^{pe})w_t^{pe} \qquad t \in T, p \in PK(k), e \in E(p) \tag{2.11}$$

Such constraint allows to define the operation scale at which the production of each robot type is carried out, framing it within its two corresponding bounds. Additionally, and together with constraints (2.9) and (2.10), it assures that the number of robots delivered from each plant to its associated DZs comes from only one production scale.

Distribution* i*nfrastructure

Distribution activities inside the demand zones (from brigades to mine contaminated areas) are usually hampered by lack or bad condition of access roads and by proneness to assaults by enemy forces. Consequently, the access is usually carried out by means of helicopters. Those aspects of the supply chain that are related to delivery into DZs are very important due to expensiveness of helicopter fleet operation and buying cost. The helicopter fleet size can be obtained by means of the following expression:

Variables

$HMAX_x$ = minimum number of helicopters used at DZ k in the planning horizon (units)

Expression for helicopter fleet minimum size

$$HMAX_k \geq H_{kt} \qquad k \in K, \quad t \in T \tag{2.12}$$

The helicopter fleet minimum size at each DZ corresponds to the maximum number of helicopters used during a given time period within the studied planning horizon.

Some other considerations about supply chain capacity

As it has been shown, in studying the previous aspects, certain relevant capacity constraints were added to the supply chain model. Nevertheless, it is necessary to include some additional capacity considerations. Two relevant constraints are respectively associated to throughput production capacity due to raw material procurement bounds, and to the necessary infrastructure to carry out the distribution process from plants to DCs and within the DZs.

Sets

I : suppliers

$PJK(j,k)$: robot types delivered from plant j to DZ k.

Parameters

HE_k = number of available helicopters in DZ k

$XMAX_{jk}^p$ = distribution capacity for type p robot from plant j to DZ k in the planning horizon (units / period)

$ZMAX_k$ = maximum number of feasible helicopter trips in DZ k

β^p = helicopter pay load capacity for transporting type p robots (robot units / helicopter)

Variables

H_{kt} = number of helicopters used at DZ k during period t (units / time period

z_{kt} = number of helicopter trips at DZ k during period t (trips / period)

Expression for distribution capacity bounds, due to supply channel capacity:

$$SMIN_i^a \leq \sum_{k \in KJ(j)} \sum_{p \in PIA(i,a)} q^{ap} y_{kt}^p \leq SMAX_i^a \qquad i \in I,\ j \in JI(i),\ t \in T, a \in AIJ(i,j) \tag{2.13}$$

The raw material used for a certain product must be adjusted within the raw material procurement bounds established by each supplier.

Expression for distribution capacity from plants to DCs:

$$y_{kt}^p \leq XMAX_{jk}^p \qquad j \in J,\ k \in K,\ t \in T,\ p \in PJK(j,k) \tag{2.14}$$

The above constraint takes into account the distribution capacity between plants and DCs.

Expression for distribution capacity within DZs:

$$y_{kt}^p \leq \beta^p \ z_{kt} H_{kt} \qquad k \in K, t \in T,\ p \in P \tag{2.15}$$

The above constraint contemplates both payload capacity and operational frequency of helicopter trips within DZs.

Expression for maximum number (maximum bound) of helicopters within DZs:

$$H_{kt} \leq HE_k \qquad k \in K, \quad t \in T \tag{2.16}$$

Expression for maximum number (maximum bound) of helicopter trips per time period within DZs:

$$z_{kt} \leq ZMAX_k \qquad k \in K, \quad t \in T \tag{2.17}$$

Demand

Data collected by the local observatory will allow the classification of an area as contaminated by mines. The consequent demand for robots is not determined by the number of mines to be detected, but the extension of the contaminated area, due to the fact that if a specific land strip is contaminated, then it has to be entirely scanned by robots, in disregard of how many mines it might have.

As for the robots, it has to be taken into account that a percentage of them will periodically be rendered useless. Additionally, when considering a Demand Zone (DZ), the model assumes a stochastic contaminated area which is scanned by robots, where each robot type has an average scanning speed defined for each period. In order to suitably model the stochastic area, chance constraints are included [Charnes and Cooper, 1959]; but this requires a certain level of compliance probability for each given constraint. The associated constraint (eq 2.16) is shown below:

Parameters

α = significance level

θ^{p} = type p robot expected scanning speed in a given planning period (scanned area units / robot)

φ^{p} = expected contingent fraction of type p robots in a given planning period (percentage / period)

π^{p} = type p robot estimated operational life span (time units)

$\Theta_k(\xi)$ = mine contaminated stochastic area in DZ k in the planning horizon (area units)

Chance constraint for DZ stochastic area robotic de-mining in the planning horizon

$$P\left\{\sum_{p \in P} \sum_{e \in E(p)} \left[\sum_{t=1}^{N-\pi^p} \theta^p \phi^p \pi^p y_{kt}^p w_{kt}^{pe} + \sum_{l=0}^{\pi^p - 1} \theta^p \phi^p \left(\pi^p - l\right) y_{k,N-\pi^p+1+l}^p \; w_{k,N-\pi^p+1+l}^{pe}\right] \geq \Theta_k(\xi)\right\} \geq 1-\alpha \qquad k \in K \tag{2.18}$$

The above constraints express the minimum permissible target probability required to scan the mine contaminated area in the planning horizon.

Variable bounds

$s_{ij}^{a} \geq 0 \qquad i \in I,\ j \in J,\ a \in A$

$x_{jk}^{p} \geq 0 \qquad j \in J,\ k \in K,\ p \in PK(k)$

$d_{k}^{p} \geq 0 \qquad k \in K, \quad p \in PK(k)$

$y_{kt}^{p} \geq 0 \qquad k \in K, t \in T,\ p \in PK(k)$ and integer

$y_{kt}^{pe} \geq 0 \qquad k \in K, t \in T,\ p \in PK(k), e \in E(p)$ and integer

$z_{kt} \geq 0 \qquad k \in K, \quad t \in T$ and integer

$H_{kt} \geq 0 \qquad k \in K, \quad t \in T$ and integer

$HMAX_{k} \geq 0 \qquad k \in K, \quad t \in T$ and integer (2.19)

Objective function

The planning model has to take into account the fixed costs of a series of supply chain activities, like construction (installation) and operation of factories and DCs, or logistic flows of raw materials and manufactured products between suppliers, plants, and DZs. In sum, the fixed costs of the procurement, production and distribution stages. Additionally, the model not only considers certain fixed costs (e.g., infrastructure) that can be estimated by assigning them a constant value along the entire planning horizon, but also those that go through periodical changes (like production and distribution), and are equally included in the planning horizon. Finally, the model follows Silver and Perterson's proposal (1985) of inventory quantification, which includes safety stock factors, lead times, and inventory cycle factors. The proposal assumes that stochastic demand and deterministic lead times are independent for each raw material.

Sets

P : robot types

Parameters

F_{ij}^{a} = type a raw material inter arrival time from supplier i to plant j (time units / planning horizon)

F_{jk}^{p} = type p robot inter arrival time between plant j and DZ k (time units / planning horizon)

FCI = inventory cycle factor (percentage)

FIS_{j}^{a} = safety stock factor for type a raw material at plant j (time units / planning horizon)

FIS_{k}^{p} = type p robot safety stock factor at DZ k (time units / planning horizon)

H = holding cost ($ / $ planning period)

L_{ij}^{a} = expected lead time for delivering raw material from supplier i to plant j

L_{jk}^{p} = expected lead time for delivering type p robots from plant j to DZ k (time / raw material)

Costs:

C_{i}^{a} = procurement cost of raw material a provided by supplier i (including transportation and duties) ($ / robot)

C_{k}^{p} = distribution cost of type p robots employed at DZ k (including transportation and duties) ($ / robot)

C_{jk}^{p} = cost of type p robot distribution from plant j to DZ k ($ / period)

C_{kt}^{pe} = production cost of type p robots used in DZ k in operation scale e during period t ($ / robot)

CC_{kt} = fuel costs at DZ k in period t ($ / helicopter trip)

CF_{j} = fixed cost of factory j ($/ planning horizon)

CF_{k} = operation fixed cost for DZ k ($ planning horizon)

CH = helicopter cost ($ / helicopter)

CH_{kt} = helicopter operation fixed cost at DZ k during period t ($/period)

CI_{j}^{a} = raw material a inventory cost at production site j ($ / planning horizon)

CI_{k}^{p} = type p robot inventory cost at DZ k ($ / period)

CM^{p} = type p robot maintenance cost ($ / robot)

$$
\begin{aligned}
MIN \quad & \sum_{k\in K}(CH)HMAX_k + \sum_{k\in K}\sum_{t\in T}(CH_{kt})H_{kt} + \sum_{i\in I} CF_j A_i + \sum_{k\in K}\sum_{t\in T}\sum_{p\in PK(k)}\sum_{e\in E(p)} C_{kt}^{pe} y_{kt}^{p} w_t^{pe} \\
& + \sum_{j\in JI(i)}\sum_{a\in AIJ(i,j)} N\,C_i^a s_{ij}^a + \sum_{j\in JI(i)}\sum_{a\in AIJ(i,j)} N\left(CI_j^a H\right)\left[L_{ij}^a + (FCI)F_{ij}^a + FIS_j^a\sqrt{L_{ij}^a}\right]s_{ij}^a \\
& + \sum_{k\in K}\sum_{p\in P} N\,C_k^p d_k^p + \sum_{k\in KJ(j)}\sum_{p\in PJK(j,k)} N\left(CI_k^p H\right)\left[L_{jk}^p + (FCI)F_{jk}^p + FIS_k^a\sqrt{L_{jp}^p}\right]x_{jk}^p + \\
& \sum_{k\in K}\sum_{t\in T}\sum_{p\in P}\sum_{e\in E(p)} CM^p(1-\phi^p)y_{kt}^p w_t^{pe} + \sum_{k\in K}\sum_{t\in T}(CC_{kt})z_{kt} + \sum_{k\in K} CF_k
\end{aligned}
\tag{2.20}
$$

2.4. Solution Procedure 1

The design of the supply chain model was based on conceiving the strategic aspects in a single time period (the planning horizon) and the tactical ones in all periods of the temporary horizon, therefore having respect for the specific nature of both types of decision. The following steps are suggested in order to obtain an MIP model, which is used as an approximation of an MINLP one:

Step 1: approximation to non-linearity

With respect to non-linear constraints, those related to distribution capacity by means of helicopters at DZs (2.15), procurement reliability (2.1) and stochastic demand area (2.18) are treated here. First of all, the variables associated to helicopter distribution capacity constraints had to be redefined. In the case of the reliability constraint (2.1), logarithmic and absolute value function properties are used. With regards to the stochastic area expression (2.18), a Gaussian area is assumed and then a deterministic approximation of such constraint is obtained. In conclusion, as a result of step 1, a less complex problem is obtained, as shown next:

- As for helicopter distribution constraints, given that:

$$\eta_{kt} = z_{kt}\, H_{kt} \qquad k \in K, \quad t \in T \textit{ and integer} \tag{2.21}$$

and replacing that expression in eq. (2.15), we have:

$$y_{kt}^{p} \leq \beta^{p}\ \eta_{kt} \qquad k \in K, \quad t \in T \tag{2.22}$$

Expression for maximum number of periodic distribution trips per fleet at DZ:

$$\eta_{kt} \leq MIN\{z_{kt}\ HE_{k}, ZMAX_{k}\ H_{kt}\} \qquad k \in K, \quad t \in T \tag{2.23}$$

- The procurement reliability constraint (2.1) is in turn replaced by the following equivalent:

$$\sum_{i \in IJ(j)} \sum_{a \in AIJ(i,j)} v_{ij}^{a} \left|\ln(PROB_{ij}^{a})\right| \leq \left|\ln(PRO_{j}^{p})\right| \qquad j \in J,\ p \in PJ(j) \tag{2.24}$$

In order to deal with the non-linearity associated to the product of the continuum and binary variables, the approximation suggested by Hanson and Martin (1990) is applied, including variable redefinition and incorporating additional constraints. The procedure is carried out as follows:

Assuming that product □ x □ appears in the model, where □ is a binary variable {0.1}, while □ is a continuous non-negative variable, then the following procedure can be carried out:

$$\mathit{\Delta} \leq \mathit{\Omega}$$

$$\mathit{\Delta} \leq \mathit{\Xi}\, M_{\mathit{\Xi}}$$

$$\mathit{\Delta} \geq \mathit{\Omega} - (1 - \mathit{\Xi}) M_{\mathit{\Omega}} \tag{2.25}$$

where:

M_{Ω}*:* maximum bound of □*,* corresponding to a positive integer parameter

M_{Ξ}*:* maximum bound of product □ *x* □*,* corresponding to a positive integer parameter

The transformation can be used to approximate the non-linearity of equations (2.20) and (2.4). As a consequence, the following variables are defined and substituted in the aforementioned constraints:

$$\psi_{kt}^{pe} = y_{kt}^{p} w_{t}^{pe} \qquad k \in K, t \in T,\ p \in PK(k),\ e \in E(p) \tag{2.26}$$

$$x_{jk}^{p} = B_{jk} d_{k}^{p} \quad j \in J, k \in K, \ p \in PJK(j,k) \tag{2.27}$$

Finally, the following constraints are incorporated to the suggested model

$$\psi_{kt}^{pe} \le y_{kt}^{p} \quad k \in K, t \in T, \ p \in PK(k), e \in E(p) \tag{2.28}$$

$$\psi_{kt}^{pe} \le GMAX_{k}^{pe} \ w_{t}^{pe} \quad k \in K, t \in T, \ p \in PK(k), e \in E(p) \tag{2.29}$$

$$\psi_{kt}^{pe} \ge y_{kt}^{p} - (1 - w_{t}^{pe})M \quad k \in K, t \in T, \ p \in PK(k), e \in E(p) \tag{2.30}$$

$$x_{jk}^{p} \le d_{k}^{p} \quad j \in J, k \in K, \ p \in PJK(j,k) \tag{2.31}$$

$$x_{jk}^{p} \le \left(z_{1-\alpha}\sigma\left(\Theta_{k}(\xi)\right) + E\left(\Theta_{k}(\xi)\right)\right)B_{jk} \quad j \in J, k \in K, \ p \in PJK(j,k) \tag{2.32}$$

$$x_{jk}^{p} \ge d_{k}^{p} - (1 - B_{jk})M \quad j \in J \ k \in K, \ p \in PJK(j,k) \tag{2.33}$$

The stochastic demand constraint (2.18) is replaced by the expression below (the corresponding procedure is presented in the Appendix A). In consequence, the stochastic area in the mentioned equation is simplified into a Gaussian distribution, which is a commonly encountered condition in practical cases

$$\sum_{p \in P} \sum_{e \in E(p)} \left[\sum_{t=1}^{N-\pi^{p}} \theta^{p} \phi^{p} \pi^{p} \psi_{kt}^{pe} + \sum_{l=0}^{\pi^{p}-1} \theta^{p} \phi^{p} \left(\pi^{p} - l\right) \psi_{k,N-\pi^{p}+1+l}^{pe} \right] \ge z_{1-\alpha}\sigma\left(\Theta_{k}(\xi)\right) + E\left(\Theta_{k}(\xi)\right) \tag{2.34}$$

$$k \in K$$

Step 2: Acquisition of valid constraints

The minimum and maximum objective bounds of the supply chain are obtained by means of a procedure that stipulates a single production scale range, containing two linear problems to be solved. In the first (second) one, the minimum (maximum) bound, is obtained by determining the maximum (minimum) scale cost for each factory-robot-period combination.

For both models, the associated procedure goes as follows: in the first place, each DZ's product flow bounds are established:

$$GMAX_k^p = Max_{e \in E(p)}[GMAX_k^{pe}] \quad k \in K,\, p \in PK(k) \tag{2.35}$$

$$GMIN_k^p = Min_{e \in E(p)}[GMIN_k^{pe}] \quad k \in K,\, p \in PK(k) \tag{2.36}$$

Flow costs are determined as shown below:

- Model 1:

$$C_{kt}^p = Max_{e \in E(p)}[C_{kt}^{pe}] \quad k \in K, t \in T, p \in PK(k) \tag{2.37}$$

- Model 2:

$$C_{kt}^p = Min_{e \in E(p)}[C_{kt}^{pe}] \quad k \in K, t \in T, p \in PK(k) \tag{2.38}$$

In this step, equations (2.24), (2.20) and (2.11) are modified, and equations (2.9) and (2.10) are eliminated. The modified constraints are shown next:

Objective function:

$$\begin{aligned}
MIN \quad & \sum_{k \in K} (CH)HMAX_k + \sum_{k \in K}\sum_{t \in T} (CH_{kt})H_{kt} + \sum_{i \in I} CF_j A_i + \sum_{t \in T}\sum_{k \in K}\sum_{p \in P} C_{kt}^p y_{kt}^p \\
& + \sum_{j \in JI(i)} \sum_{a \in AIJ(i,j)} N C_i^a s_{ij}^a + \sum_{j \in JI(i)} \sum_{a \in AIJ(i,j)} N\left(CI_j^a H\right)\left[L_{ij}^a + (FCI)F_{ij}^a + FIS_j^a \sqrt{L_{ij}^a}\right] s_{ij}^a \\
& + \sum_{k \in K}\sum_{p \in P} N C_k^p d_k^p + \sum_{k \in KJ(j)} \sum_{p \in PJK(j,k)} N\left(CI_k^p H\right)\left[L_{jk}^p + (FCI)F_{jk}^p + FIS_k^a \sqrt{L_{jp}^p}\right] x_{jk}^p + \\
& \sum_{k \in K}\sum_{t \in T}\sum_{p \in P} CM^p (1-\phi^p) y_{kt}^p + \sum_{k \in K}\sum_{t \in T} (CC_{kt}) z_{kt} + \sum_{k \in K} CF_k
\end{aligned} \tag{2.39}$$

In this objective function the production and maintenance costs were customized.

Expression for stochastic demand constraint:

$$\sum_{p \in P}\left[\sum_{t=1}^{N-\pi^p} \theta^p \phi^p \pi^p y_{kt}^p + \sum_{l=0}^{\pi^p - 1} \theta^p \phi^p \left(\pi^p - l\right) y_{k,N-\pi^p+1+l}^p\right] \geq z_{1-\alpha}\sigma\left(\Theta_k(\xi)\right) + E\left(\Theta_k(\xi)\right) \quad k \in K \tag{2.40}$$

Expression for robot flow bounds at a given DZ:

$$GMIN_k^p \leq y_{kt}^p \leq GMAX_k^p \quad k \in K, t \in T, p \in PK(k) \tag{2.41}$$

Once the problems are solved, the objective function bounds can be determined

Minimum bound –*OFMIN*–: *Min {Model 1}*

Maximum bound –*OFMAX*–: *Min {Model 2}*

The valid constraint obtained is incorporated to the original model and presented below:

$$\begin{aligned}
OFMIN \leq & \sum_{k \in K}(CH)HMAX_k + \sum_{k \in K}\sum_{t \in T}(CH_{kt})H_{kt} + \sum_{i \in I} CF_j A_i + \sum_{k \in K}\sum_{t \in T}\sum_{p \in P}\sum_{e \in E(p)} C_{kt}^{pe}\psi_{kt}^{pe} \\
& + \sum_{j \in JI(i)}\sum_{a \in AIJ(i,j)} NC_i^a s_{ij}^a + \sum_{j \in JI(i)}\sum_{a \in AIJ(i,j)} N\left(CI_j^a H\right)\left[L_{ij}^a + (FCI)F_{ij}^a + FIS_j^a\sqrt{L_{ij}^a}\right]s_{ij}^a \\
& + \sum_{k \in K}\sum_{p \in P} NC_k^p d_k^p + \sum_{k \in KJ(j)}\sum_{p \in PJK(j,k)} N\left(CI_k^p H\right)\left[L_{jk}^p + (FCI)F_{jk}^p + FIS_k^a\sqrt{L_{jp}^p}\right]x_{jk}^p + \\
& \sum_{k \in K}\sum_{t \in T}\sum_{p \in P}\sum_{e \in E(p)} CM^p(1-\phi^p)\psi_{kt}^{pe} + \sum_{k \in K}\sum_{t \in T}(CC_{kt})z_{kt} + \sum_{k \in K} CF_k \leq OFMAX
\end{aligned} \tag{2.42}$$

Summarizing, it can be said that, as a result of the solution procedure, an MIP (and therefore a more treatable) formulation of the original problem is attained. Such formulation is made up of equations: 2.2, 2.3, 2.5 to 2.14, 2.16, 2.17, 2.19, 2.22 to 2.24, 2.28 to 2.34, and equation 2.42, together with its associated objective function

2.5. Solution Procedure 2

If the production scale constraints (eq: 2.9, 2.10 and 2.11) are not directly included in the MNMIP model, but are contemplated later, once the new relaxed MIP problem has been solved, a new solution procedure can be obtained, as presented next.

