

Dealing with uncertainty in modern supply chains: vulnerability and risk management

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Abstract

The financial crisis has clearly shown the vulnerability of our global economy. New innovative tools are therefore needed to improve supply chain management thus contributing to recover from the economy slowdown. In this work we have developed a stochastic model for the automotive supply chain, dealing with uncertainty, and supporting strategic and tactical decision-making. This model takes into account the concepts of vulnerability and risk management. The model considers extreme uncertainties that may lead to serious disruptions of the supply chain.

Keywords: Supply chain management, Uncertainty, Risk, Automotive supply chain.

Introduction

The 2008 financial crisis was viewed by many economists as the worst financial crisis since the Great Depression of the 1930s. It rapidly developed and spread into a global economic shock, resulting in a number of European bank failures, declines in various stock indices, and large reductions in the market value of equities and commodities. The global financial crisis caused strong and deep contractions of many economies. Around the world we could witness a strong decline in industrial production, a record in the unemployment rate, political instability, increased emigration rates, an increase in oil prices, and a significant deterioration of living standards. This complex chain of effects has clearly shown how vulnerable our society is.

In this context, industrial organizations set their efforts more and more on the control and reduction of costs, not only as a way to fight a growing market competition but also to overcome the problems posed by the current global economic and financial crisis. The automobile is one of the most affected industrial sectors, facing a decrease in the sales of vehicles and an increase of the prices of oil and steel. The economy slowdown has contributed to a profound restructuring in this sector, as a way to react to the considerable fluctuations in sales (decrease of the automotive demand) and consequently to a higher pressure in all automotive supply chain partners. To go on being competitive, automotive companies need to improve their own networks and the way they relate with the market, to promote innovation (viewed as a critical success factor), and to invest

in activities planning and in supply chain opportunities. It is therefore fundamental for companies to be able to systematically assess and (re-)design production and distribution systems, as well as their strategies, in order to provide the desired customer service level at the lowest possible cost (Goetschalckx et al. 2002).

Consequently supply chain management can play a prominent role in the automotive industry, with the need to improve systems already in place or to design and implement new systems. More recent research is related with decisions on the allocation of products to plants, plant sizing (capacity), strategic planning processes, and investments on new facilities or on capacity expansion and supply chain design.

In this industry supply chain design strongly depends on the dynamics of markets that lead to high levels of uncertainty (risk management). This aspect has been often neglected in the literature. There is a few models related with automotive supply chain networks and basically they are all deterministic, not giving the right attention to uncertainty factors.

The main objective of our work is fulfilling this gap by proposing a model that explicitly considers the risk directly associated with uncertainty factors. The developed stochastic model takes into account the specific features of the global modern automotive supply chain and it aims at supporting strategic and tactical decision-making. Our work also approaches two types of uncertainties – extreme and typical.

The Automotive Industry: modern supply chains

In an industrial competitive environment characterized by the need to recover, along with strong changes and competition, companies need to adopt principles of the so-called modern Supply Chains. These are characterized by globalization (dimension of network), increased use of outsourcing, reduction of the supplier base (single sourcing), leanness (e.g., reduced buffers, lead times, and lot sizes), focus on customer, increase demand for just-in-time deliveries in shorter time windows/lead times, agility, shorter product life cycles and a huge number of partners. Given this complexity modern supply chains tend naturally to be more vulnerable.

In the automotive industry supply chains can be significantly more complex than usually, due to their hierarchical structure, organized around an upstream planning system, and working top-down from the OEM to his suppliers. There is another characteristic that increases complexity – the worldwide locations (global supplying and sales regions). Companies need therefore to pay attention to several “international” issues with a strong impact on multinational networks (e.g., exchange rates, income taxes). These elements may significantly increase the uncertainty associated with demand, and consequently the risk exposure.

