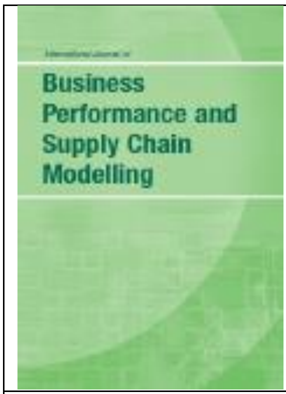

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Occupational risk management in construction supply chain

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Abstract: The building is historically a driver of the economy, creating thousands of direct and indirect jobs, moving a huge chain of suppliers of raw materials, supplies and services, besides building a country's infrastructure and the homes of millions of people. But working conditions in this sector that is so important to the country are not the best, exposing workers to risks of work accidents and occupational diseases. Therefore, this study sought to present the main occupational hazards in the construction industry, discussing alternatives for effective risk management by reducing the rates of accidents and illness among workers. In this research, case studies were done in small and medium-sized construction sector facing the residential construction market. It was also proposed solutions for the implementation of risk management and occupational health and safety for businesses to succeed and lower the rates of accidents at work, health and safety, and quality of work life in these companies.

Keywords: risk management; occupational health and safety; OHS; construction.

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1 Introduction

Accidents and occupational diseases for their harmful consequences, go beyond the boundaries of enterprises causing great damage social, becoming the responsibility of governments, the business sector and society as a whole.

According to the International Labor Organization (ILO, 2004), in the last decades there has been a significant acceleration in construction activity in various parts of the world. These activities have provided employment for thousands of workers, creating jobs of fundamental importance. However, the construction industry shows a positive image of the social point of view, but also shows a side that is not always seen with the same magnitude, as accidents have occurred despite efforts to prevent them. The risks which accompany the operation of construction engineering, which also exist in other industries, should not be considered as factors which inevitably result in accidents and illnesses. Experience proves that if there is probability of an accident with serious injury, it can be eliminated by recognising the existence of the risk and its consequences and adopting preventive measures to eliminate them or mitigate their effects. Both from the human and economic point of view, the need for a major effort to reduce the number of accidents in various spheres of activity are urgent and important.

According to ILO (1979), the main risks in the construction industry could be listed as: breakage of walls, parts of the works, stakes, massive land, collapse and fall of ladders, scaffolds, stairs, beams, falling objects, tools and work pieces, people dropping from steps, stairs, roofs, scaffolds, falls from windows and in openings on level loading, unloading, lifting, cargo transportation, on or in contact with vehicles of all kinds; operation in railways, in power plants and power transmission machinery, working with machines, loading and transporting equipment, equipment for welding and cutting; on compressed air equipment, in contact with fuels, hot or corrosive materials; in contact with hazardous gases; during blasting with explosives, using or handling hand tools; involvement with traffic on the site under construction, form and origin of the work.

This work aims to make a contribution on the subject, showing in a clear way, the management of occupational hazards in the construction industry, discussing the factors that can lead to accidents at work and occupational illnesses, in order that the firms have subsidies to implement satisfactorily and effectively provide such a system and their workers can have all the benefits of managing occupational health and safety (OHS) in the workplace.

Therefore, we tried to present and describe what it is and how a Risk Management System Occupational Safety and Health works, discuss the difficulties and problems faced by small and medium enterprises in the construction industry and suggest ways to improve the management of occupational hazards in construction companies.

1.1 Health and occupational safety

The definition of the ILO and the World Health Organization (WHO) on OHS is:

> "The goal of occupational health is to promote and maintain a high degree of physical, mental and social wellbeing for the workers, in all their activities; prevent any damage to health caused by working conditions and to protect them against the risks arising from presence of agents harmful to health; put and keep workers in jobs consistent with their physiological and psychological skills, and finally, adapting the work to the person and each person to their tasks."

According to Bendrikow (1994), the ILO definition by extension leads inevitably to consider issues not directly related to the company, including the external environment, and life in society. And also, that the activities of occupational health comprise as assumptions three main focus areas, which are:

a promoting and maintaining the health of the worker and his fitness for the job

b improving the conditions and environment work to ensure the safety and health at work

c adoption of systems of work organisation and corporate culture, capable of contributing to the safety and health at work, with a positive social environment.

Also Bendrikow states, with respect to construction, that there are indications that the knowledge of industrial hygiene used in construction, are applied empirically, usually looking up simplistically identify problems through the most frequent complaints of the workers, requiring them to use personal protective equipment, without a careful study of working conditions and their organisation, without a technical evaluation of the type of protection offered and the discomfort provided to the employee user.

Heineck (1996) states that in the construction sites of some construction companies, it is already possible to find a number of changes in the production process and its organisation. Such measures have been complemented by more radical changes, such as rationalisation and integration of the projects, using different technologies and also a total change in labour relations in the construction sites, with the enhancement of the workers and their involvement in decisions about the conduct of the work and increasing the level of communication and inter-relationships between people. This is a vision that involves the workers in planning the work and during its execution, giving them responsibility for the actions in their protection.

Lima (2001) states that the prevention of occupational diseases in the general management of the building project must be integrated with specific programmes for the prevention of occupational risks, prevention and control of diseases at work set out in specific legislation.

1.2 Nearly accidents and injuries

According to Benite (2004), the term ‘accident’ naturally suggests a vision of a sudden event that occurs by chance and that results in personal injury. However, this view is inadequate and ultimately generates difficulties in the field of accident prevention because it facilitates the concept of the following incorrect ideas:

a accidents occur by chance

b the consequences occur immediately after the event

c the accidents necessarily result in personal damage.

Dictionaries define accident as “Unfortunate happening, casual or not, and that results in injury, harm, damage, ruin, etc.; disaster” [Benite, (2004), p.65].

Still according to him, the legal definition of an accident at work is provided by Law 8213 of July 24, 1991, namely:

> “What is the performance of work in the service of the company, or by the exercise of the special work of the insured, causing injury or functional disorder that causes death, loss or reduced work ability, permanent or temporary.”

In the accidents prevention view, aggregated to standards and guides of SGSSO, being inserted in the definition of accident presented by OHSAS 18001 and BS 8800: “Accident is an undesirable event that results in death, health problems, injuries, damages and other losses”.