***Step 1**: **solving the relaxed MIP problem**:* the solution of the problem is expressed by constraints (equations) 2.2, 2.3, 2.5 to 2.8, 2.12 to 2.14, 2.16, 2.17, 2.19, 2.22 to 2.24, 2.31 to 2.34, 2.40, 2.41, and a modified objective function (eq. 2.39) from which the production cost has been removed, as shown below:

$$
\begin{aligned}
&MIN \quad \sum_{k\in K}(CH)HMAX_k + \sum_{k\in K}\sum_{t\in T}(CH_{kt})H_{kt} + \sum_{i\in I} CF_j A_i \\
&+ \sum_{j\in JI(i)}\sum_{a\in AIJ(i,j)} N\, C_i^a s_{ij}^a + \sum_{j\in JI(i)}\sum_{a\in AIJ(i,j)} N\left(CI_j^a H\right)\left[L_{ij}^a + (FCI)F_{ij}^a + FIS_j^a\sqrt{L_{ij}^a}\right]s_{ij}^a \\
&+ \sum_{k\in K}\sum_{p\in P} N\, C_k^p d_k^p + \sum_{k\in KJ(j)}\sum_{p\in PJK(j,k)} N\left(CI_k^p H\right)\left[L_{jk}^p + (FCI)F_{jk}^p + FIS_k^a\sqrt{L_{jp}^p}\right]x_{jk}^p + \\
&\sum_{k\in K}\sum_{t\in T}(CC_{kt})z_{kt} + \sum_{k\in K} CF_k
\end{aligned}
\tag{2.43}
$$

Step 2**: **integrating the production cost: In order to integrate the production cost into the model, the production scale constraints must be included. This allows to incorporate the algorithm below, starting from the optimal values of $\boldsymbol{y_{kt}^p}$ obtained in the first step, and noted here as $\boldsymbol{\Psi_{kt}^p}$

Begin
S ← 0
For k = 1 to ***N***(***k***)
    For ***t*** = 1 to ***N***(***t***)
        For ***p*** = 1 to ***N***(***p***)
            For ***e*** = 1 to ***N***(***e***)
                If $\boldsymbol{\Psi_{kt}^p} > 0$ and $\boldsymbol{GMIN_k^{pe} \leq \Psi_{kt}^p \leq GMAX_k^{pe}}$
                    Then $\boldsymbol{\Xi \leftarrow \{k, t, p, e\}}$
                            $\boldsymbol{S \leftarrow S + (c_{kt}^{pe} + CM^p(1-\varphi^p))\,\Psi_{kt}^p}$
                End If
            End For
        End For
    End For
End For
End

where $\boldsymbol{\Xi}$ is the set of indexes associated to the positive optimal flows $\boldsymbol{\Psi_{kt}^p}$, and $\boldsymbol{S}$ is the supply chain production cost. Finally, the production cost is added to the optimal solution of the objective function (eq. 2.39).

2.6. Sensibility Analysis

The sensibility analysis was performed using solution procedure 1, with the aid of a commercial LINGO 10™ software package. The computing of the scenarios was carried out on a Pentium-4 2.8 Ghz, 1GB RAM equipment, applying a Win XP-SP2 operational program. The problem comprises 20 suppliers handling 2 components each, 10 possible plant locations, 2 products in two production scales, and 20 Gaussian DZs. All possible combinations of logistic procurement connections were admitted, together with a distribution network featuring three DCs per production plant. Finally, a 5% Gaussian significance was used for the demand chance constraint. These problems have 14048 constraints and 4171 variables, of which 1241 are binary. The parameters under scrutiny were: area size, helicopter capacity and robot speed performance. Instance solutions take 500 seconds in average, with a maximum of 900 seconds. All the program runs were conducted with a maximum gap of 0.001, and most of the results were probably optimal.

The following table presents the percentage ranking of the average unitary costs that are part of the objective function:

Table 2.1: Average unitary cost percentage structure of the supply chain

CH_{kt}	CF_j	C_{kt}^{pe}	C_i^a	CI_j^a	C_k^p	CI_k^p	CM^p	CC_k^t
64	35.62	0,0725	0.0534	0,0312	0,0044	0,04025	0,05	0,0001

As it can be observed, the highest average unitary costs correspond to the strategic aspects, which are infrastructure distribution, and plant and distribution centre installation.

The sensibility analysis is applied by modifying the parameter percentage values and monitoring their impacts on the total cost of the supply chain.

Demand effect on minimum cost

Although the costs rise in direct relation to the expansion of the demand area, the non-linear nature of the problem becomes evident when changes in production scale and distribution infrastructure occur (e.g. more helicopters are required in order to satisfy a greater demand for robots). The smooth behaviour of the costs in some sections of Figure 2.1 is due to tactical changes in the supply chain. The slope remains unchanged as long as no adjustments in production or distribution infrastructure are undertaken in order to satisfy the demand, as can be observed in Figure 2.1.

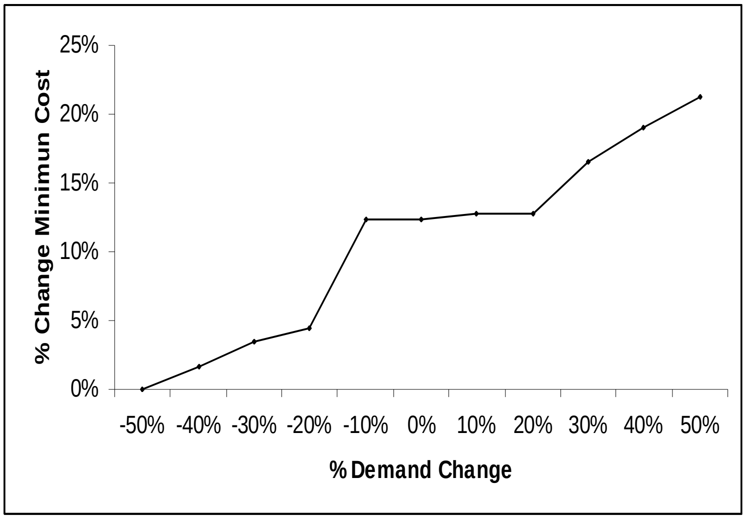

Figure 2.1: Effect of demand on minimum cost

Effect of robot scanning speed on minimum cost

Robot scanning speed appears to be the most influential cost factor, since it constitutes the link between inventory, production and distribution activities in both strategic and tactical contexts. On the one hand, the costs associated to production and distribution, diminish as scanning speed increases. On the other hand, inventory costs rise when there is an increasing number of unused robots during long time periods, as a consequence of the scanning speed increase. These two tendencies determine a general behaviour, according to which there is an overall cost percentage drop, marginally decreasing as the scanning speed is raised, due to the existence of counter-balance costs within the same objective function. (See figure 2.2).

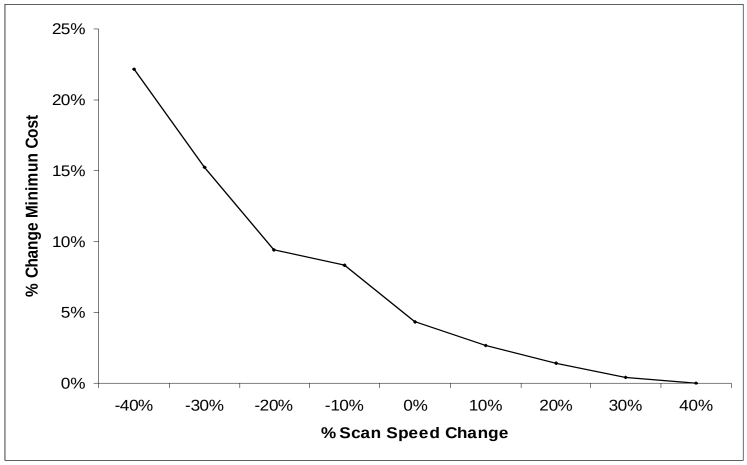

Figure 2.2: Effect of robot scanning speed on minimum cost

Effect of helicopter capacity on minimum cost

Due to the fact that helicopters offer multiple usage possibilities, it is important to analyze their potential payload percentage per trip. As shown in Figure 2.3, helicopter payload capacity has a significant impact on distribution costs, and therefore, on overall costs. Variation in total costs as a result of changes in helicopter payload capacity is similar to that shown in Figure 2.2, resulting from robot scanning speed, as far as both parameters have a similar effect on distribution costs at DZs.

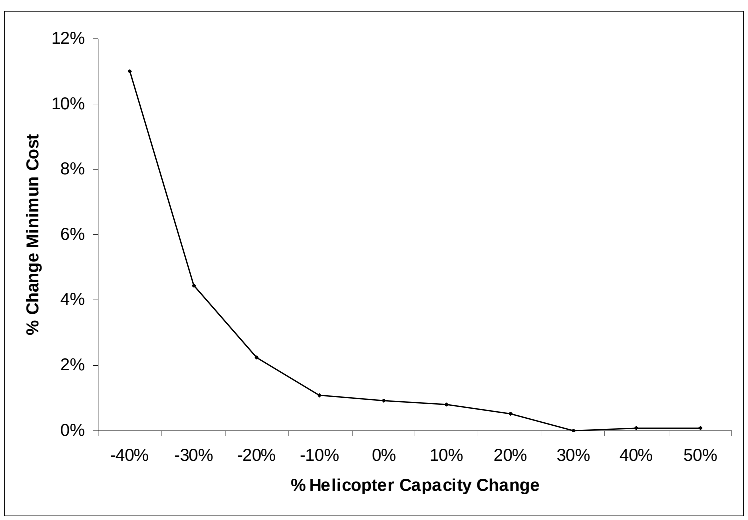

Figure 2.3: Effect of helicopter capacity on minimum cost

2.7. Conclusions

The current paper presents an MIP and an MNMIP models for anti-personal landmine disposal by means of robots that – following the recommendations found in the cited references - include and integrate strategic and tactical relevant aspects of the supply chain. For that reason the model includes certain considerations, such as uncertain procurement, stochastic inventories in plants, production scales, supply-production-distribution capacities, particular distribution-production infrastructure, location-allocation considerations, stochastic demand, and BOM. Additionally, the models detail optimal helicopter operation by considering each period's trip frequency during the planning horizon.

For their solution, two procedures are suggested, allowing to convert the original (and relatively hard) MINLP into a not so hard MIP. The efficiency of the second procedure tends to improve when the operation scales are considerable enough; otherwise, it lessens. On the other hand, the first procedure is advantageously explicit, in contrast with the second one, where the production cost is algorithmically induced.

Finally, the impact of parameter percentage variations on the overall cost is analyzed. The costs do not substantially differ if percentage variations do not entail changes in plant operation level or in the number of helicopters used in the distribution. The suggested solution procedure is considered satisfactory in terms of time for the analyzed example.

Some of the research perspectives comprise qualitative aspects, while some other comprise quantitative aspects, all of them potentially relevant for the decision making process under more specific contexts.

2.8. References

Aikens, C.H. (1985), Facility location models for distribution planning. European Journal of Operational Research. 22 263-279.

Arntzen, B.C., Brintegrated, G.G., Harrison, T.P., Trafton, L.L. (1995), Global supply chain management at digital equipment corporation. Interfaces 25 (1) 69-93.

Charnes, A., Cooper, W.W. (1959), Chance- constrained programming. Management Sciences 5, 73-79.

Chen, C., Lee, W. (2004), Multi-objective optimization of multi-echelon supply chain networks with uncertain product demands and prices. Computers & Chemical Engineering 28 1131 – 1144.

Cohen, M.A., Lee, H.L. (1988), Strategic analysis of integrated production-distribution systems: Models and methods. Operations Research 36 216-228.

Geoffrion, A.M., Graves, G. (1974), Multicommodity distribution system design by Benders decomposition, Management Science 20(5) 822- 844.

Geoffrion, A.M., Powers, R.F. (1995), Twenty years of strategic distribution system design: An evolutionary perspective. Interfaces 25 105-127.

Goetschalckx, M., Vidal, C.J., Dogan, K. (2002), Modeling and design of global logistic system: A review of integrated strategic and tactical models and design algorithms. European Journal of Operational Research 143 (1) 1-18.

Gupta, A., Maranas, C.D. (2003), Managing demand uncertain in supply chain planning. Computers & Chemical Engineering 27 1219 – 1227.

Hanson, W., Martin, R.K. (1990), Optimal Bundle Pricing. Management Science 36 (2) 155 – 174.

Landmine Monitor Report : Toward a Mine-Free World. 2003.

Silver, E.R., Peterson, R. (1985), Decision systems for inventory management and production planning, second ed., New York.

Thomas, D., Griffin, M.C. (1996), Coordinate supply chain management. European Journal of Operational Research 94 1-15.

Vidal, C.J., Goetschalckx, M. (1997), Strategic production-distribution models: A critical review with emphasis on global supply chain models. European Journal of Operational Research, 98 1-18.

Vidal, C.J., Goetschalckx, M. (2001), Modeling the effect of uncertainties on global logistics systems. Journal of business logistics, 21 (1) 95-120.

2.9. Appendix A

The chance approximation of the stochastic demand constraint is presented in the following equation:

$$P\left\{\sum_{p\in P}\sum_{e\in E(p)}\left[\sum_{t=1}^{N-\pi^p}\theta^p\phi^p\pi^p y_{kt}^p w_{kt}^{pe}+\sum_{l=0}^{\pi^p-1}\theta^p\phi^p\left(\pi^p-l\right)y_{k,N-\pi^p+1+l}^p\ w_{k,N-\pi^p+1+l}^{pe}\right]\geq\Theta_k(\xi)\right\}\geq 1-\alpha \quad k\in K \tag{A1}$$

$$P\left\{\frac{A_k(\xi)-E(\Theta_k(\xi))}{\sigma(\Theta_k(\xi))}\leq\frac{\sum_{p\in P}\sum_{e\in E(p)}\left[\sum_{t=1}^{N-\pi^p}\theta^p\phi^p\pi^p y_{kt}^p w_{kt}^{pe}+\sum_{l=0}^{\pi^p-1}\theta^p\phi^p\left(\pi^p-l\right)y_{k,N-\pi^p+1+l}^p\ w_{k,N-\pi^p+1+l}^{pe}\right]-E(\Theta_k(\xi))}{\sigma(\Theta_k(\xi))}\right\}\geq 1-\alpha \quad k\in K \tag{A2}$$

$$F\left(\frac{\sum_{p\in P}\sum_{e\in E(p)}\left[\sum_{t=1}^{N-\pi^p}\theta^p\phi^p\pi^p y_{kt}^p w_{kt}^{pe}+\sum_{l=0}^{\pi^p-1}\theta^p\phi^p\left(\pi^p-l\right)y_{k,N-\pi^p+1+l}^p\ w_{k,N-\pi^p+1+l}^{pe}\right]-E(\Theta_k(\xi))}{\sigma(\Theta_k(\xi))}\right)\geq 1-\alpha \quad k\in K \tag{A3}$$

Under the normal demand assumption

$$\frac{\sum_{p\in P}\sum_{e\in E(p)}\left[\sum_{t=1}^{N-\pi^p}\theta^p\phi^p\pi^p y_{kt}^p w_{kt}^{pe}+\sum_{l=0}^{\pi^p-1}\theta^p\phi^p\left(\pi^p-l\right)y_{k,N-\pi^p+1+l}^p\ w_{k,N-\pi^p+1+l}^{pe}\right]-E(\Theta_k(\xi))}{\sigma(\Theta_k(\xi))}\geq z_{1-\alpha} \quad k\in K \tag{A4}$$

The following is an approximate deterministic constraint of equation (A1).

$$\sum_{p\in P}\sum_{e\in E(p)}\left[\sum_{t=1}^{N-\pi^p}\theta^p\phi^p\pi^p y_{kt}^p w_{kt}^{pe}+\sum_{l=0}^{\pi^p-1}\theta^p\phi^p\left(\pi^p-l\right)y_{k,N-\pi^p+1+l}^p\ w_{k,N-\pi^p+1+l}^{pe}\right]\geq z_{1-\alpha}\sigma(\Theta_k(\xi))+E(\Theta_k(\xi)) \quad k\in K \tag{A5}$$

CHAPTER THREE

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Costos de Transacción y Formas de Gobernación de los Servicios de Consulta en Colombia: un estudio empírico *

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Abstract

The present paper considers the extent to which the establishment of the different governance forms linking hospitals to insurance companies in Bogotá, is carried out taking into account transaction costs reduction criteria. An empirical test is applied, making use of the transaction dimensions proposed by Williamson (1985). Hypotheses are tested by means of a combination of the stochastic multicriteria acceptability analysis, and multiple discriminant analysis. It is concluded that both hospitals and insurance companies seek to reduce production costs, while transaction costs are not relevant to the decision.

Palabras clave: Criterios de decisión, Organización Industrial, Costos de transacción Aplicaciones en sector salud.

JEL classification: D810, L000, D230

3.1. Introducción

Con la promulgación de la Ley 100 de 1993, se reemplaza el Sistema Nacional de Salud, que venía operando en Colombia desde 1973, por el Sistema General de Seguridad Social en Salud –SGSSS-. Uno de los objetivos que se buscaba con la implantación del SGSSS es el aumento de la eficiencia del sistema, para lo cual se introdujeron las siguientes modificaciones: i. se separaron las funciones de aseguramiento y prestación

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de servicios de salud y se permitió la participación del sector privado; ii. la relación entre aseguradores y prestadores está dada por el modelo de competencia regulada propuesta por Enthoven (1997) en el cual el estado juega fundamentalmente el papel de regulador. Estas ideas las retoman Londoño y Frenk (1997) para el planteamiento de este tipo de reformas en América Latina.