The automotive industry is a globalized industry characterized by high precision and advanced technologies, a high degree of integration, a product development cycle between 3 and 4 years (from idea to market), a production with hundreds of suppliers from different types of industries (e.g., plastics, metal, petrochemical, rubber), products with thousands of components of different dimensions, high complexity, and a wide range of technologies. Moreover the players in this sector have to take into account, not only customer requirements, but also government regulations about safety and environment, possible incentives to investments, the pressure for modernization and for green innovations. Their future in the industry is determined by the ability to adapt and to change operations with minimum damage in time, cost, resources and performance, in other words, by the way the system reacts to uncertainty – risk management.

Separately, some of these characteristics are common to other sectors, as for example aeronautics and electronics, but the specificity of the automotive industry comes from the

cohabitation of all of them in the same sector.

Nevertheless, there are some specific, distinctive characteristics of this industry: firms are extremely concentrated, with a rather small number of giant companies (Sturgeon et al., 2009); there are strong regional-scale structure patterns of integration, leading to the existence of “clusters” (Jaklic et al., 2005); only a few generic parts or subsystems can be used in end products (vehicle models) without extensive customization (Sturgeon et al., 2009).

These specific features of the automotive industry raise some interesting, challenging issues that motivated this research and the definition of a specific case study in this sector.

Literature Review

For the problem under analysis we have identified a set of associated key concepts, and have studied the main relations between those concepts. Probably more important than the way a supply chain works and evolves, are the concepts related with these processes and all the involved dynamics, such as uncertainties, vulnerabilities and risk exposure. Moreover, we explore similar problems, models and solution methods that differ in various dimensions, such as the number of periods in the planning horizon, types of uncertainty, objectives, decision variables, and so on. For supply chain design, we have seen in the last decade, a considerable development of deterministic models that are becoming more and more comprehensive and detailed. More recently, and in an attempt to bring more reality into their models, researchers have included parameters for uncertainty, mainly related to demand. Additionally, some recent natural catastrophes around the world that have provoked serious disruptions in supply chains showed the vulnerability of modern supply chains, with important negative operational and financial impacts.

Time Scope of the Models

Based on the number of time periods of the planning horizon, a decision model can be classified as static or dynamic. Static models are single-period models, adequate for decisions about the immediate re-optimization of parts of the supply chain, such as issues on the location of advanced warehouses and distribution centers (Tsiakis et al., 2001). Graves and Jordan (1995) proposed a single-period production-planning model that minimizes the amount of demand that cannot be addressed by the supply chain, the focus being on process flexibility measured by expected sales and capacity utilization for one period.

However, dynamic or multi-period models are appropriate when the consideration of a long planning horizon, divided into several equal periods, is required. For example when there are decisions on the timing of an investment, dynamic or multi-period models are appropriate.

Uncertainty

A global supply chain network involves several countries and consequently it becomes fundamental to take into account various factors related to internationalization, such as tariffs, income tax legislation, transfer prices, government policies, trade barriers and competition. Some of these factors may significantly increase the uncertainty in a supply chain network, but other frequent parameters of uncertainty are product demand, raw material prices, costs (energy, labor, production and transportation costs) and lead times. Klibi et al. (2010) argue that “extreme” events, such as natural disasters or terrorist attacks, should also be taken into account as uncertainty.

The main uncertainty factors identified in the literature are related with demand, supply,

resource capacity, production costs, exchange rates, transportation (lead times and costs), duties, prices (product and raw-material), and extreme events.

Uncertainty in the demand is the most often considered factor, but in many papers it is not the only one. Usually, models include 2 or 3 uncertainty parameters, with uncertainties related to costs being also frequent in mathematical models. More recently Klibi et al. (2010) introduced the importance of considering extreme and catastrophic events as an uncertainty, and they have shown their impact in running supply chains.

It is obvious that uncertainty cannot be eliminated, but by using more comprehensive models, we can minimize its effect in supply chain performance.

Flexibility

To adapt quickly and efficiently to changes in the environment, many companies have invested in increasing the flexibility of their supply chains. “Flexibility” here is viewed as the ability to adapt, to change or to transform, with minimum damage in time, cost, resources and performance - in other words, how well does the system react to uncertainty (Mersechmann et al., 2011). So Supply Chain Flexibility could be defined as the ability to accommodate volume and schedule fluctuations from suppliers, manufacturers and customers. This is a vital component of Supply Chain success and defines how well the system reacts to uncertainty.