Another term that will be used throughout this work is ‘near accident’ that is equivalent to the term ‘incident’, and that, according to the standards BS 8800 and OHSAS 18001, is defined as: “an unforeseen event that had the potential to generate accidents”. This definition is intended to include all events that do not result in death, health problems, injuries, damages and other losses.

According to Benite (2004), the knowledge of near accidents provides information for organisations to identify weaknesses and establish appropriate control measures, allowing to eliminate or reduce the likelihood of accidents to become real in a future situation.

According to Viégas et al. (2002), those who believe that most accidents happen simply as a result of carelessness, miss a golden opportunity every time an accident or near-accident (incident) happens.

Still according to him, when they do not examine the real and basic reasons that occurred, they fail to gather valuable information on how to prevent the event from occurring again.

1.3 Concept of occupational risk management

Risk management can be defined as the science, art and function that seeks the protection of human, material and financial resources of an organisation, in relation to the elimination, reduction or funding risks, if economically feasible, says Santos (2005).

According Marinho (2007, p.4):

> "In recent decades, particularly in developed countries, there have been changes in the focus of the professionals who work with the risks in the workplace. The preventive aspect has been more emphasized, acting on the control and elimination of hazards and risk reduction at its source, to reduce accidents and diseases. It is recognized, not without much debate and struggle, that the forms of work organization and the management practices are important factors to be considered as causes of accidents, illness and suffering. Safety and health policies in companies that take into account these aspects have been recognized as the most effective and recognized worldwide."

According to British Standard, BS 8800 (1996), in risk assessment:

> "A hazard is a source of potential harm or damage, or a situation with potential for harm or damage" and the "risk is the combination of the probability of occurrence and the consequences of a specific hazardous event (accident or incident)."

According to Marinho (2007), the modern conception of analysis and risk management is far distant from the practice of Brazilian companies, especially regarding micro enterprises and service providers in general.

Still according to him, few attitudes are taken before accidents and occupational diseases, and very often workers are accused as the main responsible for them.

The British Standard, BS 8800 (1996) further comments that the risk also has two key elements, the probability that a hazard may occur and the consequences of the hazardous event.

Thus, it becomes necessary to use the procedure for risk assessment activities at work everyday, in order to preserve health and safety of workers and meet legislation.

According to British Standard, BS 8800 (1996), the risk assessment procedure is intended to be used:

a in situations where the dangers seem to constitute a significant threat and it is unsure whether planned or existing controls are adequate

b by organisations seeking continuous improvement in its SGSSO systems, beyond minimums legal requirements.

Risk assessment involves three basic steps (British Standard, BS 8800, 1996):

a identify the danger

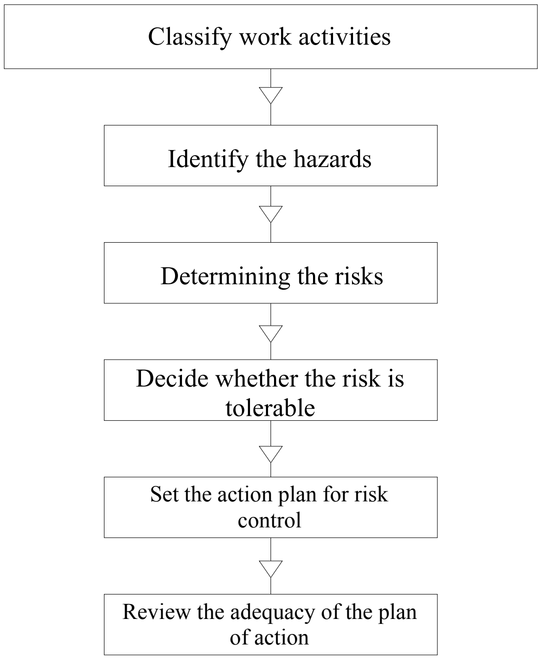
b estimate the risk, the probability and severity of the hazard

c decide whether the risk is tolerable.

For many years the risk assessment of OHS has been conducted, in general, on an informal basis. It is now recognised that the risk assessments are fundamental to managing proactive OHS, and that systematic procedures are necessary to ensure its success, describes the British Standard, BS 8800 (1996).

The British Standard, BS 8800 (1996) proposes the following risk assessment process:

Figure 1 Risk assessment



Source: Adapted BS 8800

The following criteria are required for the organisations carrying out an effective risk assessment:

a Classify work activities: Prepare a complete diagnosis of work activities covering the enclosures, production, people and procedures.

b Identify hazards: Identify all hazards in each work activity.

c Determine the risk: To estimate the risk associated with each hazard, assuming that planned or existing controls are properly sized. One should also consider the effectiveness of the controls and the consequences of their failures.

d Decide whether the risk is tolerable: To judge whether existing precautions or planned SSO are sufficient to maintain the dangers under control and meet the legal requirements.

e Action plan for risk control: Prepare a plan to deal with any issues encountered by risk assessment that require attention. Companies should ensure that the new and existing OHS remain active and effective.

f Review the adequacy of the plan of action: Reassessing the risks based on the revised controls and verify that the risks are tolerable.

According to Marinho (2007), the ideal is that all work activities are analysed, but given that in many cases this task can not be performed some factors may be considered to prioritise some activities:

a the frequency and severity of accidents: activities where accidents occur frequently or where an accident has happened with serious injuries or losses

b activities where the potential of serious injury or illness is already known, either for injuries, dangerous conditions or toxic exposure

c recent activities: due to lack of experience in such operations, hazards may not be obvious or not have been properly anticipated

d modified activities: new hazards may be associated with changes in procedures, tooling, raw materials or operations

e activities done infrequently: workers may be at increased risk when performing tasks out of their routine and a risk analysis at work (RAW) provides a means of reviewing these dangers.

The tolerable risk means that the risk has been reduced to the lowest level that is reasonably practicable, according to British Standard, BS 8800 (1996).

The British Standard, BS 8800 (1996) comments in its text that is usually not necessary to make precise numerical calculations of the risk in most cases in small and medium enterprises. The complex methods to quantify risks are normally required only when the consequences or failures can be catastrophic. Risk assessment in these cases, such as in industries that provide significant risks, relates to the approach required in other places of work, but in most organisations, much more simpler subjective methods are suitable.