En este contexto está claramente reconocida la importancia de estudiar los sistemas de pago y formas de contratación de los servicios de salud en Colombia, debido al efecto que éstos tienen sobre la calidad de los servicios y el desarrollo tecnológico del sector [Gutiérrez, et al., 1995; Álvarez et al., 2000]. Sin embargo, en los estudios realizados esta visión no se amplía a la comprensión de las formas de gobernación, que contemplan tanto sistemas de pago como formas de contratación. Este aspecto ha sido poco estudiado en el sector salud en Colombia, lo que justifica la realización de esta investigación. El estudio de las formas de gobernación de la consulta externa es parte de un conjunto de trabajos que exploran los diversos tipos de servicios de salud como son los servicios de urgencias y la cirugía programada, los cuales difieren entre sí.

Las investigaciones sobre formas de gobernación del intercambio económico de bienes y servicios se han basado teóricamente en la economía de costos de transacción, perspectiva de las capacidades organizacionales y la estrategia y referentes sociológicos como la teoría institucional o la teoría contingente [Pisano, 1988; Mang, 1994; Lewin y Volverda, 1999; Torres, 2003]. Este estudio de carácter exploratorio tiene como objetivo estudiar las formas de contratación de los servicios de consulta externa en las IPS privadas de tercer nivel de atención en Bogotá desde la Economía de los Costos de Transacción, debido a que es el referente fundamental para explicar la forma en que se organiza el sistema económico [Williamson, 1975, 1985, 1991].

La presentación del estudio está organizada de la siguiente forma. En la primera parte del artículo se presentan los principales rasgos de funcionamiento del Sistema General de Seguridad Social en Salud en Colombia y algunos aspectos distintivos de la prestación de servicios de consulta externa. En la segunda parte, se hace una exposición sobre la economía de los costos de transacción y las hipótesis de allí derivadas. Le sigue la metodología de investigación, en que se presenta el plan de análisis mediante dos técnicas matemáticas complementarias. En el siguiente numeral se exponen los resultados de la investigación y se finaliza con la discusión de los mismos.

3.2. Elementos del contexto de los Servicios de Consulta Externa

3.2.1 Legislación sobre las formas de contratación y pago en el Régimen Contributivo

En Colombia se hace referencia a las formas de pago y no a las formas de gobernación. En las referencias sobre formas de pago en Colombia los mecanismos más frecuentemente encontrados en las relaciones entre aseguradores –EPS- y prestadores –IPS- de servicios de salud son el pago por servicio, pago por paquetes de enfermedades y pago por capitación [Gutiérrez et al., 1995; Molina, 1995; Torres et al, 2004]. El pago por servicio se define como el pago realizado por la totalidad de la atención de salud prestada a un individuo. La remuneración incluye honorarios médicos, suministros, medicamentos y servicios quirúrgicos. El pago sin embargo, no se puede estipular ex-ante debido a que la atención depende de los requerimientos de cada paciente y servicio.

El pago por capitación está basado en el concepto de enfermo potencial y no en el de enfermedad sentida como en el caso anterior. El prestador de servicios tiene a su cargo la atención de un conjunto determinado de personas. Por cada persona inscrita recibe un giro periódico de la EPS, sin importar el número de veces que acuda al servicio médico cada una de las personas capitadas.

El pago por caso es una forma de contratación que contiene elementos de las formas de pago anteriores. La unidad de medida es el tratamiento global de un tipo de dolencia específica sobre la que se conocen adecuadamente los protocolos a seguir para su tratamiento, por lo tanto se conocen adecuadamente los costos de tratamiento.

Teniendo esto como punto de partida, se enuncian los elementos en que la legislación colombiana se refiere a las relaciones entre IPS y EPS. En primer lugar, en la Ley 100 de 1993 se permite que la forma de gobernación entre EPS e IPS sea la integración vertical. Aunque una misma persona jurídica no puede ejercer las funciones de aseguramiento y prestación de servicios de salud, es factible que un mismo grupo empresarial sea propietario de dos empresas independientes. Por otra parte, atendiendo de forma más clara el espíritu del pluralismo estructurado sobre el que se construyó el Sistema General de Seguridad Social en Salud los agentes económicos pueden acudir a dos formas de gobernación alternas, el mercado para la compra de servicios de salud o establecer alianzas estratégicas entre organizaciones.

El segundo elemento para comprender la relación entre aseguradores y prestadores de servicios de salud son las formas de pago. La legislación emitida sobre formas de pago no es muy amplia y se refiere de forma independiente al Régimen Contributivo y el Régimen Subsidiado. Respecto al pago por servicios prestados, el primer referente está en el Decreto 2423 de 1996 en el cual se establecen tarifas, nomenclatura y clasificación de los procedimientos médicos, quirúrgicos y hospitalarios que se intercambian entre los aseguradores de los servicios de salud y las IPS públicas y privadas para la atención de pacientes víctimas de accidentes de tránsito, desastres naturales, atentados terroristas, atención inicial de urgencias y los demás eventos catastróficos definidos por el Consejo Nacional de Seguridad Social en Salud. En la práctica este Manual Tarifario funciona como una referencia que usan aseguradores y prestadores para fijar los precios de intercambio. Por otra parte, el Decreto 050 de 2003 establece que los pagos a los prestadores de servicios no pueden tomar más de seis meses desde el momento de radicación de la cuenta de cobro.

Respecto a la forma de contratación por capitación, el Decreto 050 de 2003 señala las siguientes condiciones a cumplir: se debe garantizar la adecuada prestación de los servicios; por esta razón se considera como una práctica insegura contratar a una persona natural o jurídica para que realice la función de coordinar la red de prestación de servicios; no se podrá capitar la totalidad de los servicios de más de dos niveles de atención con la misma IPS, y los pagos a las IPS deben hacerse durante los primeros diez días de cada mes. Estos son los aspectos que la legislación colombiana tiene en cuenta para regular las relaciones de contratación entre aseguradores y prestadores.

3.2.2 *La consulta externa en los hospitales de tercer nivel*

La atención médica en el actual SGSSS de Colombia está establecida según los niveles de complejidad en la atención, encontrándose tres niveles de atención, siendo el tercer nivel el de mayor complejidad tecnológica.

El tercer nivel de atención se caracteriza por prestar servicios hospitalarios y ambulatorios de especialistas en medicina interna, pediatría, ginecología, cirugía general y ortopedia, entre otras especialidades médicas y quirúrgicas [Malagón et al., 1986], a su vez cuenta con áreas de urgencias, consulta externa, cirugía, hospitalización y cuidado intensivo. En síntesis, éste tipo de instituciones atienden los casos de mayor complejidad médica y tecnológica, lo cual implica la mayor generación de los costos de atención.

La consulta externa se entiende como la actividad alrededor de la que giran los procesos de especialización médica; siendo el espacio idóneo para diagnosticar, orientar definir la estrategia terapéutica de un paciente. En la actualidad la consulta externa cobra importancia en la medida que se torna en la puerta de entrada al sistema, lo que permite realizar un mayor control de costos. Está claro que se debe dar una interacción entre la consulta externa de los diferentes niveles de atención.

En Colombia los servicios de consulta externa de los primeros niveles de atención los realizan las EPS e IPS del primer y segundo nivel de atención, de manera que la consulta externa del tercer nivel de atención se realiza en IPS del tercer nivel; las cuales, pueden tener diversas formas de interacción con las EPS y con las IPS de primero y segundo nivel de atención [Gorbaneff et al., 2004].

3.3. Marco Teórico

Los problemas fundamentales que estudia la economía y que enfrentan las organizaciones en su vida cotidiana son la producción e intercambio de bienes y servicios. Desde el punto de vista de la organización de la actividad económica, las personas involucradas en las actividades productivas pueden solucionar estos problemas acudiendo a tres tipos de formas de gobernación [Williamson, 1991; Li, 1998; Hage y Alter, 1997]: el mercado, la integración vertical de diversos agentes económicos en una estructura jerárquica que toma la denominación de empresa y el establecimiento de relaciones de cooperación entre agentes usualmente llamadas alianzas estratégicas. Entre estos tres tipos ideales [Doty y Glick, 1994] de realización del intercambio económico se pueden encontrar formas más complejas que son producto de la mezcla de las características fundamentales de los tipos ideales señalados [Torres et al., 2004].

Las formas de gobernación genéricas establecidas en la economía de costos de transacción tienen vigencia en el sector salud y particularmente en las relaciones de intercambio que establecen las EPS e IPS. Con el fin de unificar los términos se hablará de tres (3) formas de gobernación: integración vertical, alianzas estratégicas y mercado (ver Tabla 3.1).

Es necesario hacer una mención especial sobre los incentivos económicos. Estos van a estar dados por la forma de gobernación del intercambio y por el sistema de pago que se use. El tipo de contrato determina la intensidad de los incentivos del agente, siendo bajos cuando hay un contrato de empleó como es típico en la integración vertical. Por otra parte, los incentivos se aumentan hasta llegar a su máxima expresión cuando la propiedad es individual.

Sobre las formas de pago, se debe tener claro que se pueden presentar diversas formas bajo la misma forma de gobernación. La forma de pago lo que hace es cambiar el aspecto de la transacción en el que se colocan los incentivos y la distribución del riesgo entre las partes [Seshadri, 2005]. En la forma de pago por capitación todo el riesgo es asumido por el agente y le genera un incentivo a la reducción de costos. En el pago por servicio el riesgo lo asume parcialmente el principal y el agente tiene un incentivo fuerte a la facturación.

En un intercambio de mercado se puede usar cualquier forma de gobernación con altos incentivos pero dirigidos de diferentes formas. En las alianzas estratégicas se pueden usar las tres formas de pago, pero el riesgo se distribuye entre las partes. Finalmente, en la integración vertical por definición el riesgo lo asume el principal y el agente tiene bajos incentivos.

Sobre las formas de pago es necesario hacer una aclaración. El pago por capitación implica que el intercambio no puede ser de tipo "spot", como consecuencia el intercambio de mercado tendrá un horizonte de mediano plazo; en tanto, el pago por servicios es más característico del mercado "spot".

Tabla 3.1. Dimensiones de las Formas de Gobernación del Intercambio en el Sector Salud

Atributos			***Formas de Gobernación***		
			Integración Vertical	***Alianzas estratégicas***	***Mercado***
Formas de interacción			Mandato	Acción conjunta	Competencia
Mecanismos de control			Planeación	Confianza	Sistema de precios
Marco Legal			Laboral	Amplio	Específico
Incentivos Económicos	*Propiedad*		Unificada (bajos)	Compartida (Intermedios)	Individual (altos)
	Formas de pago	*Capitación*	Bajos	Altos para ahorrar bajo acuerdos de calidad	Altos para ahorrar
		Pago por paquetes		Intermedios	Altos para vender paquetes y altos para ahorrar dentro del paquete
		Pago por servicio		Altos para gastar bajo acuerdos de control de costos	Altos para gastar

Fuente: Adaptado de Torres et al., (2004).

Como se ha mostrado, la única opción posible para realizar el intercambio de bienes y servicios no es el mercado, sino que los agentes pueden acudir a la creación de empresas y de alianzas estratégicas, ¿de qué depende esta decisión?. Siguiendo la propuesta teórica de Coase (1937) y Williamson (1975, 1985, 1991), los agentes que buscan racionalidad económica, mediante la selección de la forma de gobernación de realizar el intercambio, buscan reducir la suma de los costos de producción y los costos de transacción.

Los costos de producción están asociados a las actividades productivas directas y se encuentran representados por los diversos recursos requeridos para la prestación de los bienes o servicios, tales como el trabajo requerido para la producción, maquinaria y equipo y materias primas. Los costos de producción están determinados fundamentalmente por el tipo de tecnología disponible, ya que ésta además de establecer los costos de maquinaria y equipo afectan también los requerimientos de mano de obra. Si los agentes económicos seleccionasen las formas de intercambio en función de los costos de producción, se integrarían verticalmente cuando su consumo agotase las economías de escala y acudirían al mercado cuando su consumo fuese pequeño en relación a las economías de escala disponibles [Williamson, 1975].

Por otra parte, los costos de transacción se derivan de las actividades que están relacionadas con la búsqueda y transmisión de información sobre precios y características de los bienes, negociación de condiciones de intercambio, redacción y celebración de contratos, supervisión de las contrapartes para el cumplimiento de los contratos, demandas y adaptaciones del mismo y protección de los derechos de propiedad [Milgrom y Roberts, 1993]. Las actividades referidas como generadoras de costos de transacción tienen una doble naturaleza, contractual, y organizacional; las cuales en conjunto explican los problemas que se presentan en el intercambio mediante las formas de gobernación.

Como se puede ver los costos de transacción no tienen relación directa con los costos productivos, para explicar mejor su naturaleza es adecuada la analogía que hace Arrow (1962) al compararlos con la fricción de los sistemas mecánicos, del tal forma que son indeseables pero al mismo tiempo inevitables. Como ocurre con los fluidos que las pérdidas friccionales dependen de su viscosidad, en la organización económica los costos de transacción dependen de las características de los bienes que se intercambian. Las características de los bienes o dimensiones de la transacción que determinan los costos de transacción son: especificidad de las inversiones, dificultades de medición de los procesos y resultados, frecuencia de la transacción, incertidumbre en la prestación de los servicios [Williamson, 1991] y relaciones entre las transacciones [Milgrom y Roberts, 1993].

Como se dijo anteriormente, todas las formas de gobernación generan costos de transacción, pero estos dependen de las dimensiones de la transacción. Para la identificación de cual es la forma de gobernación que genera menores costos de transacción se debe dar una alineación entre las dimensiones de las formas de gobernación y las dimensiones de la transacción.

Williamson (1985) afirma que la dimensión que explica la mayor parte de los costos de transacción es la especificidad de las inversiones, definida para este caso como aquella situación en la que los recursos involucrados en la prestación de los servicios de salud son solamente útiles para la prestación de servicios a una EPS, lo que generaría una dependencia bilateral entre las partes. Estas inversiones que son de utilidad únicamente entre estos dos agentes, generan cuasirentas compuestas [Hart, 1991], que las partes involucradas buscarán apropiarse mediante comportamientos oportunistas [Pisano, 1988].

En esta situación de dependencia bilateral, entre el aseguramiento y la prestación de servicios, sí el intercambio se realiza a través del mercado se generarán altos costos de transacción, fundamentalmente de tipo contractual. Tales costos, se derivan de las continuas renegociaciones y adaptaciones del contrato a las nuevas condiciones, las cuales es necesario realizar en la medida que surgen contingencias que desajustan los términos iniciales de los contratos [Williamson, 1991].

La forma en que se desajusta intencionadamente el contrato inicial, es mediante argucias como la revelación incompleta de las características epidemiológicas de la población y de las características de los procedimientos médicos; o mediante la amenaza de interrupción del contrato u otras acciones que alteran los términos iniciales del intercambio [Milgrom y Roberts, 1993].

Los riesgos de interrupción prematura de los contratos de prestación de servicios de salud, los costos contractuales de renegociación de las condiciones iniciales y los costos burocráticos en que se incurre para la búsqueda de información aumentan en la medida que los recursos médicos y los resultados de las intervenciones son coespecializados[7]. Como alternativa al intercambio de mercado, las organizaciones pueden integrarse verticalmente, teniendo como resultado la reducción de los costos de adaptación a circunstancias cambiantes. Esta reducción de costos, es consecuencia de las virtudes de la integración vertical para coordinar eficientemente situaciones en las que se debe transmitir información sobre nuevas condiciones y acordar las acciones a realizar conforme a las contingencias que se han presentado [Williamson, 1991].

La integración vertical reduce los costos de transacción ante altos niveles de especificidad de las inversiones para la prestación de servicios de salud, reemplazando los altos costos contractuales por costos burocráticos requeridos para la coordinación y control de la prestación de servicios. Bajo la forma de propiedad integrada se reducen los riesgos de terminación prematura del contrato o de desajustes por la revelación incompleta de información. Lo anterior se resume en la:

[7] Los activos coespecializados son aquellos en que hay una dependencia bilateral (Teece, 1986), esto es que los recursos innovadores -I+D, diseño, ingeniería de producción- no son compatibles con los activos complementarios y viceversa.

Hipótesis 1: Existe una relación directa y positiva entre el aumento de la especificidad de las inversiones y la preferencia por formas de gobernación con mayores niveles de integración.

Cuando se establecen mecanismos burocráticos especializados para el intercambio de determinados servicios es necesario realizar esa transacción repetidas veces para poder recuperar las inversiones. Esta idea acoge el sentido de las economías de escala propuestas desde la economía neoclásica, para explicar la selección de las formas de gobernación. El costo de la estructura organizacional se distribuye entre las transacciones que se realicen, por lo tanto se propone:

Hipótesis 2: Existe una relación directa y positiva en el aumento de la frecuencia y duración de la transacción y la preferencia por establecer formas de gobernación con mayores niveles de integración vertical.

Otra fuente de costos de transacción y de especial relevancia en la prestación de servicios de salud son las dificultades de medición de la actuación de los agentes que participan en el intercambio de servicios de salud [Milgrom y Roberts, 1993]. Las dificultades de medición se definen como las limitaciones que tiene la EPS de supervisar, *ex–post* a la elaboración del contrato, el comportamiento de la IPS en la prestación de los servicios pactados [Barzel, 1989].

Los comportamientos oportunistas derivados de la especificidad de los activos se deben a la búsqueda de la apropiación de las cuasirentas compuestas mediante el desajuste del contrato. Ahora bien, cuando confluye la especificidad de los activos con la existencia de dificultades de medición, el tipo de comportamiento oportunista que surge para apropiarse de las cuasirentas compuestas, es evadir los compromisos ampliamente especificados en la fase *ex-ante* de la contratación del proyecto [Chi, 1994][8]. Una

[8] Este tipo de oportunismo, *ex–post* a la firma del contrato, afecta los resultados y eficiencia de la transacción, ya que las partes deben hacer un esfuerzo mutuo por controlar las acciones del otro, el cual se denomina riesgo moral.

situación agravante es que tan sólo después de finalizada la contratación es posible detectar el comportamiento anómalo [Alchian y Woodward, 1988].

Si bajo esta circunstancia la contratación se da en el mercado, la empresa innovadora incurrirá en altos costos de transacción, de una parte, *ex-ante,* en la recopilación de información técnica que le permita ser lo más exhaustiva en la determinación de los resultados de los servicios de salud, y por otra, en costos burocráticos *ex-post* necesarios para comprobar la forma en que se prestan los servicios de salud. La situación se debe en buena medida a que las acciones y resultados de la prestación de servicios de salud no son tangibles sino que tienen un amplio componente tácito.

El componente tácito en la prestación de los servicios de salud es el aumento de los costos de transacción y más grave aún el posible deterioro de los servicios de salud. Ante ésta situación de ineficiencia, tanto productiva como transaccional, la opción de integración vertical, en que se establecen estructuras burocráticas de control y se eliminan los incentivos fuertes, permite la reducción de las posibilidades de comportamientos oportunistas. Estas ideas se sintetizan en la:

Hipótesis 3: En la medida que aumentan las dificultades de medición en la prestación de servicios de salud se preferirán formas de gobernación con mayor grado de integración vertical.

Según Williamson (1985), la tercera fuente de costos de transacción es la incertidumbre en el comportamiento de los agentes que intercambian, en este contexto la incertidumbre en la prestación de los servicios de salud se entiende como la dificultad posterior a la contratación, de determinar las acciones y costos en los que deberá incurrir tanto EPS como IPS en la prestación del servicio de salud. Esta incertidumbre se relaciona en primer lugar, con las dificultades de predecir el comportamiento de la IPS en cuanto a la revelación de los costos de prestación de los servicios, y en segundo lugar, con la posibilidad de la EPS de enviar pacientes con enfermedades en extremo costosas, cuando la contratación se da vía capitación.