Beamon (1999) recognized some important advantages in flexible supply chain systems, for example: reductions in the number of lost sales and late orders, increased customer satisfaction, ability to respond and to accommodate demand variations (seasonality) and new products, new markets, or new competitors. In our approach, flexibility allows the system to react to “typical” uncertainties that “shake” the normal running of the supply chain but do not provoke a disruption or other long term problems or consequences.

Joshi (1998) identified “real time visibility as one of the crucial factors for efficient supply chain management”. In fact companies have an increased need for updated, correct information from the product supply chain network, this requiring a stronger coordination between all network members. Increased visibility over the global network can be critical for some key partners in the processes (in particular for first tier suppliers). And there is a global need for higher levels of flexibility and for fast response to unexpected events or changes in the demand. Cooperation and collaboration with suppliers are also vital to deal with uncertainty and directly influence the organization capability to be flexible.

In fact supply chain flexibility enables a company to respond more quickly to changes in the supply and in the demand. It is however essential to balance the benefits and the costs of flexibility and to be aware of how much flexibility is really needed.

Risk Management and Resilience

Risk Management deals with quite different types of risk that can be: internal to the company (process, control), external to the company but internal to the supply chain (demand, supply) and external to the network (environmental).

Creating a *resilient* supply chain is naturally a way to manage risks, but increasing resilience in a network requires high levels of collaboration (with higher levels of visibility between chain members), responsiveness, agility, creation of a risk management culture in the organization and efficient design.

In the corporative world resilience is associated with the ability of a company to bounce back from a large disruption. This includes for instance, the speed with which it returns to

normal performance levels. So a resilient organization is able to successfully confront the unforeseen, to return to its original state or move to a new, more desirable state after being disturbed. This means a higher capability to deal with disruptions and managing risks, and to be more flexible and adaptable.

Recently we have been confronted with several examples of strong disruptions of supply chains with a strong negative impact in companies and in the economy, sometimes not only where those disruptions have happened but affecting many members of entire supply chains or even several supply chains. These events had been growing in frequency and impact. For example, the Japanese earthquakes of 2012 (resulting in a catastrophic tsunami), the Philips NV fire of 2000 (Nokia and Ericsson reaction to the disruption), the 9/11 terrorist attacks, the Katrina hurricane in 2005, the Icelandic volcanic eruption of 2010. These catastrophes have disrupted supply chains around the world requiring the development of innovative recovery strategies.

Risk management can provide firms with significant competitive advantages. It may involve moving production among plants, interchangeable and generic parts in many products, cross-train employees, using concurrent processes of products development, ramp up and production/distribution, designing products and processes for maximum postponement of as many operations and decisions as possible in the supply chain, or aligning their procurement strategy with their supplier relationships. Developing collaborative relationships with suppliers that are closely associated with a company will in general make those suppliers more likely to be loyal allies during a crisis. But the failure of any of these suppliers can have a catastrophic effect. In a big network we should concentrate our attention in the distribution of risk along supply chain members – *risk sharing*.

Opportunities for Research

The main goal of our research was to develop a model for the automotive supply chain, to deal with (typical and extreme) uncertainties, taking into account risk and the chain vulnerabilities.

Most of the few models found in the literature for this industrial sector are of a deterministic nature, thus neglecting uncertainty. In this work we aim at extending those models to explicitly consider uncertainties, and to develop a stochastic approach to global automotive supply chain networks, that support strategic/tactical decision-making. Other characteristics should also be considered in these models, namely: multiple periods (to model impacts of changes in the future), multiple objective functions (to tackle the trade-offs between costs and customer service level), international parameters (as legislation), etc.

Some strategic decisions can be episodic. For example, a OEM is opening a new facility and wants us (first tier supplier) to build a collocated supplying plant. We need to understand how to integrate our investments and operations with his supply network, and how this interacts or conflicts with the conditions of our previous contractual agreements.