According to Barreto (2011b), the assessment of health risks associated with exposure to toxic substances and harmful energies may require, for example, measurements of concentrations of aero-dispersals and metal fumes in the air, noise exposure and chemical exposure among others.

Barreto (2011a) also comments that compliance with labour laws, adoption and implementation of indicators based on studies of costs related to workplace accidents denote the tendency for companies to implement strategies aimed at preserving the integrity of workers, seeking elements that provide the management of OHS within the companies. Some indicators of quality of work life can be improved by actions to maintain safe and healthy environments, safeguarding the health and welfare of employees.

Resende (2006) suggests that the modern management of occupational safety and health should be seen as a strategic component which value can represent to the company an important factor to its success or even survival.

2 Materials and methods

After the literature search, we detected the absence of detailed data and statistics on occupational risk management in the construction industry.

For both surveys was done in the form of a case study in building companies from the Midwest region of Minas Gerais, small and medium businesses. A questionnaire was developed with essay questions and multiple choice questions where the respondent answered based on their experience about the company where they work. We interviewed several types of workers, servant masons, masons, firefighters, carpenters, painters, the workmen, engineers, etc.

Other data were obtained from impressions taken by the interviewer in informal conversations about health and safety with the workers.

Observe that this last form of data collection was necessary because of the low education of the majority of construction workers.

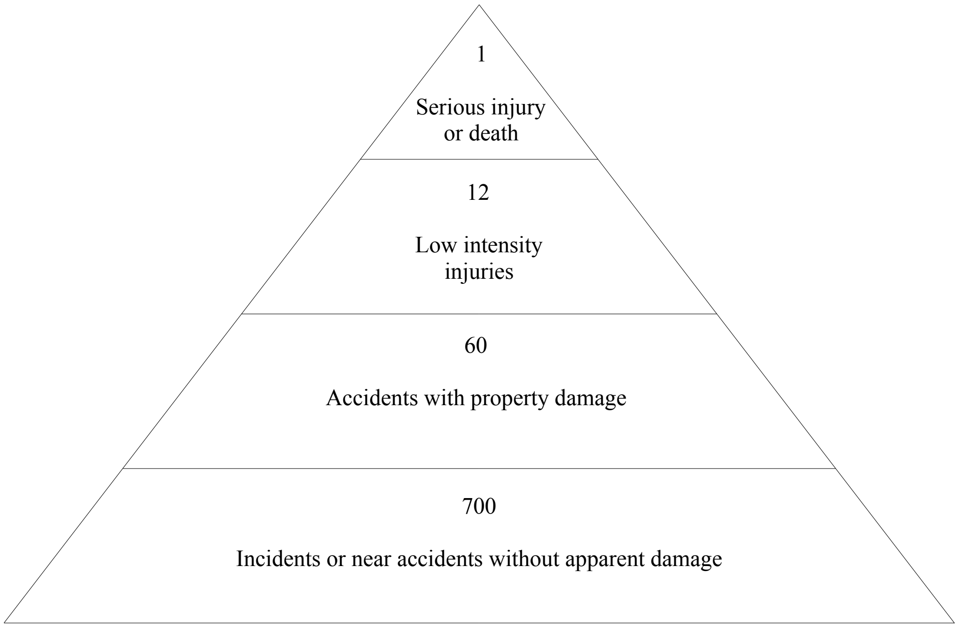
3 Results

In surveys with construction workers were found troubling data on exposures to OHS, as can be seen below.

- fall height advent of the coating façade
- fall height arising from the lack of support from scaffolds
- fall height arising from the lack of safety equipment or its misuse (seat belts and proper fixation)
- fall height arising from the absence of guardrails
- fall height arising from the lack of security in the activity of painting façades
- burial in trenching
- burial at the opening of foundations and caissons
- damage to hearing arising from the use of equipment (marble saws, table saws, jackhammers, etc.)
- damage to hearing arising from the use of heavy equipment (tractors, excavators, concrete mixer trucks, etc.)
- loss of limbs coming from cutting equipment (marble saws, table saws, etc.)
- orthopedic damage (spine, knee, shoulder, hands and feet) due to poor posture and repetitive effort
- burns and damage due to various electrical shocks
- damage to the respiratory system (silicosis) due to fine particulate matter inhaled
- damage to the respiratory system due to inhalation of solvents and other chemicals used in painting and cleaning works
- damage to the skin caused by constant exposure to the sun
- crushing caused by heavy equipment or handling materials at construction sites
- damage caused by falls of various objects over workers
- waterborne diseases caused by poor condition of some construction sites.

The results obtained in the analysed companies match the factors that can lead to accidents with great gravity, which generate permanent disability in the workers or even fatal accidents.

Figure 2 Scale of accidents and near accidents



Source: Civil Construction Company

Above, we have a range of events that precede a fatal accident, found in construction companies through the statistics of the last ten years.

4 Discussion

Just watching the case discussed above and the literature on the topic, some steps can be taken in order to make the management of risks to health and safety of construction workers.

These measures are:

- Planning occupational safety actions along with the development of the work projects.
- Risk assessment in relation to the stages of the work, anticipating the planning of occupational safety actions at the construction sites.
- Implementation of periodic health checks and depending on the position held and the risk of work activities.
- Constant and adequate training in relation to the activity performed by the employee and the use and maintenance of individual protective equipment.
- Searching for solutions for the use of collective protective equipment to the detriment of the use of individual protective equipment.

- Integration of the management of occupational risks to the quality of activities routine in the works.
- Implementation of integration policies and discussion among workers about the collected data in risk assessments.
- The company must have a strong policy of human resources and workplace safety that values the employee and that can give them a minimum of stability, so that they feel integrated in the company.
- Have a system that integrates and enter businesses and outsourced workers to the risk management, in order that all workers are involved in the activities of OHS.
- Deploy an internal audit team that makes complete surveys of risks included in all work activities within the company, researching the risk of accidents and health of the workers and suggesting immediate interventions if necessary. This team should preferably be comprised of employees from all levels and sectors in the company, in order to reach objectively the risk of each sector, producing reports that are easy to understand to all the workers.
- Focus on immediate risks and in situations with long-term effects, such as stress, occupational diseases, etc.

Possess fundamentally a willingness to change the situation and deploy not only a system of risk management, but rather a preventive culture regarding worker health and workplace accidents.