Hipótesis 4: En la medida que aumenta la incertidumbre en la prestación de los servicios de consulta externa se prefiere realizar el intercambio de servicios mediante formas de gobernación con mayores niveles de integración vertical.

3.4. Metodología de Investigación

3.4.1 *Instrumento y medición*

La unidad de análisis de la investigación fue el intercambio de servicios de consulta externa entre EPS e IPS. Esto porque para la economía de los costos de transacción [Williamson, 1975, 1985] es en este espacio económico que es posible detectar los problemas contractuales en el intercambio.

La encuesta se construyó conforme a trabajos previos empíricos que han operado variables similares a las usadas en esta investigación. Las variables independientes que conforman el modelo de investigación se midieron con múltiples proposiciones que reflejan diversas dimensiones del concepto o variable que se desea medir, permitiendo que los errores en la medición de las afirmaciones se corrijan mutuamente [Churchill, 1979]. Las proposiciones se miden con una escala Likert de 1 a 5, que permite identificar el nivel de acuerdo o desacuerdo ante una determinada afirmación relativa a las variables que se indagan [Albaum, 1997]. Es claro que la medida se hace a partir de una apreciación de la realidad.

Se efectuó una prueba piloto y como resultado se identificaron problemas de presentación de las preguntas, se efectuaron los ajustes del instrumento de medición, que posteriormente fue aplicado a la población.

En primer lugar se realizó el análisis de consistencia interna; este análisis evalúa la confiabilidad del instrumento de recopilación de información y validez de la información recolectada. La confiabilidad se refiere al grado en que la medición está libre de error y se determina mediante la correlación entre los indicadores de cada variable, la correlación corregida y él coeficiente alfa [Nunnally, 1978; Kerlinger, 1986]. La evaluación de la validez de la información se realiza mediante el análisis factorial de componentes principales [Churchill, 1979]. Esta prueba confirma si los indicadores seleccionados de una variable están midiendo el mismo fenómeno. Las pruebas de confiabilidad y validez se realizan de forma iterativa y son típicos cuando se realizan encuestas con información cualitativa.

En cada variable se realizó un procedimiento de análisis de la consistencia interna de los indicadores. La evaluación de la confiabilidad del instrumento se inició con el análisis de correlación no paramétrico de Taub-Kendall. Se usó éste estadístico debido a la naturaleza no normal de las variables. Luego se efectuaron análisis de correlación corregida y finalmente se determinó el coeficiente alfa de Cronbach [Nunnally, 1978]; se considera un alpha aceptable aquel que es mayor a 0,5.

Los análisis de confiabilidad y validez fueron efectuados paralelamente. Los resultados fueron consistentes, mostrando que los indicadores removidos presentan problemas de dimensionalidad. Las variables resultantes fueron operadas como factores con el fin de reducir información que introduce ruido en las variables. Es necesario resaltar la alta correlación de los indicadores dentro de los factores resultantes, en todos los casos fue superior a 0,53.

Teniendo en cuenta los aspectos generales descritos se presenta la operación de las variables relacionadas con las hipótesis planteadas.

Especificidad de las inversiones. Se midió con cinco indicadores relacionados con las inversiones no recuperables y la posible situación de monopolio bilateral, conforme a los trabajos de Lothia et al. (1994) y Torres (2003), los indicadores son: dificultades de reutilización de las inversiones físicas, IPS competidoras en servicios similares, IPS que podrían desarrollar servicios similares, pérdida de la rentabilidad de las inversiones físicas si se destinan a otro servicio, y grado en que es necesario modificarlas o adaptarlas para que puedan ser usadas en otros servicios. La totalidad de los indicadores fueron consistentes. El coeficiente alpha final es de 0,79. La carga de los indicadores resultantes en el factor fue de 0,67, 0,77, 0,76, 0,86 y 0,66, respectivamente y el porcentaje de la varianza extraída por el factor fue de 56,146%.

Frecuencia del intercambio en la prestación del servicio. La frecuencia y duración del intercambio en los servicios atendiendo a la idea de repetitividad y su duración temporal se midió con los siguientes indicadores: Frecuencia con la que intercambian servicios de consulta externa y tiempo durante el cual se ha prestado el servicio entre la EPS y la IPS. El coeficiente alpha asociado es de 0,54. La carga de los indicadores en el factor fue de 0,83 en los dos casos y el porcentaje de la varianza extraída por el factor fue de 68.5%.

Incertidumbre en la prestación de los servicios. Siguiendo el trabajo de Torres (2003) e indagando sobre la utilidad de los diversos mecanismos usados para tratar información sobre la prestación de servicios de salud, se definieron los siguientes indicadores para la construcción de ésta variable: Dificultades para establecer cláusulas restrictivas en el contrato, dificultades para el seguimiento de los protocolos de atención o guías de manejo, complicaciones en el manejo de los pacientes en consulta externa, dificultades para llevar a buen término el tratamiento de los pacientes y desigualdad en las conductas tomadas en el servicio. Para aumentar la confiabilidad del instrumento fue necesario prescindir de los indicadores dificultades para establecer cláusulas restrictivas en el contrato y desigualdad en las conductas tomadas en el servicio. El coeficiente alpha calculado es de 0,66. La carga de los indicadores resultantes en el factor es de 0,62, 0,87 y 0,82, respectivamente y el porcentaje de la varianza extraída por el factor fue de 60,4%.

Dificultades de medición de la actuación. Siguiendo los trabajos empíricos de Erramilli y Rao (1990) y Kim y Hwang (1992), se midió la variable usando cuatro indicadores para captar el grado de especialización y de estandarización de los conocimientos utilizados en la prestación de servicios de salud. Los indicadores definidos son: dificultad para que el paciente mida resultados de las intervenciones, dificultades para que la EPS mida resultados, dificultades para que el paciente mida la calidad de los procesos y dificultad para que la EPS mida la calidad de los procesos. No fue necesario prescindir de ningún indicador para mejorar la confiabilidad del instrumento. El coeficiente alpha asociado es de 0,81, las cargas de los indicadores resultantes en el factor son 0,81, 0,69, 0,89 y 0,83 respectivamente y el porcentaje de la varianza extraída por el factor es de 66,2%.

Relación con otras transacciones. Algunos estudios sugieren que ésta variable debe ser incluida en las contrastaciones empíricas [Mang, 1994]. Los cinco indicadores de esta variable determinados son: necesidad previa de uso de otros servicios de la IPS, necesidad previa de uso de otros servicios de la EPS, necesidad de uso del servicio de consulta externa para acceder a otro servicio de la IPS, necesidad de uso del servicio de consulta externa para acceder a otro servicio de la EPS y la atención del servicio de consulta externa implica varias transacciones. Fue necesario prescindir de esta variable para la prueba de las hipótesis; ya que el análisis de la matriz de coherencia de los indicadores no rechaza la hipótesis nula. Adicionalmente ninguna combinación de indicadores resultaba en un coeficiente alpha mayor a 0,35. Por lo tanto, siguiendo las indicaciones de Nunnally (1978) se determinó excluir la variable del modelo empírico ya que no presentaba garantías que condujeran a responder el estado diseño del proceso.
El número de indicadores que componen cada variable, el alpha de Cronbach asociado y el porcentaje de la varianza de los indicadores explicada por los factores se presenta en la Tabla 3.2.

Forma de gobernación: Se construyó como una variable categórica con la posibilidad de adoptar las opciones de integración vertical, alianzas estratégicas, mercados a largo plazo (capitación) y mercados a corto plazo (pago por servicio).

Tabla 3.2. Síntesis Resultados Análisis de Confiabilidad

Factor	***Especificidad***	***Frecuencia del intercambio***	***Incertidumbre y complejidad***	***Dificultades de medición***
Indicadores Componentes	5	2	3	4
Alpha de Cronbach	0,79	0,53	0,65	0,81
Varianza explicada %	56,14	68,54	60,44	66,19

3.4.2 *Análisis de Información*

El procesamiento de la información se hace en tres etapas. En la primera, haciendo uso del Análisis de Aceptabilidad Multicriterio Estocástico –SMAA[9]- técnica desarrollada por Bana (1986, 1988) y Ladhelma et al. (1997) que identifica las formas en que se deben combinar las dimensiones de la transacción para que cada una de las formas de gobernación de la variable dependiente sea seleccionada. Esta se expresa como la probabilidad de aceptación de las formas de gobernación como alternativas posibles, según las variables independientes. En la segunda etapa, se caracteriza de forma general la relación entre las variables independientes mediante pruebas estadísticas descriptivas.

En el tercer paso se prueban las hipótesis mediante el ADM. El uso de esta técnica estadística paramétrica permite identificar la relación entre variables independientes continuas y una variable dependiente categórica [Press y Wilson, 1978], mediante la asignación de las observaciones de la muestra a los grupos de la variable dependiente. Esto se realiza mediante la construcción de funciones discriminantes en las que se involucran las variables independientes.

3.5. Resultados

3.5.1 *Descripción de la población*

La muestra está conformada por 30 IPS privadas de tercer nivel ubicadas en la ciudad de Bogotá. Por lo tanto el estudio tiene un carácter censal y no muestral. En el estudio no se incluyeron las IPS de la red pública ni las adscritas a los regímenes de excepción. Lo

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[9] Stochastic Multicriteria Acceptability Analysis.

anterior no implica que los resultados del estudio puedan extrapolarse a toda la población. Esto porque no se indagó por todas las transacciones que realizaron las IPS de la muestra con todas las EPS con las que tienen algún tipo transacción, sino que se indagó por la transacción con una EPS.

Más del 70% prestan sus servicios hace más de 20 años y la totalidad de ellas realizan procedimientos de alta complejidad. Son centros de referencia nacional para el manejo de pacientes que se complican a pesar del tratamiento que se les ha dado en otras instituciones.

Sólo dos de ellas hacen parte de complejos empresariales, y son las clínicas de Colsubsidio y Saludcoop, mientras que las otras surgieron de manera independiente aunque muchas tienen alianzas con aseguradoras. La Fundación Cardioinfantil y la Clínica de la Fundación Abood Shaio se han subespecializado en el manejo de patologías cardiovasculares, aunque prestan servicios de todas las especialidades características del nivel. La Clínica del Niño y el Hospital la Misericordia se caracterizan por atender a la población pediátrica. El Hospital San Ignacio y la Clínica El Bosque, son universitarios.

Inicialmente, la forma de gobernación de intercambio de servicios de salud contemplaba cuatro categorías, las cuales se redujeron a dos en el análisis empírico. La razón que explica este hecho es que en el trabajo empírico la gobernación del intercambio de servicios de consulta externa se dio mediante pago por servicio y capitación.

3.5.2 *Análisis de las características de la decisión con SMAA*

A partir de las distribuciones de las respuestas de cada uno de los indicadores de las variables, se identificó, según las hipótesis, la forma de contratación que genera menores costos de transacción para cada forma de intercambio. En la tabla 3 se presentan las distribuciones de las respuestas asociadas a cada indicador utilizado en el análisis.

Los resultados muestran calificaciones relativamente bajas de los indicadores de la variable de especificidad de las inversiones, lo que se permite pensar que la forma de gobernación más eficiente es pago por servicio. Los indicadores de la variable frecuencia del intercambio presentan valores relativamente altos, éste comportamiento sugiere que la capitación puede ser la forma más eficiente de intercambio. Los indicadores de incertidumbre en la prestación de los servicios y dificultades de medición, presentan bajas calificaciones lo que según la teoría de costos de transacción sugiere que la forma de gobernación a seleccionar sería el pago por servicio.

Tabla 3.3. Distribuciones de Probabilidad –Datos porcentuales-

Variables	***Escala Likert de Respuesta***				
	1	***2***	***3***	***4***	***5***
Esp. 1. Dificultades reutilización inversiones físicas	23,3%	50%	20%	6,7%	0%
Esp. 2. IPS competidoras	20%	46,7%	33,3%	0%	0%
Esp. 3. IPS que podrían desarrollar servicios	23,3%	40%	20%	16,7%	0%
Esp. 4. Pérdida de rentabilidad si cambia de uso	30%	46,7%	20%	3,3%	0%
Esp. 5. Necesidad adaptar servicios	16,7%	16,7%	43,3%	23,3%	0%
Frec. 1. Frecuencia de intercambio	0%	6,7%	6,7%	43,3%	43,3%
Frec. 2. Estabilidad de los contratos	0%	6,7%	36,7%	30%	26,7%
Incert. 1. Dificultades seguimiento de protocolos	73,3%	20%	3,3%	3,3%	0%
Incert. 2. Complicaciones manejo de pacientes	76,7%	20%	0%	3,3%	0%
Incert 3. Dificultades para terminar tratamientos	43,3%	50%	3,3%	3,3%	0%
Dific. 1. Dificultad de medir resultados el paciente	70%	23,3%	6,7%	0%	0%
Dific. 2. Dificultad de medir EPS los resultados	80%	13,3%	3,3%	3,3%	0%
Dific. 3. Dificultad de medir calidad el paciente	80%	16,7%	3,3%	0%	0%
Dific. 4. Dificultad de medir calidad la EPS	70%	23,3%	3,3%	3,3%	0%

Dados los anteriores resultados, el tipo de contratación que minimiza los costos de transacción en la prestación de servicios de consulta externa no es fácilmente determinable, ya que las variables no muestran una clara línea de decisión sobre la manera como debe establecerse el intercambio.

Para poder intentar dar solución al problema se puede hacer uso de técnicas que permiten indagar más a fondo sobre la decisión. El SMAA surge como una herramienta de decisión adecuada. La técnica indica el aporte de cada criterio a la minimización de los costos de transacción, expresada en el término utilidad, en cada una de las formas de gobernación posibles para el intercambio económico. Esto se hace operativo a través de una adecuada función de utilidad aditiva como la que se presenta a continuación:

$$u_i = \sum_j w_j u_{ij} \tag{3.1}$$

donde: u_i = Utilidad total de la alternativa i; u_{ij} = Utilidad del criterio j para la alternativa i; w_j = Peso del criterio j.

El análisis proporciona estimaciones de los pesos de las variables -w_j-, que permiten calcular la utilidad de cada una de las posibles opciones de decisión. La técnica determina los rangos de las combinaciones de las ponderaciones que hacen a cada una de las formas de gobernación dominante sobre las demás en términos de utilidad. También calcula el volumen del conjunto de las combinaciones de pesos de las variables que hacen dominante a cada alternativa a las que se ha denominado, índices de aceptabilidad. Finalmente determina los vectores de ponderaciones típicos –promedio- de cada una de las opciones, como un centroide de cada uno de los hiperespacios que soportan el dominio de una alternativa. –ver el Anexo B para una descripción detallada de la metodología de análisis SMAA determinística-.

La utilidad, en este caso normalizada, de cada criterio por alternativa, fue calculada como el promedio de las percepciones de cada una de las observaciones en las dos categorías de la variable dependiente. Las utilidades típicas se presentan en la Tabla 3.4. La variable que presenta una mayor diferencia en su valoración en las dos formas de gobernación es la frecuencia del intercambio, por lo tanto se esperaría de esta variable una mayor capacidad de discriminación. Las variables que siguen son especificidad e incertidumbre. Por su parte, dificultad de medición presenta valores de utilidad muy similares para las dos alternativas consideradas. Los resultados de las características de los pesos de las variables, rangos de aceptabilidad y los vectores típicos para cada alternativa obtenidos se muestran en la Tabla 3.5.

Tabla 3.4. Utilidades típicas de cada variable para las formas de gobernación alternativas

Criterios Típicos de las formas de gobernación alternativas				
Criterios	***Especificidad***	***Frecuencia del intercambio***	***Incertidumbre del servicio***	***Dificultad de Medición***
Capitación	0,42	0,90	0,33	0,28
Pago por Servicio	0,47	0,72	0,26	0,26

El análisis de los rangos mínimos y máximos de los vectores se dividió según la dominación del tipo de contratación, en su orden capitación y pago por servicio. Se especificó así para cada dimensión de la transacción los 2 pesos óptimos que hacen a una alternativa más útil que la otra.

Tabla 3.5. Rangos de los Vectores de los criterios que soportan a cada alternativa

DOMINIO CAPITACIÓN				
	W1	***W2***	***W3***	***W4***
REF MAX W1	0,782504	0,217496	0	0
REF MIN W1	0	1	0	0
REF MAX W2	0	1	0	0
REF MIN W2	0	0	1	0
REF MAX W3	0	0	1	0
REF MIN W3	0	1	0	0
REF MAX W4	0	0	0	1
REF MIN W4	0	1	0	0
DOMINIO PAGO POR SERVICIO				
	W1	***W2***	***W3***	***W4***
REF MAX W1	1	0	0	0

REF MIN W1	0,300194	0	0	0,699806
REF MAX W2	0,782504	0,217496	0	0
REF MIN W2	1	0	0	0
REF MAX W3	0,585838	0	0,414162	0
REF MIN W3	1	0	0	0
REF MAX W4	0,300194	0	0	0,699806
REF MIN W4	1	0	0	0
VECTOR PONDERADO CENTRAL				
W_1^c	0,20995005	0,26339754	0,26847778	0,25817462
W_2^c	0,66231843	0,05331346	0,10478811	0,17975886

Notación: Capitación, i = 1; Pago por servicio, i = 2; Especificidad, j=1; Frecuencia y Duración del intercambio, j=2; Incertidumbre y Complejidad del servicio, j=3; Dificultad de Medición de la actuación, j=4.

El vector ponderado central que señala como forma de gobernación más adecuada a la capitación -W_1^c- está dado por valores relativamente bajos en todas las dimensiones de la transacción. Por otra parte, el vector ponderado central que muestra como forma de gobernación más adecuada al pago por servicio –W_2^c- está dado por valores relativamente altos de la especificidad -0,66-, valores bastante bajos de incertidumbre -0,10- y dificultades de medición -0-17- y valores muy bajos para la frecuencia de la transacción. En general los resultados son consistentes con las hipótesis; exceptuando el signo de la especificidad de las inversiones, que muestra un sentido contrario. Valores más altos cuando la forma de gobernación es el pago por servicio -0,66- que cuando se opta por la capitación -0,20-.

Los mínimos y los máximos de cada una de las dimensiones que hace preferible capitación o pago por servicios muestran, en general, que los rangos de dominancia son bastante amplios. Para la incertidumbre se discuten los resultados continuación. El vector factible que hace dominante a la capitación sobre el pago por servicio mediante la maximización de la especificidad es: Especificidad = 0,78, Frecuencia del intercambio = 0,21, Incertidumbre del servicio = 0, Dificultad de Medición de medición = 0. Mientras que el vector factible que hace dominante a la capitación sobre el pago por servicio mediante la minimización de la especificidad es: Especificidad = 0, Frecuencia y

Duración del intercambio = 1, Incertidumbre y Complejidad del servicio = 0, Dificultad de Medición de la actuación = 0.

Por otra parte el límite del rango posible que hace que el tipo de contratación de pago por servicio sea dominante y que maximiza la ponderación de especificidad es 1, con las demás ponderaciones de los criterios iguales a cero. A su vez el rango factible que minimiza el valor de la ponderación del criterio de especificidad hace que éste tome un valor de 0,3 y la dificultad de medición de la actuación tome 0,699 en la ponderación con las demás variables ponderadas al 0. Análisis similares se realizan para los demás criterios.