This model should be able to support decision-making for a yearly operations strategy planning, helping us understand how the supply chain network might evolve in a long-term horizon, to optimize the profitability of operations. For this purpose, the model must be able to: define different scenarios for the future evolution of supply, demand, transportation and other critical elements of the supply chain network; analyze relevant new investment alternatives (opening or closing factories, increasing or decreasing capacity, opening or closing warehouses); simulate and optimize investment decisions in time; or perform sensitivity analysis to understand under which conditions different investment alternatives might become more attractive. In line with these concerns, we have defined the scope of our research project as shown in figure 1.

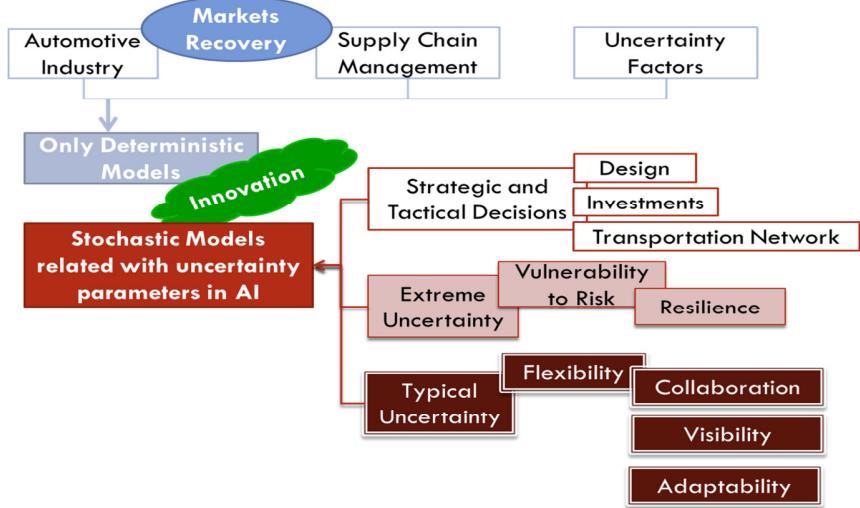


Figure 1: Research map

Mathematical Model

In an attempt to fill the above identified gaps, we have been working in a stochastic model for the automotive supply chain network, designed to help and support organizations in taking strategic-tactical decisions. To support this research we have established a partnership with an industrial company in the sector, that provides us data, guidelines, and the main user requirements. Comparing and merging the industrial and the literature inputs, allowed us to define the components to be included in the model.

The model should be able to support decision-making concerning network design, investments and transportation. Additionally, to model the stochastic components of the problem, we had to identify the main uncertainty factors in this industrial sector.

Observing and analyzing the daily operation of the pilot company, as well as the procedures they use for strategic and tactical decision-making, we have identified inflation as the current main uncertainty, in terms of market sustainability. Another uncertainty factor is related to the exchange rates, due to the globalization of automotive companies and to the fact that several countries and their currencies need to be considered. Nevertheless, in our case study the impact is low due to the “euro normalization” during contract celebration. The impact of the energy price (mostly electricity) is also broadly recognized, so we need to consider this price as one uncertainty factor with a strong impact in practice. Nowadays, the electricity production sector is being restructured following the liberalization of some national markets (e.g., Spain). New sources of electricity generation (e.g., solar, wind), and incentives to own generation and tax policies also play an important role. Finally, the oil price is also a key uncertainty. However in general, when it goes up, it influences all different actors and factors in a similar way (raw materials and transportation costs). So, theoretically, in general if a country is currently competitive because it offers a low price for the transportation and raw-materials costs, we expect it to be competitive in the future.

To illustrate our general approach, and taking into account the case study requirements, we have simply investigated the impact of inflation as an uncertainty factor. However, in this work we are basically concerned with the possible different values and evolution of the inflation

rate, for different zones in Europe (e.g., Eastern Europe, Central Europe, and the Iberian Peninsula) and not for the European Union as a whole.