5 Conclusions

We conclude that risk management is an important tool in the prevention of occupational accidents and prevention of OHS of the construction workers.

But, we see the difficulties faced by companies in the implementation of risk management and prevention of occupational hazards in general, whether for the lack of investment by the firms in training and qualification policies, lack of organisation and planning the works, the workers not being aware of their labour rights and working conditions, seasonality of work and high turnover of workers.

In this sense, the construction industry is an important lever in a country's economic growth, creating jobs and developing infrastructure in the country, but its workers are exposed to high risks of occupational accidents and diseases and this problem must be faced by the construction companies, with the use of OHS and risk management tools.

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Modelling to assess the impact of technological innovation capacity in the performance of high complexity environments

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Abstract: Recently, studies have referenced innovation as a key factor affecting the performance of firms. Companies make use of its innovative capacities to achieve sustainable competitive advantage. The objective of this paper is to contribute to innovation planning policies in highly complex environments. Thus, a modelling proposal is presented to assess the impact of technological innovation capacity on the performance of high-tech companies in Brazil. This procedure was prepared according to the following phases: phase 1: determination of the conceptual model; phase 2: verification of the conceptual model. The research was initially conducted based on the specialised literature, which extracted the data regarding the constructs/ structure and content in order to build the model. To demonstrate the modelling feasibility, it used a survey of high-tech companies in Brazil. The research involved the intervention of experts knowledgeable on the object studied, selected by technical-scientific criteria. The data were extracted using an assessment matrix. To reduce subjectivity in the results achieved the following methods were used complementarily and in combination: multicriteria analysis, multivariate analysis, psychometric scaling and neurofuzzy technology. The data were extracted using an assessment matrix and the results were satisfactory, validating the modelling approach.

Keywords: modelling; assessment; impact of technological innovation capacity; performance of high complexity environments.

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1 Introduction

Recently, relevant changes have made organisational boundaries more fluid and dynamic in response to the rapid pace of knowledge diffusion (Abrahamson, 1991; Griliches, 1990; Teece, 1986), and innovation and international competition (Chesbrough and Rosenbloom, 2002; Christensen, 2003; Damanpour, 1996). This helps to reassess how to succeed using innovation (Teece et al., 1997; Tidd et al., 1997; Teece, 1986; Martin et al., 1999; Wheelwright and Clark, 1992). Thus, innovative companies make use of their capabilities to appropriate the economic value generated from their knowledge and innovations (Griliches, 1990; Teece, 1986). Therefore, the supply of innovative products is presented as a quality standard in the race for pressing demands.

It is believed that companies that can offer their products to customers more efficiently and faster will probably be in a better position to create a sustainable competitive advantage (Prahalad and Hamel, 1990; Amit and Schoemaker, 1993; Nonaka and Takeuchi, 1995; Calanton et al., 1995) due to knowledge and innovation (Teece et al., 1997; Nelson and Winter, 1982; Nonaka and Takeuchi, 1995; Leonard-Barton, 1995; Grant, 1996a, 1996b; Johannessen et al., 1999). In this dichotomy, technical efficiency is a parameter of the developing capacity of innovative products, which translates into one of the most remarkable logical arguments to potentialise and encourage competitive advantage (Wheelwright and Clark, 1992; Brown and Eisenhardt, 1995). One of the main challenges is to develop products in high complexity environments. Solutions to these challenges have been offered by the companies' equally innovative technical capabilities, greater efficiency, productivity and high quality (Wheelwright and Clark, 1992).

Developing products is not a recent phenomenon, but reconstruction presents successful and unsuccessful experiences. Any attempt to encourage reconstruction and interpretation refers to, first of all, a proper analysis of the difficulties and peculiarities of the product development chain, the "opposite semantics due to the systems' diversity of features – structures, methods and organization". The reconstruction then uses a 'mantle' that takes advantage of the experience accumulated by the actors in the product development process of the value chain, considering the learning process for the construction of knowledge. In any case, product development is a complex chain of events and decisions, which can break at any of the weakest link: some projects lost due to unrealistic predictions or the absence of its real role in the agenda, or other motivations that somehow followed ideas that had many missteps or a detail error.

It is feasible to offer innovative products as it enables companies to have incremental gains and competitive advantage, in particular industries dealing with high-technology/ technological innovations. Technological innovation is a dynamic process, and perhaps the most dynamic of all industrial activities (Schumpeter, 1943; Achilladelis and Antonakis, 2001). This requires the combined effort of various innovative activities, a condition of limited resources.

Traditionally, the literature references two main types of innovation activities: internal and external (Cassiman and Veugelers, 2002). External activities are related to licensing knowledge access through external sources, R&D outsourcing, and hiring highly qualified researchers, with relevant knowledge (Aurora and Gambardella, 1990), and others. Internal innovation activities use the firm's internal capacities, where knowledge production is internalised (Frenz and Ietto-Gillies, 2007). Recently, the state of the art introduced a third innovation activity route, cooperation with other partners to develop innovations (Chen and Yuan, 2007), which can be considered a combination of internal and external innovation (Pisano, 1990).

The state of the art has significant bearings on the advances of studies on the innovative technology capacity of firms. In a research conducted by Wang et al. (2008), the technology capacity of firms under uncertainty was evaluated using the fuzzy set theory that adapts naturally to conditions of uncertainty produced in the decision-making processes. The results were plausible and enabled to assess the extent of high-tech firms' innovative technology capacity (R&D, manufacturing; marketing; learning, organisational; strategic planning and resource allocation). Lau et al. (2010) also conducted empirical studies to assess the technology innovation impact on the performance of innovation in Hong Kong. The results were satisfactory and enabled to show that the R&D capacities, resource allocation, strategy learning and planning, can significantly improve the results of the firms' business. Moreover, it showed that R&D and resource allocation also have a significant effect on the introduction of new products. But not everything is 'perfect'. There are inconsistencies along the way. Yam et al. (2004) conducted an empirical study on technological innovation in the industrial enterprises in the Peking area (Guan et al., 2005, 2006; Guan and Ma, 2003) and the innovation capacity results (R&D, manufacturing, marketing, learning, organisation, strategic planning and resource allocation) were inconsistent, as they did not yield propositions or hypotheses, which to a certain degree weakened the research findings (Lau et al., 2010).