Tabla 3.6. Índices de Aceptabilidad

Índices de Aceptabilidad (ai)	
Capitación	0,930
Pago por servicio	0,070

Finalmente, en la Tabla 3.6 se presentan los índices de aceptabilidad para cada alternativa. Éstos muestran que aproximadamente el 93% de las combinaciones factibles de las ponderaciones de los criterios responden a favor de la contratación de capitación. Esto implica que la capitación debiese ser la forma de gobernación fundamental mediante la cual se intercambiasen los servicios de consulta externa.

De lo anterior se puede concluir que la importancia de las variables en la selección de las formas de contratación de los servicios de consulta externa cambia en función de la forma de contratación. Si la frecuencia del intercambio es muy alta, es claro que el pago por servicio es la forma más importante y la decisión se tomará en términos de costos de operación, no obstante si la frecuencia es baja implica que el servicio se debe realizar mediante capitación en tanto la especificidad sea alta, debido a la poca importancia de la frecuencia en ésta forma de gobernación. Para frecuencias moderadamente bajas se debe evaluar la especificidad, la incertidumbre y las dificultades de medición, variables que tienen alta importancia en la capitación. Esto quiere decir que si el servicio es poco específico y moderadamente bajas la incertidumbre y dificultades de medición son bajas se deberá realizar el intercambio mediante pago por servicio, por el contrario si las frecuencias son altas se debe contratar por capitación.

Como conclusión, dadas las condiciones de consulta externa lo más recomendable en general es usar capitación, como se muestra en la Tabla 3.6.

3.5.3 *Análisis del error de contratación: Pruebas estadísticas preliminares*

Para el cumplimiento de las hipótesis estadísticas del ADM se deben satisfacer las siguientes condiciones:

Normalidad de las variables independientes: la prueba estadística utilizada es la de Kolmogorov-Smirnov. La hipótesis nula de normalidad de la variable es rechazada cuando la significancia es inferior a 0,05, lo que implica un 95% de confianza del test.

Correlación entre las variables explicativas: las pruebas estadísticas utilizadas corresponden a los coeficientes de correlación lineal de Pearson y Taub-Kendall, cuya Hipótesis nula es la de no correlación entre las variables, la cual es rechazada cuando la significancia es inferior a 0,05.

El grupo con menor cantidad de observaciones debe ser mayor al número de variables, la distribución de observaciones entre los grupos debe ser similar y debe haber *homogeneidad de varianzas* en las categorías o grupos de la variable dependiente, el estadístico utilizado es el de Levene el cual se rechaza a un nivel se significancia de 0,05, ante la hipótesis nula de igualdad en la homogeneidad de varianzas en los grupos de la variable. El último supuesto, siendo ésta la prueba más relevante, es el de igualdad de las matrices de covarianzas, el estadístico utilizado es el M de Box el cual se rechaza cuando la significancia es inferior a 0,05 ante hipótesis nula de igualdad entre las matrices de varianzas-covarianzas de los grupos. Los resultados de éstas pruebas se presentan a continuación.

Análisis de normalidad de las variables explicativas

La prueba de normalidad fue aplicada a los cuatro factores, sólo se rechazó la hipótesis nula de ajuste de los datos a una normal en la variable dificultades de medición, con un alpha de 0,009. Los resultados se presentan en la Tabla 3.7.

Tabla 3.7. Normalidad de los Factores

Variables	***Especificidad***	***Frecuencia del intercambio***	***Incertidumbre***	***Dificultad de Medición***
Significancia	0,856	0,518	0,157	0,009

Análisis de correlación entre las variables explicativas: Se utilizó el coeficiente de correlación de Pearson y Taúb-Kendall. Los resultados se presentan en la Tabla 3.8. Se encontró que en general hay baja correlación entre las variables del modelo. La correlación más alta se encuentra entre frecuencia y especificidad de las inversiones, lo que se pudo también analizar en el SMAA.

Tabla 3.8. Prueba de Correlación entre los Factores

Variables	***Especificidad***	***Frecuencia***	***Incertidumbre***	***Dificultades***
Especificidad	-	-0,296 (0,030)	0,041 (0,769)	-0,115 (0,416)
Frecuencia	-	-	0,091 (0,526)	-0,015 (0,920)
Incertidumbre	-	-	-	0,248 (0,099)
Dificultad	-	-	-	-

En paréntesis la significación estadística.

Análisis de homogeneidad de covarianza:

En la prueba de homogeneidad de varianza de Levene no se rechazó la hipótesis nula de homogeneidad de varianza en ninguna de las variables. Los resultados se presentan en la Tabla 3.9.

Tabla 3.9. Prueba de Homogeneidad de Varianza de las categorías de los Factores

Prueba de homogeneidad de la varianza	*Estadístico de Levene*	*Significación*
Especificidad	0,487	0,491
Frecuencia y duración del intercambio	0,094	0,762
Incertidumbre y complejidad	1,592	0,217
Dificultad de medición de la actuación	2,6	0,118

Tabla 3.10. Prueba de Homogeneidad de las matrices de Covarianza

M de Box		24,546
F	*Aprox.*	2,059
	Gl1	15
	Gl2	3,147,17
	Significación	0,024

El último supuesto a probar en el análisis discriminante tiene que ver con la prueba de igualdad de las matrices de covarianza; el estadístico M de Box rechazó la hipótesis nula de igualdad de las matrices de covarianza a un nivel de confianza del 95%. Es importante comentar la debilidad de la prueba ante la presencia de no normalidades en las variables y ante tamaños de muestras pequeños. No obstante, aún en este caso se posibilita continuar con la prueba debido a que como lo afirman Brown y Forsythe (1974) el nivel de significancia real suele ser mayor al sugerido. Los resultados se presentan en la Tabla 3.10.

3.5.4 Análisis Discriminante Múltiple –ADM-

El análisis discriminante fue utilizado para identificar la importancia de cada variable en la clasificación de las observaciones en los tipos de contratación contemplados. Hair et al. (1992), señalan tres pasos para la validación: i. determinar si la diferencia entre la media de los grupos, definida por las funciones discriminantes, es estadísticamente significativa; ii. examinar la precisión con que las funciones discriminantes clasifican las observaciones en los grupos; y, iii. examinar la contribución de las variables individuales en la discriminación.

Tabla 3.11. Pruebas de igualdad de las medias de los grupos

Pruebas de igualdad de las medias de los grupos	***F***	***gl1***	***Gl2***	***Sig.***
Especificidad de los servicios de salud	0,878	1	28	0,357
Frecuencia y duración del intercambio de servicios de salud	15,908	1	28	0,000
Incertidumbre y complejidad consulta externa	3,695	1	28	0,065
Dificultad de medición de la actuación consulta externa	0,474	1	28	0,497

El ADM evalúa la importancia relativa de las variables y la significancia estadística de la distancia entre la media de los grupos: la significancia de la diferencia entre la media de los grupos está dada por la prueba F de igualdad de las medias de los grupos, la hipótesis nula de la prueba establece la igualdad de la media de los grupos. En el paso siguiente, se analiza la contribución relativa de cada variable a la discriminación global del modelo, y posteriormente, se estudia la participación de las variables significativas en la diferenciación entre las dos categorías de contratación de la prestación de los servicios de consulta externa. Los resultados se ilustran en la Tabla 3.11.

Las variables que son estadísticamente significativas son: frecuencia del intercambio e incertidumbre, esto significa que la participación en la discriminación de las demás variables debe ser cuidadosamente analizado.

La contribución relativa de cada variable en el modelo se define a partir de los coeficientes discriminantes de las funciones incorporadas, los cuales se pueden ver en la Tabla 3.12. El primer resultado relevante es la identificación de las variables no significativas. Valores grandes de los coeficientes estandarizados presumen la importancia de la variable en la discriminación, sin embargo la importancia real de la variable solo puede estar justificada por el principio de parsimonia.

Tabla 3.12. Coeficientes estandarizados de las funciones discriminantes canónicas

Coeficientes estandarizados de las funciones discriminantes canónicas	***Función***
Especificidad de los servicios	-0,05
Frecuencia y duración del intercambio de servicios	0,921
Incertidumbre	0,536
Dificultad de medición de la actuación	0,121

Se presentan ponderaciones relativamente altas en la mayoría de las variables en la función discriminante, con la excepción de especificidad de las inversiones. Para profundizar en el análisis se estudia la matriz de estructura; esta matriz permite determinar el grado de correlación dentro de los grupos, entre las variables explicativas y la variable de estudio. Altos valores de los coeficientes suponen altas correlaciones de la variable con la función discriminante. Los resultados de la matriz de estructura se presentan en la Tabla 3.13.

Los análisis permiten confirmar la importancia de la variable de frecuencia del intercambio de servicios de salud y la poca importancia de la variable de especificidad y dificultades de medición. Estas dos últimas variables relacionadas con los costos de transacción no tienen capacidad de discriminación y por lo tanto no deben ser tenidas en cuenta.

Tabla 3.13. Coeficientes de Correlación de los Factores con la Función discriminante

Matriz de estructura	***Función***
Frecuencia y duración	0,825
Incertidumbre y complejidad consulta externa	0,398
Especificidad de los servicios	-0,194
Dificultad de medición de la actuación	0,142

Análisis posteriores se hacen necesarios para establecer la robustez de la función discriminante; la cual se da cuando se tienen autovalores altos, alta correlación canónica y valores pequeños del Lambda de Wilks; este último tiene asociado una prueba chi cuadrado a la hipótesis nula de no diferencia entre las medias de los grupos, la prueba es rechazada para valores de significancia inferiores a 0,1. Los resultados se presentan en la Tabla 3.14.

Tabla 3.14. Pruebas de Validación de la Función Discriminante

Autovalor	0,568	
Correlación canónica	0,602	
Lambda de Wilks	0,638	(0,000)

De esta información se concluye que la función discriminante es estadísticamente significativa. La correlación canónica indica que el 60,2% de la varianza de la variable dependiente es explicada por las variables frecuencia del intercambio y la variable incertidumbre. La prueba chi cuadrado rechazó la igualdad de las medias de los centroides de las dos formas de contratación de la prestación de los servicios de consulta externa a cualquier nivel de confianza.

Valoración de la precisión clasificatoria de las funciones discriminantes. El análisis discriminante permite determinar las observaciones del servicio de consulta externa que se clasifican de forma correcta. En 26 de los 30 casos se encontró una clasificación correcta de las observaciones, esto es un 86,2%. Para que la precisión clasificatoria sea aceptable debe ser un 25% mayor a la probabilidad proporcional [Hair et al. 1992], que para el caso es: 50% * 1,25 = 62,5%, por lo tanto el modelo tiene una adecuada capacidad de clasificar correctamente las observaciones de la población. La tabla 3.15 muestra la clasificación.

Tabla 3.15. Tabla de Clasificación

Resultados de la clasificación	***Forma de Contratación***	***Grupo de pertenencia pronosticado***		***Total***
		Capitación	Pago por servicio	
Recuento	*Capitación*	11	2	13
	Pago por servicios	2	15	17
%	*Contratación*	84,6	15,4	100%
	Pago por servicio	11,8	88,2	100%

El porcentaje de observaciones correctamente clasificadas -hit ratio- por las funciones discriminantes es del 86,7%, siendo bien clasificados el 84,6% de los casos de capitación y 88,2% de pago por servicio. Es importante resaltar la importancia de cada una de las dos variables consideradas por los tomadores de las decisiones; en este caso la discriminación es debida en un 76,7% a la variable de frecuencia del intercambio de servicios de salud, mientras que el restante 10% se le abona a la variable de incertidumbre en la prestación de los servicios, la cual aporta únicamente a la buena especificación de los casos de capitación.

3.6. Discusión de Resultados

El análisis discriminante múltiple muestra que las variables significativas en el modelo son la frecuencia del intercambio e incertidumbre en la transacción. Esto quiere decir que en la definición de la forma de gobernación de los servicios de consulta externa responde fundamentalmente a la reducción de costos de producción mediante el logro de economías de escala en la prestación del servicio de consulta externa. De forma adicional, la incertidumbre en los resultados de la consulta externa afecta la forma de gobernación de este tipo de servicios por parte de las EPS, y apoya a la toma de decisiones a favor de la capitación cuando se considera alta.

Las aseguradoras contratan la prestación de servicios de consulta externa con las IPS teniendo en cuenta el número de pacientes que remiten a cada institución. Cuando el número de pacientes es bajo se contrata por servicios y cuando el número es alto se hace mediante capitación. En estas circunstancias las IPS se ven forzadas a la reorganización de los servicios de consulta externa tratando de estandarizar procesos para permitir el logro de economías de escala y por lo tanto reducir los costos de prestación de los servicios de salud.

Otro resultado agregado relevante es que solo la incertidumbre en la transacción, como factor generador de costos de transacción, fue relevante en el modelo empírico. Esto significa que en la prestación de servicios de consulta externa, la decisión sobre la forma organizacional del intercambio está poco afectada por la existencia de costos de transacción. Sin duda existirán costos de transacción y serán diferentes en las dos formas de gobernación tenidas en cuenta en este estudio, pero no son tomados en cuenta en la decisión que se está analizando. La implicación de este hallazgo es que posiblemente en el intercambio de servicios de consulta externa se estén dando ineficiencias transaccionales por la preponderancia que se le da a los costos de operación en la prestación del servicio. Sobre este mismo aspecto, también cabe la posibilidad de que sea un cargo administrativo muy alto el de tipificar la consulta externa para imputar su costo a una determinada forma de contratación, no obstante a que los análisis favorezcan a la contratación por capitación.

Por otra parte, la especificidad de las inversiones, además de no ser estadísticamente significativo en la discriminación de las formas de gobernación muestra que el signo es contrario al planteado en la hipótesis. Esto puede estar mostrando que en la toma de decisiones sobre las formas de gobernación son poco importantes los factores asociados a los costos de transacción. Teniendo en cuenta éstos hallazgos se considera relevante profundizar sobre las variables transaccionales entre EPS e IPS en la prestación de servicios de consulta externa[10].

[10] Una consideración que posiblemente deba hacerse es diferenciar entre las actividades médicas y administrativas. Si se hace referencia a la variable especificidad, altos valores se encontrarán en los procesos administrativos y no médicos. Estos últimos podrían darse cuando alguna EPS tenga una población con ciertas características que impliquen de forma preferencial cierto tipo de tratamiento o de dolencias, como podría ser con la atención de pilotos de aviación.

Por último, posiblemente el establecimiento de mecanismos de comunicación y control característicos de las jerarquías en las prestación de servicios de consulta externa mediante formas capitadas se hace con el fin de soportar la prestación del servicio de salud y disponer de información que permita planear y ajustar actividades futuras, no para ejercer control de costos y del tipo de servicios que se prestan en cada una de las intervenciones. Esto porque la EPS, cuando compra de forma capitada lo que busca es precisamente reducir sus costos de auditoría.

3.7. Referencias

Albaum, G. (1997), The likert scale revisited: an alternative version. Journal of the Marketing Research Society 19(2) 331-348.

Alchian, A., Woodward, S. (1988), The firm is dead; long live the firm. A review of Oliver E. Williamson´s: The economic institutions of capitalism", Journal of Economic Literature 26 65-69.

Álvarez, B. Pellisé, L., Lobo, F. (2000), Sistemas de Pago a Prestadores de Servicios de Salud en Países de América Latina y de la OCDE. Revista Panamericana de Salud Pública 8 55-70.

Arrow, K. J. 1962. Economic Welfare and the Allocation of Resources for Invention, versión en castellano, Rosenberg, N. Economía del cambio tecnológico, México, Fondo de Cultura Económica, 1979.

Bana, C. (1986), A Multi-criteria Decision Aid Methodology to Deal With Conflicting Situations on the Weights. European Journal of Operational Research 26 22-34.

____ (1988), A Methodology for Sensitivity Analysis in Three Criteria Problems: A case study in municipal management. European Journal of Operational Research, 33: 159-173.

Barzel, Y. 1989. Economic Analysis of Property Rights, Cambridge uk, Cambridge University Press.

Brown, M.B., Forsythe, A.B. (1974), Robust Tests for the Equality of Variances Journal of the American Statistical Association, 69: 364-367.

Chi, T. 1994, Trading in Strategic Resources: Necessary Condition, Transaction Costs Problems And Choice Of Exchange Structure. Strategic Management Journal 15 (4) 271-290.

Churchill, G.A. (1979), A paradigm for developing better values of marketing constructs. Journal of Marketing Research 16 64-74.

Coase, R. H. (1937), The nature of the firm. Economica, November: 386-405.

Doty, D. H., Glick, W. H. (1994), Typologies as a Unique Form of Theory Building: Toward Improved Understanding and Modeling. Academy of Management Review 19 230-251.

Enthoven, A. C. 1997, The Market-based Reform of America`s Health Care Financing and Delivery System: Managed Care and Managed Competition. A Conference Sponsored by the World Bank March 10-11.

Erramilli, M.K., Rao, C. P. (1990), Choice of Foreign Market Entry Modes for Service Firms: Role of Market Knowledge. Management of International Review 30 135-150.

Gorbaneff, Y., Torres, S., Contreras, N. (2004), Anatomía de la Cadena de Prestación de Salud en Colombia en el Régimen Contributivo. Cuadernos de Administración 3(6) 88-106.

Gutiérrez, C., Molina, C. G., Wüllner, A. (1995), Las Formas de Contratación entre Prestadoras y Administradoras de Salud, Fedesarrollo, Bogotá.

Hair, J. F., Anderson, R. E., Tatham, R. L., Black, W. C. (1992), Multivariate Data Analysis, Prentice Hall, 4a Edición, New Jersey.

Hart, O. (1991), Incomplete Contracts and the Theory of the Firm. Williamson, Oliver, The Nature of the Firm, Oxford University Press, New York Oxford. 138-158.

Hage, J., Alter, C. (1997), A typology of interorganizational relationships and networks. Contemporary Capitalism: The embeddedness of institutions, J. R. Hollingsworth R. Boyer (Eds.), Cambridge University Press. 94-126.

Johnson, R., Wichern, D. (1999), Applied multivariate statistical analysis, Fourth Edition, Prentice Hall.

Johnson, R., Wichern, D. (1987), The Detection of Influential Observations for Allocation, Separation, and the Determination of Probabilities in a Bayesian Framework. Journal of Business and Economic Statistics 5(3) 369-381.

Kim, W. C. Hwang, P. (1992), Global Strategy and Multinationals Entry Mode Choice. Journal of International Business Studies 23: 29-53.

Kerlinger, F. N. (1986), Foundations of Behavioral Research, Harcout Brace College Publishers, 4a Edición, Fort Worth.

Lahdelma, R., Hokkanen, J., Salminen, P. (1997), SMAA–Stochastic multiobjetive acceptability analysis. European journal of operational research,106 137-143.

Lewin, A. Y., Volverda, H. W. (1999), Prolegomena on coevolution: A framework for research on strategy and new organizational forms. Organization Science 10(5) 519-534.

Li, P. (1998), Toward a Geocentric Framework of Organizational Form: A Holistic, Dynamic and Paradoxical Approach. Organization Studies 19 829-861.

Londoño, J. L., Frenk, J. (1997), Pluralismo Estructrurado: Hacia un Modelo Innovador para la Reforma de los Sistemas de Salud en América Latina, Banco Interamericano de Desarrollo. Documentos de Trabajo No. 353.

Lothia, R., Brooks, C. M., Krapfel, R. E. (1994), What constitutes a transaction specific asset?. Journal of Business Research 30 261-270.