In a first stage we have developed a “base model” dealing with the possible different values and evolution of the inflation rate. This was a first attempt to assess and validate an approach to be extended to a second model capable of dealing with other decisions and uncertainty factors, simultaneously (Brent costs and extreme events).

Problem Description

In previous stages of the research we have used some simplified problems directly motivated by a first version of the case study. Afterwards, we have modeled a second version with 4 possible extensions to the base model (Model 1). These extensions are as follows: 1) to allow changes in the stock capacity in (own or outsourced) warehouses and the production capacity of each plant; 2) to study the possibility of opening new infrastructures (plants or warehouses); 3) and 4) to consider uncertainty parameters (extreme events and Brent cost fluctuations).

We have separately considered the different extensions and a global model integrating those extensions (Model 2). Test instances have been created with specific data collected in our real case study. Model 2 is a multi-period, multi-objective (minimization of cost, maximization of potential new business), bi-stage decision (strategic level decisions, tactical level decisions). Stochasticity is modeled by a decision tree approach based on the definition of scenarios.

Figure 2 shows the design process followed during the development of this model.

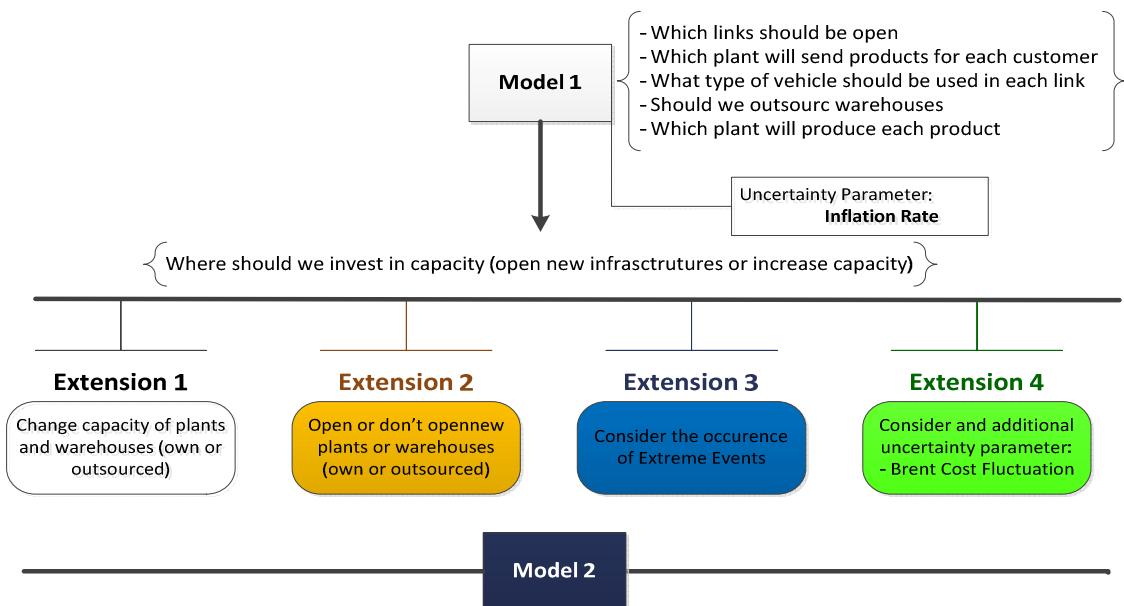


Figure 2: Scope of models and extensions

Let us assume a company has a supply chain with suppliers (r), customers (c), advanced warehouses (w), plants (with own warehousing and production) (l), potential locations for opening new advanced warehouses (h), finished products (p) and raw-materials (m). Suppliers (r) are companies that can send raw materials and/or components to warehouses or directly to the plants. Warehouses (w) are all storage units that are not located at the production units (plants), so they can be advanced warehouses or distribution centers. These entities can receive materials

(m) from suppliers and send finished products (p) to customers. For this reason they are duplicated in this model. Warehouses are always linked to plants (they send raw materials/components and they receive finished products). Plants (l) are all units of production (they convert raw materials/components into finished products) that belong to the supply chain under study. In these plants we also find (internal) warehouses for raw materials and finished products.