Deciding on an ideal balance regarding innovation activities is a complicated issue (Chen and Yuan, 2007), there are barriers to be challenged and substantially reconfigured (Assink, 2006) in order to obtain an optimal and combined convergence of the various activities in confluence with the firms' desired and acceptable performance. Innovation activities are admittedly complex and risky. Thus, it is difficult to accurately assess (Afuah, 1998; García-Muiña and Navas-López, 2007; Bellman and Zadeh, 1970) the innovation capacity and also discern the firms' range of acceptable performance. All these elements are difficult to accurately define and interpret. As it is a procedure in which attributes have subjective characteristics, reference methods and compliant and robust assessment techniques have to be reformulated, considering not only the objective attributes, but also the subjective dynamics produced within the decision context.

Of the literature investigated, none of these studies demonstrated the assessment of the firms' impact on technology innovation performance for an optimal efficiency rate. An optimal efficiency rate should be understood here as a minimum and desirable value to achieve the firms' desired performance, produced by converging the combined interactions of innovation activities to a single parameter. It is feasible to decide on a parameter, since it allows firms to offer the best combination of innovation activity strategies in agreement with their expected business results. Furthermore, promoting a firm's innovation capacity should feature the confluence of technical capacities, in order to balance the objective and subjective attributes that result from the decision-making process.

This work submits an attempt to make use of these technical instruments by constructing a modelling approach to determine a decision parameter. It is hoped that this proposal can contribute toward a new planning approach in high-complexity/high-tech environments. For the case in question, Brazilian companies were surveyed. This planning stage is frequently devoid of efficient and appropriate tools, making use of the 'ready things', resulting in the managers indefinitely postponing the reorganisation process. An integrated modelling proposal that is connected, simple and robust is presented. The model is structured according to the following phases and steps:

Phase 1 Determination of the conceptual model

Phase 2 Verification of the conceptual model:

- Step 1 Modelling the technological innovation performance capacities in firms, in two sub-steps:
  - a identification
  - b evaluation of technological innovation capacities in the companies' performance.
- Step 2 Determining the correlations between innovation capacities and performance dimensions of companies.
- Step 3 Prioritising the technological innovation capacities of companies in relation to the technological innovation performance of companies.
- Step 4 Modelling the efficiency rate (optimal rate) of technological innovation capacity to achieve the companies' expected performance.

It is also believed that once the feasibility and plausibility of the proposed model is demonstrated, the research problem (How should a model to assess the impact of technological innovation capacity in high-tech companies in Brazil be structured, in order to contribute to a planning policy in companies of this category?) Can be solved and the goal achieved (contribute to an innovation planning policy in highly complex environments. For this a modelling proposal is presented to assess the impact of technological innovation capacity on the performance of high-tech companies in Brazil). The classical model of planning innovation should be renewed, with creative elements and procedures opposed to the technocratic ones.

In this reference framework, the importance of having more efficient tools is reaffirmed, overcoming the traditional models that attempt to describe and rationalise the innovative capacity assessment (strategies) for the performance of highly complex environments, based on purely mathematical models, which are no longer sufficient to describe complex application situations, translating diametrically opposite results. Human experiences and intuition are important in decision processes that require high tolerance to ambiguity. It is held that old practices are no longer justified, which requires letting go of outdated values and introduce suitable effects that are appropriate to this time. This understanding is not followed closely by those who manage innovation. Failed attempts at planning innovation give way to reinforcing the importance of their role, taking a leap towards more innovative and risk-free models. It is not about substituting an absolute control power of innovation activities, or disregarding what has already worked, but rather encouraging pragmatism when implementing responsible innovation planning. It is about a more pragmatic and efficient guideline to assist the development of innovative products in the long term.

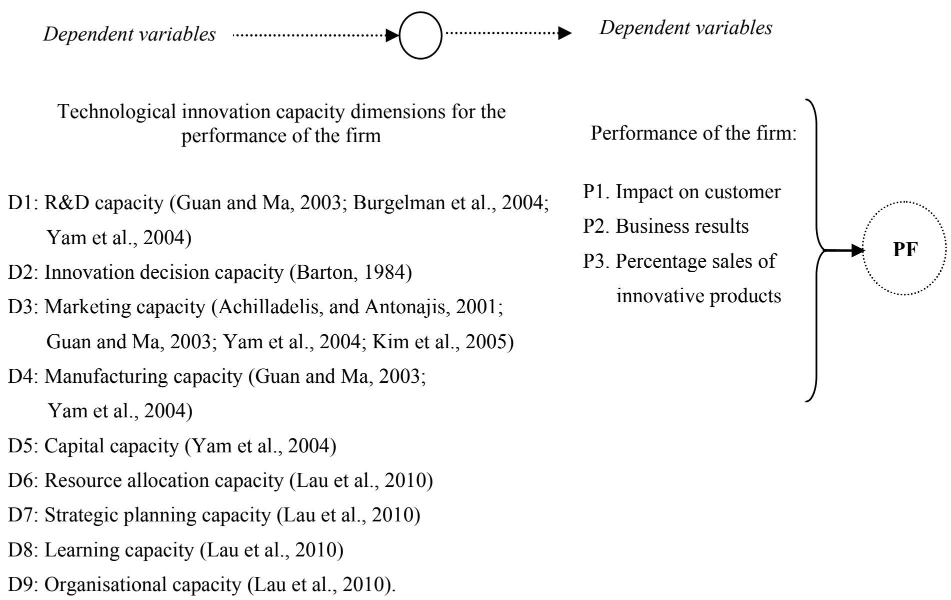
Within this context, this paper is structured according to the following sections: methodology, which presents the conceptual model and the methodological procedures; verification of the conceptual model and analysis of the results; the paper concludes with the final considerations.

2 Methodology

2.1 Conceptual model: constructs and hypotheses

This section examines the conceptual model (Figure 1) and presents the hypotheses to be tested throughout this work.