Malagón, G. y Otros (1986), Administración Hospitalaria, Editorial Médica Panamericana, Bogotá, Colombia.

Mang, P. Y. (1994), The economic organization of innovation by R&D-Intensive firms: An empirical analysis of the biopharmaceutical industry, Doctoral Dissertation, Harvard University, Boston.

Milgrom, P., Roberts, J. (1993), Economía, organización y gestión de la empresa, Ariel Economía, Barcelona.

Molina, C. (1995), Las Formas de Contratación entre Prestadoras y Administradoras de Salud en el Nuevo Marco de Seguridad Social, Fundación Social, Bogotá.

Nunnally, J. C. (1978), Psycometric Theory, McGraw Hill, New York.

Pisano, G. P. (1988), Innovation through markets, hierarchies, and joint ventures: Technology strategy and collaborative arrangements in the biotechnology industry, Doctoral dissertation, University of California, Berkeley.

Porter, M., Fuller, M. B. (1986), Coalitions and global strategy. In Competition in global industries, Michael Porter (Ed.), 315-343.

Press, J., Wilson, S. (1978), Chosing Between Logit and Discriminant Analysis. Journal of Economic Literature 73 699-705.

Rencher, A. C. (1992), Interpretation of Canonical Discriminant Functions, Canonical Variates and Principal Components. The American Statistician 46 217-225.

Seshadri, S. (2005) Sourcing strategy. Estados Unidos. Springer

Teece, D. J. 1986. Profiting from Technological Innovation: Implications for Integration, Collaboration, Licensing and Public Policy. Research Policy 15 285-305.

Torres, S. (2003), Firm boundaries in the technological innovation chain: the machine-tool industry in the Basque Country. Management Research 2(1) 49-65.

____, Gorbaneff, Y., Contreras, N. (2004), Caracterización de las formas de gobernación del intercambio económico. Cuadernos de Administración 17(27) 63-86.

Steuer, R., (1986), Multiple Criteria Optimization: Theory, Computation, and applications, John Wiley and sons, New York.

Williamson, O. E. (1975), Markets and hierarchies, analysis and antitrusth implications, Free Press, New York.

____ (1985), The Economic institutions of capitalism, Free Press, New York.

____ (1991), Comparative economic organization: The analysis of discrete structural alternatives. Administrative Science Quarterly 36 269-296.

Apéndice B. Análisis de Aceptabilidad Multicriterio Estocástica –SMAA-

Notación:

Constantes:

m = Número de alternativas

n = Número de criterios

Índices:

$i \in \{1, 2, ...m\}$ índice para las alternativas.

$j \in \{1, 2, ...m\}$ índice para los criterios.

Otros símbolos:

g_{ij} = Valor del criterio j para la alternativa i

u_i = Utilidad total de la alternativa i

$u_j(g_{ij})$ = Función de utilidad del criterio j dentro del rango [0,1]

u_{ij} = Utilidad del criterio j para la alternativa i

w = Vector de pesos $[w_1 \ldots . w_n]$

w_j = Peso para el criterio j

w_i^b = Peso básico favorable para la alternativa i

w_i^c = Peso central del vector para la alternativa i

W = Conjunto de posibles vectores de peso

W_i = Conjunto de vectores de peso favorables para la alternativa i

Metodología:

La técnica se encuentra apoyada en el valor típico de cada criterio para cada alternativa (g_{ij}). A partir de dichas decisiones se calculan las funciones de utilidad de cada criterio j para cada alternativa i mapeándolas en el intervalo uniforme [0,1]. Se utilizará una función de utilidad aditiva -la cual no es restrictiva-, de tal manera que la utilidad total de la alternativa i será el resultado de la suma de los productos de las ponderaciones convexas factibles de cada criterio por la función de utilidad de cada criterio de la alternativa i. La descripción matemática se muestra a continuación:

$$u_{ij} = u_j(g_{ij})$$

$$u_i = \sum_j w_j u_{ij}, \qquad w \in W \tag{B.1}$$

$$W = \left\{ w \in R^*;\ w \geq 0 \wedge \sum_j w_j = 1 \right\}$$

Una alternativa será dominante cuando su función de utilidad supere a las funciones de utilidad de las alternativas competidoras. Dado que el espacio factible *W*, es un politopo convexo de dimensión (*n-1*), el problema de hallar una solución básica del conjunto de pesos favorables para la alternativa *i*, puede ser resuelto a partir de una formulación de programación lineal. Esta se representa a continuación:

$$\max 0$$

$$\sum_j w_j u_{ij} \geq \sum_j w_j u_{kj}, \quad k = 1,\ldots,m; k \neq 1$$

$$\sum_j w_j = 1 \tag{B.2}$$

$$w_j \geq 0$$

La solución del problema permite determinar si existe por lo menos un vector de pesos que hagan a la alternativa *i* dominante. Por razones de la convexidad del politopo el conjunto solución es una combinación convexa de sus vértices, lo cual se expresa a continuación:

$$w_i = \left\{ w \in R+ : w = \sum_b \alpha^b w_i^b \wedge \sum \alpha^b = 1 \wedge \alpha^b \geq 0 \right\} \tag{B.3}$$

Los rangos de los pesos es un factor importante para la toma de la decisión, ya que los pesos deben cumplir con algunas condiciones impuestas por la naturaleza del problema. Los rangos pueden ser eficientemente obtenidos a partir de la siguiente formulación:

$$\min(\max) w_j$$

$$\sum_j w_j u_{ij} \geq \sum_j w_j u_{kj}, \quad k = 1,\ldots,m; k \neq 1$$

$$\sum_j w_j = 1 \tag{B.4}$$

$$w_j \geq 0$$

Un resultado importante para la decisión final, es la determinación del índice de aceptabilidad para cada alternativa, el cual se encuentra definido como la probabilidad del volumen de los pesos de la alternativa en relación con el volumen de pesos factibles. Valores cercanos a cero de una alternativa, indica un bajo volumen de combinaciones de pesos factibles que hacen a la alternativa dominante. La representación matemática se expresa a continuación:

$$vol(W_i) = \int_{w_i} dw$$

$$a_i = \frac{vol(W_i)}{vol(W)} \tag{B.5}$$

Finalmente podemos argumentar que sin conocimiento a priori de las decisiones de los tomadores de la decisión, el vector de pesos central es la mejor representación de un decisor típico. Se define como el centro de gravedad del volumen factible de los pesos de la alternativa; como se expresa en la siguiente ecuación:

$$w_i^c = \frac{\int_{w_i} w\,dw}{\int_{w_i} dw} \tag{B.6}$$

CHAPTER FOUR

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Status: Accepted

Integral Analysis Method – IAM*

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Abstract:

This paper presents the theoretical foundations of the new Integral Analysis Method (IAM), and its application to a facility location problem. This methodology integrates the cardinal and ordinal criteria of combinatorial stochastic optimization problems in four stages: definition of the problem, cardinal analysis, ordinal analysis and integration analysis. The method uses concepts of Stochastic Multicriteria Acceptability Analysis (SMAA), Monte Carlo Simulation, Optimization Techniques and Elements of Probability. The proposed method (IAM) was used to determine optimal locations for the retail stores of a Colombian coffee marketing company.

***Key Words**:* Multiple Criteria Analysis; Multiple Objective Programming, Combinatorial Optimization; Simulation; Integral Analysis Method.

4.1. Introduction

Integral Analysis Methodology - IAM - is a decision-making technique that comes out as a response to the technical difficulties that emerge in considering cardinal and ordinal variables when they are both relevant to a stochastic optimization problem.

Just like previous techniques developed by the pioneer works of Bana e Costa, Hokkanen, Lahdelma, Miettinen, Salminen, Makkonen and Tervonen (1998-2007), Integral Analysis Methodology is used whenever it is impossible or inconvenient to determine *a priori* the importance of each of the variables that support the decision.

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This new methodology for decision-making problem solving is a combination of optimization techniques (i.e., mathematical programming, heuristics or simulation), SMAA techniques, probability elements, and the development of new concepts framed in the four phases proposed: definition of the problem, cardinal analysis, ordinal analysis and integration analysis.

IAM is based on the technical processing of variables depending on their particular type (ordinal or cardinal). It's indicators are expressed in homogeneous units that can be naturally integrated. The technique is particularly appropriate when the decision environment is characterized by randomness, and deterministic simplifications are not acceptable as possible solutions. In simpler contexts the problem can be solved by using more traditional approaches like optimization or SMAA-type techniques.

4.2. Background

The decision-making process of multicriteria methods is based on the selection of a set of alternatives by means of preference information provided by the decision-makers [Keeney and Raiffa, 1976]; [Saaty, 1980]; [Steuer, 1986]; [Zeleny, 1990]; [Vincke, 1992].

However, in public decision making environments, problems may arise when those who are responsible for the decision making process are unwilling or unable to openly express their preferences. In order to solve this problem, Bana e Costa (1986, 1988), introduced a procedure based on indicators that suggested the acceptance of a single alternative when the decision is supported on three variables. Later on, and based upon the above mentioned work, Lahdelma, Hokkanen, Salminen, Miettinen and Tervonen (1998-2007)[12] furtherly developed the methodology in various ways: they initially generalized it into a multi-dimensional space [Lahdelma, et al., 1998], and then, depending on the nature of each alternative's matrix of variable values, they presented

[12] These methodologies are here referred to as Stochastic Multiobjective Acceptability Analysis (SMAA).

more sophisticated treatment mechanisms, such as different versions of SMAA for imprecise data [Miettinen and Salminen, 1999] and stochastic data values [Lahdelma, et al., 1998]. In turn, SMAA-O applies for mixed cardinal and ordinal data values [Lahdelma, et al., 1999] and is currently capable of treating missing and imprecise preference information as well [Lahdelma, et al., 2003]. Other works include Gaussian criteria [Lahdelma, et al., 2006], cross confidence factors [Lahdelma and Salminen, 2006a], SMAA-D, which has been developed for Data Envelopment models [Lahdelma and Salminen, 2006b] and SMAA implementation techniques [Tervonen and Lahdelma, 2007]. Finally, cardinal and ordinal data can well be dealt with in the new approach to multi criteria decision methods called Dominance-based Rough Set Approach [Greco, et al., 2001, 2005], [Slowinski, et al., 2005].

One of the possible limitations of multiobjective decision-making techniques arises when not all the ranking values are of the same kind. For example, if the prevailing type is that of ordinal values, the cardinal variables must be expressed in ordinal terms.

On the other hand, in spite of the evident advantages of optimization techniques in providing optimal solutions to different problems, they do not allow the inclusion of relevant variables that cannot be expressed in terms of their objectives, and must then be ignored. In such context, IAM was developed with the purpose of gathering and taking advantage of the most relevant features of the mentioned techniques.

4.3. The Process of IAM

The two types of variables (ordinal and cardinal) inherent to many optimization problems have a manifest operational complexity resulting from the metric and epistemological difficulties that hinder their integration. This difficulty reduces the possibility of finding well-designed solutions, and allows the use of more-relaxed approximations. The conflict that arises when dealing with ordinal and cardinal variables at the same time can be caused by:

- The impossibility to express ordinal variables that are relevant to the ‘optimal’ solution of the problem, in cardinal terms (that is, regarding the objective goals). In this case, such variables are not included and cannot be integrated in the optimization technique that supports the decision.

- The relaxation of cardinal variables as a result of transformations (for example, of the ordinal type). In this case, important information contained in the variable is lost and validity problems arise due to the categorization procedure.

Mathematical techniques such as simulation and optimization are commonly used when the inclusion of the ordinal variables involved in the problem is considered irrelevant, or when such variables cannot be taken into account due to either information or implementation restrictions.

On the other hand, some multiobjective decision-making techniques fall into the second type of inadequate specification, since they show difficulties in the treatment of causality, and in the finding of suitable solutions to optimize the relevant objectives.

Due to the technical and practical impossibility that arises in homogenizing ordinal aspects in cardinal terms, optimization techniques often resort to the relaxation of many aspects that are relevant to the problem, therefore providing sub- optimal solutions.

IAM actually aims to overcome the obstacles that arise with some methodologies that do not include all the relevant variables of a stochastic problem because they are not adequately expressed in terms of their objective performance valuation. This methodology provides the technical means that allow relevant ordinal variables to be taken into account, therefore attaining closer to reality solutions.

This methodology comprises four steps: Definition of the Problem, Cardinal Analysis, Ordinal Analysis, and Integration Analysis; which are now explained in more detail:

4.3.1. Definition of the Problem.

At this stage, both the type of problem (cardinal and/or ordinal) and its stochastic or deterministic nature are established, and so are the objective(s), variables and performance constraints for the selected models, together with their solving techniques. Several reliable information collecting mechanisms are necessary to determine the parameters, together with adequate procedures to estimate them, so that they correspond to the models in use.

This is the most sensitive step of IAM in terms of consistency, due to methodological difficulties and restrictions in the information sources. At this point, Delphi techniques may help to create an atmosphere where agreements between the parties involved in the project can take place.

4.3.2. Cardinal Analysis.

In a combinatorial problem, if the number of binary decision variables α is an unrestricted and known quantity, it could entail up to 2^{α} solving possibilities (also called alternatives). Only then are the characteristics of the cardinal solution analyzed.

Sets and constants

F: Alternatives set

N(*): Number of states of the set *

m: Number of selected alternatives and cardinal rankings associated with them, where $m \leq 2\alpha$

Other Symbols

$z(i)$: Cardinal ranking for alternative i

Φ_k: Binary variable, where $\Phi_k \in \{0, 1\}$

e^i: Binary variable vector for alternative i, where $e^i = \{\Phi 1, \Phi_{2,\ldots} \Phi_m\}$.

$p(e^i)$: Joint cardinal probability distribution for alternative i

$p(\Phi_k)$: Marginal cardinal probability distribution for variable k

h_i : Random variable for alternative i

$g(h_i)$: Probability density function for alternative i

E^i: Expected cardinal value for alternative i

σ_i^2 : Variance cardinal value for alternative i

E: Overall central cardinal value

σ^2: Overall dispersion cardinal value

In order to deal with the stochastic nature of the parameters employed in optimization techniques, a Monte Carlo simulation is applied. The mathematical optimization model is executed as many times as necessary until the results can be estimated with sufficient precision. As a result of the Monte Carlo simulation, the joint cardinal probability distribution is obtained.

The marginal cardinal probability distribution can be easily calculated from the joint cardinal probability distribution, as follows:

$$P(\phi_k = 1) = \sum_{i=1}^{m} p(e^i) \quad \forall k \tag{4.1}$$

The joint cardinal probability distribution mentioned above depends on the interaction between the probability functions of the random variables of the problem's parameters. At this stage of the solution of the problem, a set F, constituted by the m selected alternatives of interest to be analyzed by the DMs (which correspond to the number of associated cardinal rankings), comes out as a result of the process. A possible selection procedure consists in removing of the analysis those alternatives with very low probability of occurrence. The prevailing alternatives will be studied later, in the ordinal and integration analysis stages.

On the other hand, the cardinal ranking of each alternative will depend on its probability of occurrence; the higher the latter, the lower the former.

The objective function value associated to an alternative solution is a continuous random variable h_i with an associated density $g(h_i)$. The expected cardinal value and the variance cardinal value of each of the selected alternatives are computed as follows:

$$E^i = \int_{-\infty}^{\infty} h_i g(h_i) dh_i \quad \forall i$$

$$E^i = \int_{-\infty}^{\infty} (h_i - E^i)^2 g(h_i) dh_i \quad \forall i$$

(4.2)

Finally, and based upon the expected cardinal values of the alternatives, the overall central value and the dispersion cardinal value are obtained.

$$E = \sum_{i=1}^{m} E^i p(e^i)$$

$$\sigma^2 = \sum_{i=1}^{m} (E^i - E) p(e^i)$$

(4.3)

4.3.3. Ordinal Analysis.

The ordinal analysis is based on Stochastic Multiobjective Acceptability Analysis with ordinal data (SMAA-O) and is restricted to the *m* alternatives resulting from the cardinal analysis. This phase is particularly complex because of the difficulties that usually arise when defining the matrix of typical relative values that will be used as input for SMAA-O. The utility of each alternative solution is a function of the particular utilities of all its ordinal variables.

The SMAA-O method allows working with both ordinal and cardinal criteria. Although widely used, this procedure has the following undesirable feature:

- Risk of distorting the information contained in the cardinal variable as a result of the transformation. When using this method, it is necessary to subordinate the number of categories of each cardinal variable to the number of ordinal variables. In addition, a new problem arises when trying to define the categories of the cardinal variables because the usefulness of the categories of the ordinal and cardinal variables is far from being homogeneous. This happens because the exclusive values of the categories of both types of variables are not equally useful. Therefore, decision-making under these conditions can be imprecise and inadequate.

When working with preference information, Likert Tables are used to convert particular aspects into ordinal variables [Albaum, 1997]. According to IAM, the use of SMAA-O is restricted to ordinal variables.

Each of the original binary variables of an optimization problem usually has several ordinal associated variables that are defined by the decision makers. These variables will be used to characterize the ordinal analysis, but before explaining the method it is necessary to define the concept of class as a set of alternatives that have identical utilities for all the associated ordinal variables.

The particular features of SMAA-O concerning its use by IAM will now be explained in more detail [Lahdelma, et al., 2003] and [Lahdelma, et al., 2002]:

Indexes, sets and constants:

r : Ordinal ranking, where: $r \in \{1, 2, ...N(r)\}$ and $N(r) \leq m$.

s: Class number, where $s \leq m$

A: Class set, where each class $a \in \{1,2,...,s\}$

$F(a)$: Alternatives concerning class a

C: Ordinal ranking

C_i: Ordinal ranking for alternative i

n: Number of ordinal variables

Other Symbols:

X_{aj} : Ordinal criteria values of ordinal variable j for class a

w_j : Weights vector of ordinal variable j

$u_j(X_{aj})$: Mapping of ordinal criteria values of variable j for class a

γ_{jr} : Random number taken from a [0,1] uniform distribution

ε_{aj} : Stochastic cardinal values of criterion ordinal variable j in class a)

W_a^r : Set of favourable weights in ordinal ranking r for class a:

W: Set of non-negative normalized weights

b_a^r : Ordinal acceptability index for class a

b_i^r : Ordinal acceptability index for alternative i

c^i: Number of ordinal rankings of alternative i

R^i : Ordinal ranking central value for alternative i

V^i: Deviation value of the ordinal ranking for alternative i

The ordinal analysis is based on determining the utility values that support each class. The utility function can be additive, as in the following case:

$$u(X_a, w) = \sum_{j=1}^{n} w_j u_j(X_{aj}) \tag{4.4}$$

The process starts by generating random numbers out of a uniformly distributed [0, 1] interval and sorting them along with 1 and 0 in decreasing order, as shown below:

$$\gamma_{j1} > \gamma_{j2>.......}\gamma_{jj^{\max}}, \textit{ where: } \gamma_{j1} = 1, \gamma_{jj^{\max}} = 0, \textit{ and } \gamma_{jk} \leftarrow U(0,1), \quad k = 2,3,..,j^{\max} - 1 \tag{4.5}$$

Such procedure ranks these random numbers just as in previous works [Miettinen et.al. 1999; Lahdelma et al., 2002]. The distinctness of γ_{jr} can be ensured by rejecting sets containing identical values. On the other hand j^{max} refers to the maximum number of different rank categories of possible solutions for each of the selected variables.