Customers (c) are the final entities in the supply chain. They receive finished products from plants and/or warehouses. Materials (m) are raw-materials, components, sub-components used in the production process of finished products. Products (p) are finished products sent to customers. The potential locations (h) are “suggestions” for new locations possibly to be included in the current supply chain. A new location could be a distribution center/warehouse closer to the customers and/or suppliers. According to the company’s strategy, these new warehouses can be acquired, leased or “subcontracted”.

Trying to minimize the total costs to operate the supply chain, the model decides about the quantity to move between any two entities, where each product should be produced, if we should open new facilities and where these should be located (network design), and if we should increase the capacities (plants or warehouses). The model should also define the connections to be established, which warehouses to use, the quantity of each material required by the different production processes, and how to transport the materials and finished products (which mode).

The model is characterized by two decision stages (dynamic model) in order to explicitly consider uncertainty. In the example, we will consider several possible scenarios (s) taking into account different inflation rate evolutions in the five considered periods. Each scenario s involves two events (e), one per each time period (t) between the stages. An event is an evolution of the uncertainty factors being studied. Each event has associated a probability of occurrence pb_{et} . For extension 4 we consider an extra uncertainty parameter related to the Brent cost fluctuation. Extension 3 involves a set of extreme uncertainty parameters (e.g. catastrophes) not related with regular uncertainty parameters.

Mathematical Formulation

To simplify the notation, we will in general assume that flows occur between origins $i \in I$ and destinations $j \in J$. Let K be the set of goods (M – raw materials and P - finished products). $k \in K = \{M \cup P\}$. Each type of vehicle has associated a different cost per usage (tariff) depending on dimensions, mode and route (origin and destination). The set V represents all types of vehicles considered in this model.

We have structured the model in two decision stages, with uncertainty modeled by different scenarios s , each with an associated specific probability of occurrence. A scenario s is a path in a decision tree, with a number of nodes equal to the number of stages plus 1.

In the 1st stage we will take *structural decisions* related with the definition of the physical configuration of the supply chain, considering the data available at that moment. In the 2nd stage we will make *contingent decisions* taking into account the behavior of the system during the first time period and the evolution of the uncertainty factors.

The paradigm chosen to deal with uncertainty was the *decision tree*, with conditional probabilities associated to each scenario, i.e., the probability of each branch depends on what has happened in the previous periods. If we consider 2 periods (between moments 0 and 1, and between moments 1 and 2), and 3 different types of uncertainty behavior (one per branch), we will have 9 different scenarios. So, in instant 0 we will take decisions about the network

configuration and about the flows of goods for time period t_1 . In instant 1 we will decide again based on the uncertainty factors, but only about the flows, as we are assuming that the network configuration is very complex and expensive to be changed. We will adapt the supply chain network to a new reality represented by one of three alternatives.

Each tree branch represents an event e (i.e., an evolution of the uncertainty factors, in a specific period) and it has associated a probability of occurrence.

In our model we are considering parameters related with: labor (cl), investment (icc,ic), production (cpp), fixed (fc), handling (vch), inventory (vc) and material (cv) costs; capacity of production (cp; cs; cap) and of vehicles (tc); distances (d), demand (df), starting inventory (is), opening new links (co) and transportation (g) costs; available space (as) and the quantities to be produced (rw). In addition we also take into consideration parameters related with: annual inflation rate (ir), probability of occurrence (Pb), business potential (cb), vulnerability (ev) and cost of brent (bc).

Decision Variables

With this model we want to decide about the quantities of goods k to be sent from any entity i to any entity j , by vehicle type v during a period t (q_{kijvt}); where each product should be produced (u_{pcl}); if we should open new facilities, where these facilities should be located and which level of capacity should they have (x_{hat}); which connections should be established (y_{kijt}); if we should increase the capacity of existing facilities and how much (x_{hat}); and which warehouses will we use (z_{wt}).