Figure 1 Conceptual model of the study



Acknowledged as one of the most significant forms of globalisation, technological innovation stands out as a potential to ensure the firms' long-term survival and growth (Ancona and Caldwell, 1987). Therefore, technological capacity is understood as an organisation's complete set of characteristics that facilitates and supports its technological innovation strategies (Burgelman et al., 2004). Within this outlook, it is possible that R&D is the central component of firms' technological innovation activities. It is believed that the organisational efficiency in these activities that lead to innovation enables the firms to achieve the satisfactory and desired performance, traditionally measured by sales growth, net income growth and return on investment (Tallon et al., 2000).

Dependent variables: the following dependent variables were selected for this research: impact on customer; business results; percentage sales of innovative products. *Independent variables:* the independent variables, companies' technological innovation capacities, were based on the literature. Therefore, the following dimensions were considered as independent dimensions: firms' dimensions of technological innovation capacity:

- D1 R&D capacity (Guan and Ma, 2003; Burgelman et al., 2004; Yam et al., 2004)
- D2 innovation decision capacity (Barton, 1984)
- D3 marketing capacity (Achilladelis, and Antonajis, 2001; Guan and Ma, 2003; Yam et al., 2004; Kim et al., 2005)
- D4 manufacturing capacity (Guan and Ma, 2003; Yam et al., 2004)
- D5 capital capacity (Yam et al., 2004)
- D6 resource allocation capacity (Lau et al., 2010)
- D7 strategic planning capacity (Lau et al., 2010)
- D8 learning capacity (Lau et al., 2010)
- D9 organisational capacity (Lau, Yan and Tang, 2010).

The following hypotheses were formulated using the conceptual model:

Hypothesis 1 The technological innovation capacities have positive impact on the companies' business performance.

Hypothesis 2 The optimal efficiency rate depends on the combination and interaction of innovation capacities of the high-tech companies.

2.2 Research design

2.2.1 Scope of the study

The Brazilian high-tech companies are very sensitive to technology advancement and demonstrate high innovation growth. These are industries characterised by high intensive capital, highly technical level and complex production process, short life cycle and high R&D investments. These companies require robust and efficient tools to support their decisions.

2.2.2 Sample and data collection

The objective of this study is to identify the impact of technological innovation on the performance of high-tech companies in Brazil. This research treated Brazil's high-tech industries as the empirical targets. The researcher selected the more well-known firms. Thus, an integrated and chain model proposal was designed, based on the literature and confirmed by the assessment of experts. This proposal contains its guiding elements in the technological innovation capacities of Brazilian high-tech companies. Following the logic underlying in the guidelines of the model, the data collection is permanently and periodically applied to the specialists, hence permeating all intermediate phases and steps addressed to the legitimacy and strength of the proposal. The term 'priorities' repeatedly referenced herein consists of determining the strength with which the various elements of a level influence the elements of the next higher level, in order to compute the relative strengths of the impacts, which contributed significantly to the result analysis achieved at each phase and step of the elements on the level below and on the general objectives (Saaty, 1991).

The data collection was performed using a scale/matrix assessment questionnaire. The technique used was the stated preference, taking into account that these methods work with the preferences of the decision makers, revealed by the choice made among the alternatives selected from a set of real alternatives, or not. In this classification framework, the research interviews and consultations with the experts are highlighted. With this procedure, the information collected can be set apart in different parts by adjusting the phases and steps of the model. In the data set collected it was necessary to apply a removal cleaning procedure called filtering, to first eliminate inconsistent and incomplete data, and secondly, to discard data that are irrelevant to the model. This enabled a better analysis of the variables involved, and also to obtain improvement in the quality of the data provided to the model. This removal procedure used the psychometric scaling method of the Law of Categorical Judgments. All of the variables were measured by multiple questions to ensure reliability, and were measured with a Thurstone scale whenever possible.

Data collection was conducted in two blocks. The first was to collect data to feed the development of the proposed model, extracting construct and content data from the specialised literature. This proposal was confirmed by a survey with experts who issued their opinions through a scale/matrix questionnaire. The second was to demonstrate the feasibility and plausibility of the model through a survey addressed to the specialists who have direct or indirect ties to high-tech companies in Brazil. The experts issued their judgements through a scale questionnaire for the first external validation. For the internal reliability of the items, the internal consistency of Cronbach's alpha technique was used, which reached 0.84, considered a satisfactory result for this type of application.

Before applying the final collection instrument, a pre-test was conducted with five experts to clarify whether the instructions were clear and objective; to verify that the questions were objective and without interpretation ambiguity; and to investigate possible comprehension problems by the experts on the expected responses. There were few adjustment suggestions. Next, a survey was conducted with 20 experts, selected according to their technical-scientific criteria. The researcher regarded the new product project managers, experienced product planning personnel, innovation managers, organisational managers, R&D managers, technology managers, planning, technological innovation and modelling managers. The targeted respondents of the survey were senior product development managers, vice presidents and directors. The background education of most engineers is in engineering, business administration, economics, engineering and management, business administration and economics, engineering and economics, their ages ranged between 27 and 65. They were requested to fill out the questionnaire. Follow-up phone interviews were conducted. The questionnaire respondents should have full understanding in innovation product development. A general mapping of the specialists was conducted in order to ensure better accuracy and consistency in the quality of the results to be achieved with the answers, and also to ensure plausible outcomes. Cury (1999) recommends a sample of 20 to 30 experts. These specialists are directly or indirectly related to the objective of the study, they have experience and technical knowledge on high-tech companies in Brazil, which are related to the following sectors: electronics, petrochemical and metal-mechanic. The data collection instrument was sent to 35 experts. Of this total, 20 returned answered. The phases and steps of the model were based on the following methods:

1. Thurstone's Law of Categorical Judgement psychometric scaling
2. multivariate analysis
3. multicriteria: compromise programming, Promethee II, and Electre III.

Next, these procedures were detailed, which contributed significantly to the analysis of the results achieved in each phase and step of the modelling.

3 Conceptual model verification and underlying analyses

This section presents the verification procedures for the conceptual model. To solve the research problem and achieve the intended goal, the subcomponents of technological innovation capacity of high-tech companies are first identified and prioritised. After this procedure, the assessment of global technological innovation capacity is modelled in relation to the performance of high-tech companies. Finally, the optimum efficiency rate of the technological innovation capacity performance is modelled using the interaction between all the independent variables. Thus, once the problems identified have been defined (How should a model to assess the impact of technological innovation capacity in high-tech companies in Brazil be structured, in order to contribute to a planning policy in companies of this category?), the actions to solve the research problem and achieve the intended goal are set. This procedure was done based on the flexible system methodology. The choice for the flexible system methodology applied to this work is because the problem is considered to be systemic, and includes the description of intellectual constructs and human activities purposeful to judge possible changes that can be introduced into a real-world situation.