These numbers are used as a sample of stochastic cardinal values of criterion ordinal variable j in class a (ε_{aj}), so that for each class a, the corresponding value is equal to γ_{jr}; thus:

$$u_j(X_{aj}) = \varepsilon_{aj} \tag{4.6}$$

where the elements of $\varepsilon \in X$ are distributed according to $f(\varepsilon)$: $X = \{\varepsilon \longrightarrow f(\varepsilon)\}$, being ($X$) the set of stochastic cardinal utilities. All stochastic cardinal assignments must comply with the following requirements in order to find the weight sets:

$$\varepsilon_{aj} = \gamma_{jr}, \quad r = X_{aj} \tag{4.7}$$

Thus, the accepted stochastic cardinal values and convex weights will be those that conform to the ordinal ranking of the alternative. In order to make sure that each alternative is assigned an adequate ranking, the (alternatives') utility functions are compared by means of the following function:

$$\boldsymbol{rank}\ (\varepsilon_a, w) = 1 + \sum_{k=1}^{s} \rho(\varepsilon_k w > \varepsilon_a, w), \textit{ where: } \rho(true) = 1,\ \rho(false) = 0 \tag{4.8}$$

Here each alternative is ranked from 1 to s. The ranking function's objective is to obtain the set of feasible variable weights associated to each ranking, by assigning cardinal utilities. The process is mathematically represented as follows:

$$W_a^r(\varepsilon) = \{w \in W\text{: } \boldsymbol{rank}\ (\varepsilon_a, w) = r\}$$

$$W = \left\{ w \in R^n : w \geq 0, \quad \sum_{j=1}^{n} w_j = 1 \right\} \tag{4.9}$$

Finally, the ordinal acceptability index, which assesses the variation between different values under ranking r in class a, is calculated through a multidimensional integral over the criteria distributions and the favourable rank weights:

$$b_r^a = \int_X f(\varepsilon) \int_{w_a^r(\varepsilon)} f(w)\, dw\, d\varepsilon \tag{4.10}$$

Each of the alternatives' ordinal ranking can be easily obtained by assigning them to the ordinal ranking that corresponds to the class to which they belong, so that

$$b_r^i = b_r^a \Leftrightarrow i \in F(a) \tag{4.11}$$

Decision making in this ordinal context consists in setting an agreement that is based on the particular features of the feasible weights and the acceptability indexes; the latter support the ordinal ranking of each alternative.

Thus, as a result of the cardinal modelling process, a set *F* of optimal possible solutions for the combinatorial problem is obtained. This set is made up of *m* alternatives that constitute the input of the ordinal analysis, as a result of which, a set of ordinal rankings (C_i) associated to each alternative is also obtained.

$$C_i \in \{1,2,..,s\}, \textit{where: } N(C_i) = c_i \leq m \tag{4.12}$$

The number of ordinal rankings for each alternative is lower or equal to *m*, because there may be some alternatives with zero ordinal acceptability indexes for some ordinal rankings. Finally, the number of ordinal rankings for the set (*C*) of alternatives is given by:

$$N(C) = \sum_{i=1}^{m} c_i, \quad where: s \leq N(C) \leq m^2 \tag{4.13}$$

For each alternative, the ordinal ranking central value and its associated (ordinal ranking) deviation value are given by:

$$R^{i} = \sum_{r=1}^{m} r b_{r}^{i}$$

$$V^{i} = \sum_{r=1}^{m} (r - R^{i})^{2} b_{r}^{i} \tag{4.14}$$

It is important to point out that these two values respectively correspond to the ordinal ranking expected value and the ordinal ranking variance value, for the class to which the alternative belongs.

4.3.4. Integration Analysis.

The cardinal and ordinal analyses help to determine a set of results that significantly support the decision making process. At the same time, these results are the input of the integration procedure that provides the indicators which are going to facilitate the analysis of the problem in a broader context.

An important methodological consideration is the selection of the number of both types of rankings. As it was previously mentioned, removing low probability alternatives may be an appropriate procedure to limit the number of cardinal solutions. Moreover, the class concept allows the grouping of the selected alternatives, thus reducing the complexity of the ordinal analysis. On the other hand, the number of ordinal rankings that were used in the integration stage may be restricted to the first ranking in most practical cases. However, decision makers are the ultimate responsibles for the definition of the problem size in its different analysis stages. The integration ranking of each alternative is conditioned by the ordinal analysis ranking because each optimal cardinal solution may have a different ordinal ranking status. The integration analysis is presented as follows:

The joint integral index is defined as: $p_r(e^i)$

This value provides an integral assessment of each alternative's ordinal ranking. If the two values (ordinal and cardinal) are independent, it can be calculated as:

$$p_r(e^i) = p(e^i) b_r^i \tag{4.15}$$

The input of the deterministic SMAA [Lahdelma, et al., 1998] applied to complete the integral analysis stage of IAM is a utility matrix composed of *m* alternatives and two result variables (cardinal and ordinal) Thus, the process is simplified and the central weight vectors of two dimensions and two ranges of favourable weights that complement each other are obtained, as well as the integral acceptability indexes for each alternative.

The SMAA discussed in this paper has been transformed in accordance with the IAM proposal.

Indexes and sets:

O_r^i: Integral ranking in ordinal ranking *r* for alternative *i*, where $i \in \{1, 2, ...m\}$, and $r \in \{1, 2, ...m\}$

O_r : Integral ranking in ordinal ranking *r*, where $r \in \{1, 2, ...m\}$

Other symbols:

$u^{i,r}$: Overall utility in ordinal ranking *r* for alternative *i*.

$p(e^i)$: Utility of cardinal result variable for alternative *i*

b_r^i : Utility of result ordinal variable in ranking *r* for alternative *i*.

W_r: Set of feasible weight vectors $[wp^r, wq^r]$ in ordinal ranking *r*.

w_r^j : Weight of result variable *j* in ranking *r*

$w_r^{i,b}$: Basic favourable weight vectors in ordinal ranking *r* for alternative *i*.

$w_o^{i,r,c}$: Central weight vector of integral ranking *o* in ordinal ranking *r* for alternative *i*.

W_r^i : Set of favourable weight vectors in ordinal ranking *r* for alternative *i*.

$d_o^{i,r}$: Integral acceptability index *o* in ordinal ranking *r* for alternative *i*.

o_r^i : Number of integral states in ordinal ranking r for alternative i.

$p_r(e^i)$: Joint integral index in ordinal ranking r for alternative i.

The overall utility of each alternative is based on the typical relative values of its result (that is, the utility of cardinal and ordinal result variables). An additive utility function will be used, so that the overall utility of each alternative will be the result of adding the products of the feasible convex weight of each variable and its associated utility. The following is the mathematical description:

$$
\begin{aligned}
&u_r^i = w_r^p\, p(e^i) + w_r^q b_r^i, \qquad w \in W, \quad r \in R \\
&W_r = \left\{ w_r \in R^2, \quad w_r \geq 0, \quad w_r^p + w_r^q = 1 \right\}
\end{aligned}
\tag{4.16}
$$

The set of favourable weight vectors W_r is a one-dimensional simplex in the bi-dimensional weight space. An alternative is dominant when its utility surpasses those of all other alternatives. The problem of finding a set of basic favourable weights for integral ranking o is solved for each ordinal ranking r by means of the following LP:

$$
\begin{aligned}
&Max \quad 0 \\
&subject\ to: \\
&w_r^p\, p(e^i) + w_r^q b_r^i \geq w_r^p\, p(e^h) + w_r^q b_r^h \quad h = 1,2,..m,\ h \neq i \\
&w_r^p + w_r^q = 1 \\
&w_r^j \geq 0 \quad j \in \{p, q\}
\end{aligned}
\tag{4.17}
$$

The set of basic favourable weights w_r^i is a convex polytope that can be represented as a convex combination of its vertices:

$$
w_r^i = \left\{ w_r \in R^+: \quad w_r = \sum_b \alpha_r^b w_r^{i,b}, \quad \sum_b \alpha_r^b = 1, \quad \alpha_r^b \geq 0 \right\}
\tag{4.18}
$$

The set of basic favourable weights for each result variable constitutes an important element in the decision making process, since it must comply with the conditions imposed by the nature of the problem. These sets can be efficiently obtained for each ordinal ranking r from the solution of the following LP:

$$
\begin{aligned}
& \min(\max) \quad w_r^j \\
& subject \quad to \\
& w_r^p\, p(e^i) + w_r^q b_r^i \geq w_r^p\, p(e^h) + w_r^q b_r^h \quad h = 1,2,..m, \quad h \neq i \\
& w_r^p + w_r^q = 1 \\
& w_r^j \geq 0 \quad j \in \{p,q\}
\end{aligned}
\tag{4.19}
$$

The integral acceptability indexes for each alternative in ordinal ranking *r* are defined as the ratio between the alternative's weight volume and feasible weight volume, both in that same ranking; which gives the alternative an integration ranking *o*. A low integral acceptability value *o* (close to zero) for an alternative in any ordinal ranking *r* implies a low number of favourable weight combinations, which makes this (alternative) the dominant one. The following is the mathematical representation:

$$
\begin{aligned}
& vol\left(W_o^{i,r}\right) = \int_{w_r^i} dw_r \\
& d_o^{i,r} = \frac{vol\left(W_o^{i,r}\right)}{vol\left(W_r^i\right)} \quad vol\left(W_r^i\right) > 0
\end{aligned}
\tag{4.20}
$$

Finally, it can be stated that without any prior knowledge of the decision makers' expertise, the central weight vector is the best representation of a typically non biased decision maker. The central weight vector in ordinal ranking *r* for integral ranking *o*, is defined as the center of gravity of the polytope:

$$
w_o^{i,r,c} = \frac{\int_{w_r^i} w\,dw}{\int_{w_r^i} dw}
\tag{4.21}
$$

The set of integral rankings in ordinal ranking *r* for each alternative *i* (O_r^i), is given by the following states: $O_r^i \in \{1, 2,.., m\}$; which is made up of o_r^i states:

$$
N(O_r^i) = o_r^i \leq m
\tag{4.22}
$$

Therefore, the integration set in a particular ranking O_r is presented as the union of sets O_r^i:

$$O_r = \bigcup_{i=1}^{m} O_r^i, \quad where: N(O_r) \leq m^2$$

(4.23)

Since the integral ranking of each alternative is associated to the analyzed ordinal ranking, different integral sets are created. The number of states resulting from such integration for an alternative *i,* is:

$$N(O^i) \leq m^2$$

(4.24)

4.4. Practical application of IAM

4.4.1 Definition of the problem

The location of logistic facilities is a key strategic factor for a supply chain's performance, not only because short and medium term investments are at stake, but also because the peculiar dynamics of the short term operational costs that emerge once these facilities have been bought or built, are also affected.

In so far, the mathematical programming models that have been used to support strategic decision-making in supply chains have mainly focused on the optimization of financial performance values [Beamon, 1998]. On the other hand, the most relevant aspects considered there are associated to activities like procurement, distribution, and location-capacities-logistic specialization of production plants and distribution centers [Geoffrion and Powers, 1995], [Vidal and Goetschalckx, 1997; 2000], [Sha and Che, 2006]. Other solution approaches to the facility location problem have been proposed by Figueiredo and Guimaraes (2003) and Lahdelma et al., (2002). The former proposed a statistical procedure resorting to logistic and Poisson regressions. Even though this technique allows the inclusion of ordinal aspects in a context of multiple facility locations, it does not allow the optimization of the financial goals of the problem. The second approach proposed a solution to the problem of locating several solid waste treatment plants by using SMAA-O.

The ongoing study case was carried out on OMA S.A., a Colombian company that purchases and roasts high-quality whole bean coffees and sells them along with a variety of pastries through its retail stores. One of OMA's key success factors is related to retail stores location. This problem is treated in this paper.

After the first stage of IAM, the decision supporting managerial considerations ascertained that the choice of an optimum facility location is linked to certain cost and revenue constraints. These constraints are in turn related to the way the overall income is affected by the overall cost and the overall rent. Some other relevant constraints are: stochastic demand, facility average depreciation cost, and fixed average cost of operating the facility in the selected location. Finally, procurement was not considered restrictive.

Given that the unitary deterministic profit of each product was not available, the unitary stochastic income minus the stochastic unitary cost per economic transaction was used as a valid approximation. In order to obtain this stochastic profit parameter, and due to the impossibility to establish its real probability function, its maximum and minimum bounds were determined, therefore allowing to consider it as a uniform random variable between them.

The following are the variables that were impossible to express in cardinal objective terms (considered as ordinal variables in the context of IAM): visibility, distance to the point of reference, and facility size. These ordinal variables were defined according to the business policies and the company's client profile. The results obtained for each selected location can be observed in Table 4.1:

Table 4.1: Parameters and other symbols of the facilities location problem

k	Visibility	Distance	Size	Ownership Cost (US$)	Capacity (persons)	Demand (transactions)[13]
1	1	2	2	188	12144	N(4313, 431.3)
2	2	3	2	971	18480	N(7410, 741)
3	2	1	2	792	2 24151	N(5706, 570.6)
4	1	1	3	530	26009	N(1520,152)
5	2	1	2	468	20944	N(6033, 603.3)
6	1	1	1	360	29920	N(27770, 2777)
7	1	1	1	562	36920	N(25262, 2526.2)
8	2	1	3	168	14960	N(484, 48.4)
9	1	2	2	919	25960	N(5460, 546)

From: [García et al., 2004].

Table 4.2 shows the other stochastic parameters.

Table 4.2: Stochastic cost parameters

Parameter	Adaptation Costs (US$)	Cost/Transaction (US$)	Income/Transaction (US$)
Minimum	6550	0.6	1.0
Maximum	952	0.7	1.1

From: [García et al., 2004].

4.4.2 Cardinal Analysis

A new combinatorial mathematical program issuing several relevant features for domestic supply chains [Geoffrion and Graves, 1974], [Geoffrion and Powers, 1995] was used to model the problem, applying the following mathematical notation

Constants and indexes:

P: Maximum number of permissible locations

M: Minimum permissible income

N: Number of available locations

Parameters:

B_t : Capacity at facility location t

$D_t(\xi)$: Stochastic demand at location t

π : Overall cost / overall income *(percentage)*

---

[13] N(a,b) to denote the normal distribution with mean a and variance b.

Θ : Overall ownership / overall income (percentage)

Costs and revenues:

$u_t(\xi)$: Stochastic income at location t per transaction

F_t : Facility adaptation cost at location t

E_t: Facility ownership cost at location t

$\lambda_t(\xi)$: Stochastic cost at location t per transaction

Variables:

Y_t = Binary variable: 1 if facility t is open, and 0 otherwise.

Objective Function:

$$\text{Max} \quad \sum_{t=1}^{\mathrm{P}} (u_t(\xi) - \lambda_t(\xi)) D_t(\xi) Y_t - \sum_{t=1}^{P} F_t Y_t - \sum_{t=1}^{P} E_t Y_t \tag{4.25}$$

Constraints:

Overall cost vs Overall income expression:

$$\pi \sum_{t=1}^{P} u_t(\xi) D_t(\xi) Y_t \geq \sum_{i=1}^{P} \lambda_t(\xi) D_t(\xi) Y_t + \sum_{i=1}^{P} (F_t + E_t) Y_t \tag{4.26}$$

Rent costs vs Overall income expression:

$$\theta \sum_{t=1}^{P} u_t(\xi) D_t(\xi) Y_t \geq \sum_{t=1}^{P} \lambda_t(\xi) D_t(\xi) Y_t + \sum_{t=1}^{P} E_t Y_t \tag{4.27}$$

Income expression:

$$\sum_{t=1}^{P} u_t(\xi) D_t(\xi) Y_t \geq M \tag{4.28}$$

Capacity expression:

$$D_t(\xi)Y_t \leq B_t \qquad t \in N \tag{4.29}$$

Expression for number of facilities:

$$1 \leq \sum_{t=1}^{P} Y_t \leq P \tag{4.30}$$

The model was executed 100.000 times in a GAMS optimization software package, which corresponds to a 95% level of confidence and 10% error sample, thus guaranteeing an adequate estimation of the joint probability distribution (see Table 4.3).

Table 4.3: joint cardinal distribution of probability

Alternative	Considered Facilities	Frequency	Probability
1	1-2-3-5-7	2200	0,022
2	1-2-3-6-7	800	0,008
3	1-2-3-7-9	200	0,002
4	1-2-5-6-7	6200	0,062
5	1-2-5-7-9	200	0,002
6	1-3-5-6-7	700	0,007
7	1-5-6-7-9	100	0,001
8	2-3-5-6-7	55200	0,552
9	2-3-5-7-9	4100	0,041
10	2-3-6-7-8	100	0,001
11	2-3-6-7-9	5100	0,051
12	2-5-6-7-9	24300	0,243
13	3-5-6-7-9	700	0,007
14	3-5-9-7-9	100	0,001

The input of the marginal probability mass calculation was the joint probability distribution per alternative, as shown in Table 4.4

Table 4.4: marginal cardinal distribution of probability

i	1	2	3	4	5	6	7	8	9
$P(\Phi_k=1)$	0,104	0,984	0,692	0	0,938	0,932	1	0,001	0,341

The marginal probability distribution discarded location 4 and showed alternatives 7, 2, 5 and 6 as the most favored options, in order to focus on which, a Pareto analysis was carried out on over 80% of the solutions, including those showing an occurrence of more than 1%. Thus, 6 solutions were analyzed and their probability readjusted as follows (see Table 4.5).

Table 4.5: Adjusted joint probability distribution

i	*Z(i)*	Included Facilities: (e^i)	Frequency	Probability: $P(e^i)$
1	6	1-2-3-5-7	2200	0,02265705
2	3	1-2-5-6-7	6200	0,0638517
3	1	2-3-5-6-7	55200	0,5684861
4	5	2-3-5-7-9	4100	0,04222451
5	4	2-3-6-7-9	5100	0,05252317
6	2	2-5-6-7-9	24300	0,25025747

In order to determine the density function of each alternative, a Kolmogorov-Smirnov's a statistic test of goodness of fit was applied with a 95% confidence level using SPSS and Crystal Ball. Each alternative's density distribution was adjusted to a Gaussian function in most of the cases, except for solutions 3 and 4, which did not follow any theoretical probabilistic model. In these two cases, the sample average was used as a valid estimator of the corresponding expected values. The expected objective value and the standard deviation for each solution were estimated. The results can be seen in Table 4.6.

Table 4.6: Expected cardinal values and deviation cardinal values

iI	1:1-2-3-5-7	2:1-2-5-6-7	3:2-3-5-6-7
p-value	0.99	0.435	0.00
E^i (US\$)	48970	72757	72030
Deviation (σ^i) US\$	3510	3452	6132
I	4:2-3-5-7-9	5:2-3-6-7-9	6:2-5-6-7-9
p-value	0.00	0.991	0.879
E^i (US\$)	62194	71071	72008
Deviation (σ^i) (US\$)	12565	3883	4166

Finally, the overall cardinal values specified by IAM are shown in Table 4.7

Table 4.7: Expected overall value of the objective and
Overall deviation value of the objective for the location problem

E (US$)	71077
Deviation (σ) (US$)	8243

4.4.3 Ordinal analysis

The ordinal variables associated to each location were provided by the decision makers (see Table 4.1).

In order to calculate each alternative's categorical variable ordinal value, its location ordinal criteria values were added and then classified according to the three categories specified in the following Likert Table [Albaum, 1997].