The decision variables q and y are *contingent* variables, so they represent values that can be changed in the future depending on the supply chain behavior. The decision variables u_{pcl} are *structural* because they cannot be changed after the start of production, due to the costs directly associated to these changes (this assumption is based on the requirements of the case study).

Objective Functions and Constraints

The model comprises 3 objective functions:

- (1) the minimization of the total cost to operate the supply chain, including the transportation costs, the costs to open links between two entities, the costs of materials required for the production, the production costs, as well as, the fixed and variable costs with plants and warehouses;
- (2) and (3) are related to the choice of locations for new infrastructures, and are based on “easiness of doing business” and the “labor costs” of each geographic zone, when deciding about future investments taking into account the uncertainty parameter – the inflation rate.

Objective (1) is extended to three new sub-objectives (1), (2) and (4), taking into account the extension of the original model as explained above. Objectives (2) and (3) are only influenced by extension 2. Finally, extension 4 provides a new objective function (4), related to uncertainty parameters – occurrence of extreme events in each geographic zone.

The model considers an aggregation of these objective functions, with weights that can be parameterized. Constraints impose that all customer demands, for all products are satisfied; plants receive enough material to produce the required quantities of products; and the conservation of flows is guaranteed. These constraints also ensure that flows can only be established between two open entities and through open links. All entities considered in the model have installed capacities (plants, warehouses, suppliers) that have to be satisfied. We assume that a product for a given customer will only be produced by one plant (in practice this

happens because production requires a set of specific expensive tools and equipment that cannot be duplicated).

Extension 2 requires more constraints to guarantee that new infrastructures will only be open near existing markets, and that if anew infrastructure is open in a given period then it also be open in the following period. Finally, extension 1 requires additional constraints to guarantee that in same period will be change once 1 level of capacity, and guarantee the change in capacity is add in current capacity.

Conclusions and further developments

In this work, a model for supply chain design in the automotive industry, dealing with uncertainty, has been developed. In particular, this stochastic model supports strategic-tactical decision making. Moreover the model covers a set of different features of real, practical environments, namely: multi-periods planning horizons, multi-criteria assessment of policies, international issues such as exchange rates, and some major specific concerns of companies. However further work needs to be done in enhancing this model and make it more realistic and of broader application.

The approaches we are currently developing should further support decision making in operations strategy planning, and also in understanding how the supply chain network should evolve in a long term horizon, in order to optimize the profitability of operations. For such purpose, these models will require the definition of scenarios for future evolution of supply, demand, transportation and other critical elements of the supply chain network.

Acknowledgments

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References

Beamon, Benita M. 1999. Supply chain design and analysis: Models and methods. *International Journal of Production Economics* **55**: 281-294.

Goetschalckx, Marc; Vidal, Carlos J.; Dogan, Koray. 2002. Modeling and design of global logistics systems: a review of integrated strategic and tactical models and design algorithms. *European Journal of Operational Research* **143**: 1-18.

Jaklic, Marko; Svetina, Anja Cotic; Zagorsek, Hugo. 2005. *Specific responses to universal pressures in the industry – comparing European automotive clusters*. University of Ljubljana, Faculty of Economics.

Joshi, Sumit. 1998. A framework to analyze comparative dynamics in a continuous time stochastic growth model. *Economic Modelling* **15**(1): 125-134.

Klibi, Walid; Martel, Alain; Guitouni, Adel. 2010. The design of robust value-creating supply chain networks: a critical review. *European Journal of Operation Research* **203**: 283-293.

Merschmann, Ulf, and Ulrich W. Thonemann. 2011. Supply chain flexibility, uncertainty and firm performance: An empirical analysis of German manufacturing firms. *International Journal of Production Economics* **1308**(1): 43-53.

Sturgeon, Timothy J. 2009. Globalization of the automotive industry: main features and trends. *International Journal Technological Learning- Innovation and Development* **2**(1and2): 7-24.

Tsiakis, P.; Shah, N.; Pantelides, C. C. 2001. Design of Multi-echelon Supply Chain Networks under Demand Uncertainty. *Industrial Engineering Chemistry Research* **40**(16): 3585-3604.