In this spectrum, to solve the problem and achieve the intended research goal, the next step was to prioritise the dimensions (sub-components) (Figure 1) of the technological innovation capacity in relation to the global performance of the high-tech companies.

3.1 Phase 1: Prioritisation of the sub-components of technological innovation capacity in relation to the overall performance of high-tech companies

The technological innovation capacity dimensions are prioritised in relation to the performance of high-tech companies. This procedure is developed using the Law of Categorical Judgments psychometric scaling method (Thurstone, 1927). The Categorical Judgement method is understood as the modelling of mental behaviour that aims to explain the structure of the experts' preferences regarding a set of stimuli. In this work, the choice of Thurstone's Law of Categorical Judgments method is justified as a strategic tool to be tested in order to prioritise, by importance, the technological innovation capacities based on the performance of high-tech companies. This method considers the mental behaviour to explain the structure of the preferences of the decision makers on the characteristics prioritised.

The procedures to apply the instrument are systematised in the following steps:

Step 1 Determine the frequencies of preferences per stimuli pairs, where O_i is equivalent to the characteristics and O_j to the experts – O_i] O_j. The data systematised here were obtained from the experts' preference in relation to the capacities (field survey using questionnaire/judgement matrix). The characteristics appear as stimuli subjected to ordinal categories.

Step 2 Determine the frequencies of ordinal categories, using the data extracted from the previous step. The matrix [πij] of the cumulative relative frequencies is then calculated. The results are classified in ascending order of importance. For a better technical understanding, the following literature is recommended (Thurstone, 1927).

Step 3 Determine the matrix [πij] of the cumulative relative frequencies, with the results of the frequencies of ordinal categories, then, the matrix of cumulative relative frequencies is calculated.

Step 4 Determine the inverse of the standard normal cumulative frequency (INPFA), with the results obtained in the previous step, the inverse of the standard normal cumulative frequency is calculated. The results reflect the experts' intensity probability of their preferences in relation to stimuli (capacities). The method was achieved from the research results with the experts, who expressed their preference by stimuli pairs (in this case, the technological innovation capacities), and these were submitted to the ordinal categories C_1 = 5th place, C_2 = 3rd place and C_3 = 4th place). The result of preferences is then presented in increasing order of importance (Table 1).

Combining the dimensions, there is significant predominance of the learning capacities, R&D and planning. R&D efficiency reflects the product development process dynamics, reduces time-to-market, improves product profitability, increases productivity, as well as other benefits. Studies on R&D efficiency have many applications as a management tool. R&D is strong performance measure, similar to ROI. It can also be used as a means of comparison (benchmark). R&D efficiency is also an aggregate measure of the overall success of a company's product in the development effort. R&D brings the percentage of researchers employed; success rate of R&D products; patent number and R&D intensity; the decision for innovation capacity informs the degree of innovative R&D ideas; the collaboration intensity with other companies or R&D centres; R&D sharing capacity; forecast and evaluation of innovative technology initiatives for business innovation.

Table 1 Prioritising the of technological innovation capacity dimensions of the firm regarding to the firm's performance

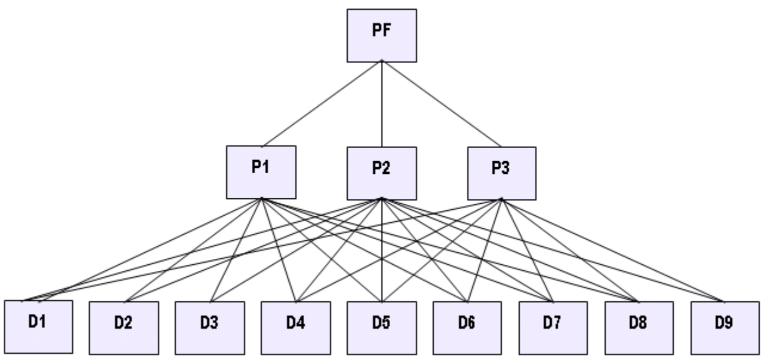
Dimension (stimulus)	*C1*	*C2*	*C3*	*C4*	*Total*	*Ranking*
Learning from R&D, failures and manufacturing process/company's capacity to identify internal and external weaknesses and strengths. opportunities and threats, to formulate plans according to the corporate outlook and missions	*–1.22067*	*–1.22067*	*–1.22067*	*–0.13971*	*–3.8017*	*1*
Optimal capital allocation/return on investment	*–1.22067*	*–1.22067*	*–1.22064*	*0.430728*	*–3.2313*	*3*
Collaboration intensity with other companies or R&D centres/R&D sharing capacity/success rate of R&D products/degree of R&D innovation ideas/business innovation initiatives/percentage of researchers employed	*–1.22067*	*–1.22067*	*–0.76471*	*–0.43073*	*–3.6368*	*2*
Capacity to ensure the organisational culture of the company	–1.22064	–0.76471	–0.76471	0.76471	–1.9854	6
Number of patents	–1.22064	–1.22064	0.430728	1.220642	–0.7899	11
Capital intensity	–1.22064	–0.76471	0.13971	0.76471	–1.0809	8
Advanced manufacturing technology	–1.22067	–0.76471	–0.43073	0.430728	–1.9854	6
Forecast and assessment of technological innovation	–1.22064	–0.76471	0.76471	0.76471	–0.4559	12
Product time cycle/product quality level/commercialisation success rate	*–1.22067*	*–1.22064*	*–0.76471*	*0.76471*	*–2.4413*	*4*
Capacity to obtain funds	–1.22067	–1.22064	–0.13971	1.220642	–1.3604	7
Market share	–1.22067	–1.22064	0.13971	1.220642	–1.081	10
Competitive degree of new product/follow-up of market forces	*–1.22067*	*–1.22067*	*–0.43073*	*0.430728*	*–2.4413*	*4*
Capacity to manage internal and external cooperation between departments and communication with suppliers and customers (Wan et al., 2003)	–1.22064	–0.76471	0.430728	1.220642	–0.334	13
Specialised marketing unit/personal quality level	*–1.22067*	*–1.22064*	*–0.13971*	*0.430728*	*–2.1503*	*5*
Percentage of exports	–1.22067	–0.43073	0.13971	0.430728	–1.081	9