Table 4.8: Likert Table

Criteria	Ordinal value
If it sums < 7.5	1
If 7.5 ≤ sums < 12.5	2
If it sums ≥ 12.5	3

As already mentioned, the ordinal analysis is based on SMAA-O, whose inputs are the preferential ordinal values obtained from Table 4.8, and here presented in Table 4.9, where it can be seen how ordinal variable 3 (size) is the same for all alternatives. Therefore this variable was not considered in the analysis. Table 4.9 also includes the ordinal acceptability indexes for each alternative.

Table 4.9: Ordinal values associated to each class and Ordinal acceptability indexes

a	$F(a)$	j =1	j = 2	j =3	b_r^i	R=1	r=2	r=3
1	{1 , 4}	2	2	2	i= 1, 4	0	0	1
2	{2 , 5 , 6}	1	2	2	i = 2, 5, 6	0.5	0.5	0
3	{3}	2	1	2	i =3	0.5	0.5	0

The ordinal acceptability index (result variable of the ordinal type) shows that alternatives 3, 2, 5, and 6, are dominant. Thus, the choice will depend on the importance given to both visibility and distance variables: if $w_1 > w_2$, then alternatives 2-5-6 will beat alternative 3. On the other hand, alternatives 1 and 4 display a lower performance when compared to those mentioned before, and are therefore ranked third if w_1 and w_2 are different; otherwise, they are ranked second.

IAM enables us to calculate joint indicators in order to appropriately evaluate each alternative. The ordinal ranking central values for each class were defined within the indicators established by this methodology during the integral analysis stage, therefore allowing to see how the dominant alternatives (2, 3, 5 and 6) were positioned between rankings 1 and 2, while options 1 and 4 were in the third ranking.

Table 4.10: Ordinal ranking central values

i	1	2	3	4	5	6
R^i	3	1,5	1,5	3	1,5	1,5

4.4.4. Integration analysis

In this stage of the process, IAM considers the joint integral index, which is the acceptability fraction of each alternative on a specific ordinal ranking. Table 4.11 shows the joint probability values:

Table 4.11: Joint integral indexes

$p_r(e^i)$	r=1	r=2	r=3
I =1: {1-2-3-5-7}	0	0	0.023
I =2: {1-2-5-6-7}	0.032	0.032	0
I =3: {2-3-5-6-7}	0.284	0.284	0
I =4: {2-3-5-7-9}	0	0	0.042
I =5: {2-5-6-7-9}	0.0265	0.0265	0
i =6: { 2-5-6-7-9}	0.125	0.125	0

Since each ordinal ranking can be seen in context, the number of integration analyses to be performed depends on the particular needs of the problem. In this case, the analysis was applied to ordinal ranking 1, as it was the only one that proved to be of interest for the decision makers.

The integration analysis stage is based on the result variables, which are shown in Table 4.12.

Table 4.12: Cardinal and ordinal result variables

i	1	2	3	4	5	6
$p(e^i)$	0.023	0.064	0.568	0.042	0.053	0.25
b_1^i	0	0.5	0.5	0	0.5	0.5

The central weight vector analysis is carried out for the first integral ranking. On average, the weights of the cardinal and ordinal variables of alternative 3 ($w_1^{3,1,c}$) are both 0.5, a fact that implies that, regardless of which weight values support the two result variables, alternative 3 will always be dominant. In addition, there are no possible weight combinations (cardinal and ordinal) capable of highlighting any other alternative as a dominant one in the integral analysis for the first ordinal ranking, with the exception of w_q =1, where the cardinal nature of the problem is not considered.

Table 4.13: Integral acceptability indexes in ordinal ranking 1

$d_o^{i,1}$	$o = 1$	$o = 2$	$o = 3$	$o = 4$	$o = 5$	$o = 6$
$i = 1$	0	0	0	0	0	1
$i = 2$	0	0	1	0	0	0
$i = 3$	1	0	0	0	0	0
$i = 4$	0	0	0	0	1	0
$i = 5$	0	0	0	1	0	0
$i = 6$	0	1	0	0	0	0

In the present case, given the particular features of the information contained in the result variables, the integration analysis leads to a "trivial" determination of the integration ranking for the alternatives in the studied ordinal ranking. The results are shown in Table 4.13. Finally, the set of feasible weight vectors for the first ordinal ranking was calculated as presented in Table 4.14.

Table 4.14: Favourable weight ranges in ordinal ranking 1

w_1^j	w_1^p	w_1^q
REF MAX	1	1
REF MIN	0	0

The indicators supplied by IAM allowed establishing that alternative 3 was the most feasible and useful one, since it presents the best values for the two result variables (cardinal and ordinal).

The results demonstrated the significant advantages of IAM in the decision making process. This method allowed the company to express and properly use its expertise in an orderly and technical way.

4.5. Conclusions

IAM was conceived to deal with problems that have a significant complexity, due to the necessity of including aspects that cannot be quantified in the objective function of the combinatorial problems.

IAM is carried out in four stages: the first one establishes the type of problem (cardinal and/or ordinal) and its stochastic or deterministic nature. In the second stage the alternatives are selected considering optimization criteria and variability of the cardinal variables, an analysis in which Monte Carlo Simulation and probability elements are employed as optimization techniques. In the third stage, the alternatives are further analyzed by means of SMAA-O and probability elements. In the final stage the alternatives are analyzed again in both ordinal and cardinal aspects using a transformed version of deterministic SMAA and probability elements. Conclusions are finally drawn from the indicators obtained in the three last stages.

The technique allows a deeper analysis of the problem, as far as it provides multiple indicators that describe the ordinal and cardinal information concerning each of the alternatives. It must be pointed, however, that in applying IAM to practical cases, the number of a study's alternatives needs to be restricted as to make the technique applicable.

As for the future, three areas of possible further research can be recognized: in the first place, reliability and validity of a more general methodology that enables researchers to define the problem and determine the relevance of variables and data collection processes. In the second place, the identification of new indicators that strengthen the methodology; and last, the application of the methodology on other optimization problems in a more general context than the one considered in this article.

4.6. References

Albaum, G. (1997), The Likert scale revisited: an alternative version. Journal of the Market Research Society 39 (2) 331-348.

Bana E Costa, C.A. (1986), A multicriteria decision-aid methodology to deal with conflicting situations on the weights. European Journal of Operational Research 26 22-34.

Bana E Costa, C.A. (1988), A methodology for sensitivity analysis in three-criteria problems: A case study in municipal management, European Journal of Operational Research 33 159-173.

Beamon, B.M. (1998), Supply chain design and analysis: models and methods, International Journal of Production Economics 55(3) 281-294.

Birge, J.R. Quasi-Monte Carlo methods for option evaluation. Technical Report, Department of Industrial and Operations Engineering, University of Michigan (Ann Arbor, MI), 1994.

Birge, J.R., Louveaux, F.V. Introduction to Stochastic Programming. Springer-Verlag, New York, 1997.

Brown, P.A., Gibson, D.F. (1972), A quantified model for facility site selection applied to a multipoint location problem. AIIE Transactions 4 1-10.

Churchill, G.A. (1979), A paradigm for developing better values of marketing constructs. Journal of Marketing Research 16 64-74.

David, H.A. Order Statistics. Wiley, New York; 1970.

Durbach, I. (2006), A simulation-based test of stochastic multicriteria acceptability analysis using achievement functions. European Journal of Operational Research 170(3) 923-934.

Dyer, J.S. Remarks on the Analytical Hierarchy Process. Management Science 1990; 3; 249-258.

Figueiredo, O., Guimaraes, P. (2003), A tractable approach to the firm location decision problem. The Review of Economics and Statistics, Cambridge 85(1) 201-204.

García, R.G., Aráoz, J.A., Palacios, F. (2005a), The integral analysis method. Reports of the Departament d'EIO. Sección Informática, Universitad Politécnica Catalunya DR, 07.

García, R.G., Caro, M.P., Díaz, H., Sánchez, L.L., Carrillo, M.H. (2004), Metodología marco de referencia para la localización de instalaciones, Ingeniería y Universidad 8(2) 139-157.

García, R.G., Palacios, F., Aráoz, J.A. (2005b), Implementation of the integral analysis method in strategic supply chain. Reports of the Departament d'EIO. Secció Informática, Universitad Politécnica Catalunya DR, 08.

Geoffrion, A.M., Graves, G. (1974), Multicommodity distribution system design by Benders decomposition, Management Science 20(5) 822- 844.

Geoffrion, A.M., Power, R.F. (1995), Twenty years of strategic distribution system design: An evolutionary perspective. (Implementation in OR/MS: An evolutionary view). Interfaces 25(5) 105-128.

Greco, S., Matarazzo, B., Slowinski, R. (2001), Rough sets theory for multicriteria decision analysis. European Journal of Operational Research 129(1) 1-47.

Greco, S., Matarazzo, B., Slowinski, R. 2005. Decision rule approach. Chapter 13 [in]: J.Figueira, S.Greco and M.Ehrgott (eds.), Multiple Criteria Decision Analysis: State of the Art Surveys, Springer-Verlag, New York; 2005. p. 507-562.

Hokkanen, J., Lahdelma, R., Miettinen, K., Salminen, P. (1998) Determining the implementation order of a general plan by using a Multicriteria Method. Journal of Multi-Criteria Decision Analysis 7 273-284.

Hokkanen, J., Lahdelma, R., Salminen, P. (1999), A multiple criteria decisions model for analyzing and choosing among different development patterns for the Helsinki Cargo Harbor, Socio-Economic Planning Sciences 33 1-23.

Hokkanen, J., Lahdelma, R., Salminen, P. (2000), Multicriteria decision support in a technology competition for cleaning polluted soil in Helsinki. Journal of Environmental Management 60(4) 339-348.

Kall, P., Wallace, S.W. Stochastic Programming. John Wiley & Sons, New York; 1994.

Keeney, R.L., Raiffa, H. Decisions with Multiple Objectives: Preferences and Value Tradeoffs. Wiley, New York; 1976.

Khumawala, B.M. (1972), An efficient branch and Bound Algorithm for the warehouse location problem. Management Science 18 718-732.

Lahdelma, R., Hokkanen, J., Salminen, P. (1998), SMAA - Stochastic Multiobjective Acceptability Analysis. European Journal of Operational Research 106(1) 137-143.

Lahdelma, R., Makkonen, S., Salminen, P. (2006), Multivariate Gaussian criteria in SMAA. European Journal of Operational Research 170(3) 957-970.

Lahdelma, R., Miettinen, K., Salminen, P. (2003), Ordinal criteria in Stochastic multicriteria acceptability analysis. European Journal of Operational Research 147 117-127.

Lahdelma, R., Salminen, P. (2001), SMAA- 2: Stochastic multicriteria acceptability analysis for group decision making. Operations Research 49(3) 444-454.

Lahdelma, R., Salminen, P. (2006a), Classifying alternatives in SMAA using cross confidence factors. European Journal of Operational Research 170(1) 228-240.

Lahdelma, R., Salminen P. (2006b), Stochastic multicriteria acceptability analysis using the data envelopment model. European Journal of Operational Research 170(1) 241-252.

Lahdelma, R., Salminen, P., Hokkanen, J. (2002), Locating a waste treatment facility by using stochastic multicriteria acceptability analysis with ordinal criteria. European Journal of Operational Research 142 345-356.

Martin, R.K. Large Scale Linear and Integer Optimization: A unified approach. Kluwer Academic Publishers, Boston; 1999.

Miettinen, K., Salminen, P. (1999), Decision – aid for discrete multiple criteria decision making problems with imprecise data. European Journal of Operational Research 119 50-60.

Pooley, J. (1994) Integrated production and distribution facility planning at Ault Foods. Interfaces 24(4) 113-121.

Rietveld, P. Multiple Objective Decision Methods and Regional Planning. Studies in Regional Science and Urban Economics; Volume 7, North Holland Publishing Company. North-Holland, Amsterdam; 1980.

Rietveld, P., Ouwersloot, H. (1992), Ordinal data in multicriteria decision making, a stochastic dominance approach to sitting nuclear power plants. European Journal of Operational Research 56(2) 249-262.

Saaty, T.L. The Analytic Hierarchy Process. McGraw-Hill, New York; 1980.

Schrijver, A. Theory of Linear and Integer Programming. Wiley, New York; 1986.

Slowinski, R., Greco, S., Matarazzo, B. 2005. Rough set based decision support. Chapter 16 [in]: E.K. Burke and G. Kendall (eds.), Search Methodologies: Introductory Tutorials in Optimization and Decision Support Techniques, Springer-Verlag, New York; 2005. p. 475-527.

Steuer, R. Multiple Criteria Optimization: Theory, Computation and applications. Wiley, New York; 1986.

Tervonen T., Lahdelma R. (2007), Implementing Stochastic Multicriteria Acceptability Analysis. European Journal of Operational Research 178(2) 500-513.

Torres, S., García, R.G., Quintero, J. (2005), Formas de CONTRATACIÓN de los servicios de urgencias: una APROXIMACIÓN desde la economía de los costos de transacción. Economía Institucional 7(12) 97-127.

Vidal C.J., Goetschalckx M. (1997), Strategic production-distribution models: A critical review with emphasis on global supply chain models. European Journal of Operational Research 98 1-18.

Vidal, C.J., Goetschalckx, M. (2000), Modeling the effect of uncertainties on global logistics systems. Journal of Business Logistics 21(1) 95-120.

Vincke, Ph. Multicriteria Decision –Aid. Wiley, New York; 1992.

Watson, S.R., Buede, D.M. Decision Synthesis: The principles and practice of decision analysis. Cambridge University Press; 1987.

Zeleny, M. Multiple Decision Making. McGraw-Hill, New York; 1982.

INTRODUCTION REFERENCES

Aikens , C.H. (1985), Facility location models for distribution planning. European Journal of Operational Research 22 263-279.

Artz, K.W., Norman, P.M.. (2002), Buyer-supplier contracting: contract choice and ex-post negotiation costs. Journal of Managerial Issues 14(4) 399-417.

Bhatnagar, R., Chandra, P., Goyal, S.K. (1993), Models for multi-plant coordination. European Journal of Operational Research 67 141-160.

Beamon, B.M. (1998), Supply chain design and analysis: models and methods. International Journal of Production Economics 55(3) 281-294.

Brennan, C.D. (1998), Integrating the healthcare supply chain. Healthcare Financial Management 52 (1) 31-34.

Coase, R. H. (1937), The nature of the firm. Económica 4 (16) 386-405.

Cohen, M.A., Lee, H.L. (1988), Strategic analysis of integrated production-distribution systems: Models and methods. Operations Research 36 216-228.

Dwyer, F.R., Schurr, P., Oh, S. (1987), Developing buyer-seller relationships. Journal of Marketing 51 (2) 11-27

Geoffrion, A.M., Power, R.F. (1995), Twenty years of strategic distribution system design: An evolutionary perspective. (Implementation in OR/MS: An evolutionary view). Interfaces 25(5) 105-128.

Giannakis, M., Croom. S. (2004), Toward the development of a supply chain management paradigm: a conceptual framework. Journal of Supply Chain Management 40 (2) 27-37.

Goetschalckx M., Vidal C.J., Dogan K. (2002), Modeling and design of global logistic system: A review of integrated strategic and tactical models and design algorithms. European Journal of Operational Research 143 (1) 1-18.

Grover, V., Malhotra, M.K. (2003), Transaction cost framework in operations and supply Chain management research – Theory and measurement. Journal of Operations Management 21 (4), 457-473.

Gu, Q. Multiple-period Supply Chain Contract Modeling with Dynamic Stochastic and Price-elastic Demand. Doctoral Dissertation. Florida Atlantic University, Boca Raton 2001.

Harrison, T.P., Hau, L.L., Neale, J.J., (Eds.). The Practice of Supply Chain Management: Where Theory and Application Converge. Kluwer Academic Publishing, Boston, 2003.

Heide, J.B. (1994), Interorganizational governance in marketing channels. Journal of Marketing 58 (1) 71-85.

Johnson, J.C., Wood, D.F., Wardlow, P.R., Murphy, Jr. Contemporary Logistics. Simon and Schuster, New York, 1999.

Kim, K., Frazier, G.L. (1996), A typology of distribution channel system: a contextual approach. International Marketing Review 13 (1) 19-32.

Lambert, D. M., Cooper, M.C., Pagh, J.D. (1998), Supply chain management: implementation issues and research opportunities. The international Journal of Logistics 9 (2) 1-19.

Lambert, D.M, García-Dastugue, S., Croxton, K.L. (2005), An evaluation of process-oriented supply chain management frameworks. Journal of business Logistics 26 (1) 25-51.

Lummus, R.R., Vokurka, R.J. (1999), Defining supply chain management: a historical perspective and practical guidelines. Industrial Management & Data Systems 99 (1) 11-17.

McKone-Sweet, K., Hamilton, P., Willis, S. (2005), The ailing healthcare supply Chain: a prescription for change. Journal of Supply Chain Management 40 (1) 4-17.

Moriarty, R.T., Moran, U. (1990), Managing hybrid marketing systems. Harvard Business Review 68 (Nov.-Dec.) 146-155.

O'Toole, T., Donaldson. B. (2000), Managing buyer-supplier relationships archetypes. Irish Marketing Review 13 (1) 12-20.

Palay, T.M. Comparative institutional economics: the governance of rail Freight contracting. Journal of Legal Studies 1984; 13 (June): 265-288.

Paulraj, S.C. A. Towards a unified theory in supply chain management: critical constructs and their effect on performance. Bussiness Administration Doctoral dissertation. Cleveland State University, Cleveland, 2002.

Porter, M.E. (1987), Managing value – from competitive advantage to corporate strategy. Harvard Business Review 65 (3) 43-60.

Prahalad, C.K., Hamel, G. (1990), The core competence of the corporation. Harvard Business Review (May-June); 79-91.

Quinn, F. J. (1997), What's the buzz?. Logistics Management 36 (2) 43-46.

Shapiro, J.F. (2001), Modelling the Supply Chain. Duxbury Thomson Learning Inc., Pacific Grove (CA).

Shin, H., Collier, D., Wilson, D.D. (2000), Supply management orientation and supplier/buyer performance. Journal of Operations Management 18(3) 317-333.

Tan, K.C. (2001), A framework of supply chain management literature. European Journal of Purchasing and Supply Management 7 (1) 39-48.

Thomas D., Griffin, M.C. (1996), Coordinate supply chain management. European Journal of Operational Research 94 1-15.

Tsay, A.A., Nahmias, S., Agrawal, N. Modeling Supply Chain Contracts: A Review, Quantitative Modelling for Supply Chain Management. Kluwer Academic Publishers, Norwell (MA); 1999.

Vidal C.J., Goetschalckx M. (1997), Strategic production-distribution models: A critical review with emphasis on global supply chain models. European Journal of Operational Research 98 1-18.

Weng, Z.K. (1995), Modeling quantity discounts under general price–sensitive demand functions: Optimal policies and relationships. European Journal of Operational Research 86 (2) 300-314.

Williamson, O.E. Markets and hierarchies; analysis and antitrusth implications. New York; 1975

_______________. The Economic institutions of capitalism. New York; 1985.

_______________(1991), Comparative economic organization: The analysis of discrete structural alternatives. Administrative Science Quarterly 36 (2) 269-296.

_______________(1993), Calculativeness; trust and economic organization. Journal of Law and Economics 36 (2) 453-486.