Technological innovation is multi-dimensional in nature and no single model is sufficient to explain the performance of technological innovation and innovative behaviour of high-tech companies, especially when it comes to evaluating the organisation's technological innovation activities. However, learning is often used to describe the innovation process. It is true that companies innovate through constant learning processes that generate new technological knowledge (Nonaka and Takeuchi, 1995). Here, the main features of the technological innovation process are (Teece, 1986; Nelson and Winter, 1982) continuous in nature; irreversible and affected by uncertainty. The essence of the technological innovation process is the accumulation of knowledge over time. The increase of the knowledge volume is produced through different creative mechanisms associated with different learning modes, such as: learning from R&D or 'Learn before doing' (Pisano, 1990); 'Learning by doing', which arises spontaneously in the production process (Arrow, 1962); 'Learning by using' (Rosenberg, 1982); and 'Learning by failing', from the analysis of bad decisions by top managers (Madique and Zirger, 1984). Such learning modes, particularly the last three, have a clearly progressive nature in that it generates a continuous flow of technological innovations or new knowledge. Traditionally, more importance has been given to R&D than to other learning modes. And technological innovation in companies is a learning process through a stream of new knowledge. And the capacities are generated for the companies to mobilise and expand their technology, human and financial resources in the innovation process. Resources are always a critical factor for all kinds of activities and processes. Evangelista et al. (1997) propose that technology resources will increase its importance as a strategic factor for the company's performance in the near future. Some studies have also found that resource allocation capacity enables to sustain competitiveness (Yam et al., 2004; Guan and Ma, 2003). Then, an overall performance evaluation of technological innovation capacity was developed for the dimensions considered in the performance of high-tech companies.

3.2 *Phase 2: Modelling the overall performance of technology innovation capacity for the performance of high tech companies*

This section evaluates the dimensions of technological innovation capacities for the performance of companies. This procedure was developed using the multi-criteria analysis.

Figure 2 Evaluation of the technological innovation capacity dimensions for the performance of the firm (see online version for colours)



The methods used were compromise programming, Electre III and Promethee II. The results achieved confirm Hypothesis 1: the technological innovation capacities have positive impact on the performance of high-tech companies, and assigning values to each criterion, we arrive at a matrix of Criteria × Alternatives that together with the vector weights provides the necessary support to apply the multicriteria methods. In other words, one applies the selection and classification methodology of alternatives, using the compromise programming, Promethee II and Electre III methods. The compromise programming due to its wide diffusion and application simplicity and understanding renders it an alternative to evaluate problems as referenced in this application. The problem solution compromise is the one that comes closest to the alternative. This method was designed to identify the closest solution to an ideal one, therefore it is not feasible, using a predetermined pattern of distances. In Promethee II there is a function of preferences for each criterion among the alternatives which must be maximised, indicating the intensity of an alternative to the other one, with the value ranging from 0 to 1.

Of the Electre family (I, II, III, IV and V), Electre III is the one considered for the cases of uncertainty and inaccuracy to evaluate the alternatives in the decision problem. All these methods enable to analyse the discrete solution alternatives, and taking into consideration subjective evaluations represented by numerical scores and weights. As these are problems involving subjective aspects, the methods that best fit the situation of this research are the methods of the family Electre and Promethee. It should be mentioned that although the compromise programming method is not part of this classification, it has similar characteristics, showing much simplicity in order to understand its operation, which makes it feasible for this application.

Within this perspective, the multicriteria methods are viable instruments to measure the performance of the innovation capacity dimensions for the performance of high-tech companies. The results produced by this prioritisation enable managers to better focus their efforts and resources on managing the capacities that perform best, which results in achieving the goals sought by the companies The structure of this prioritisation (classification by hierarchical analysis) is proposed at three planning levels in a judgement matrix, in which at the first hierarchical structure level it defines the goal, which is to achieve the performance of the companies that will feed the system; the criteria are in the second level, which are the performances of the companies: P1: impact on the customer; P2: business results; P3: sales percentage of innovative products; the dimensions of technology innovation capacities are in the third level, the alternatives, which are: D1: R&D capacity (Guan and Ma, 2003; Burgelman et al., 2004; Yam et al., 2004); D2: innovation decision capacity (Barton, 1984); D3: marketing capacity (Achilladelis, and Antonajis, 2001; Guan and Ma, 2003; Yam et al., 2004; Kim et al., 2005); D4: manufacturing capacity (Guan and Ma, 2003; Yam et al., 2004); D5: capital capacity (Yam et al., 2004); D6: resource allocation capacity (Lau et al., 2010); D7: strategic planning capacity (Lau et al., 2010); D8: capacity learning (Lau et al., 2010); D9: organisational capacity (Lau et al., 2010). The prioritisation process obeys the judgement of the evaluators (experts). With the results of the judgement matrix, the methods were applied: Promethee II, Electre III and compromise programming to evaluate the innovation capacities in relation to the performance of the companies. Table 2 shows the results produced.

Table 2 Assessment of preferences – technological innovation capacity × performance of high-tech company

Technology innovation capacity dimensions	*Classification*		
	Promethee II	*Compromise programming*	*Electre III*
R&D capacity/learning	1[a]	1[a]	1[a]
Strategic planning capacity	2[a]	2[a]	3[a]
Resource allocation capacity/organisational capacity/capital capacity	3[a]	3[a]	2[a]
Marketing capacity	4[a]	4[a]	2[a]
Manufacturing capacity	4[a]	4[a]	3[a]

The results produced by the methods demonstrate the R&D and learning capacities as the most significant ones to ensure the performance of the company. When comparing the results in terms of performance, the compromise programming and Promethee II methods did not differ in their classifications. For Electre III, the results were incompatible. And this is because the p, q and v veto thresholds, respectively, of indifference, strong preference and veto or incomparability have a discrepancy in the structure of their results (classification). Electre III presents a set of solutions with a more flexible hierarchical structure. This is due to the conception of the method, as well as the quite explicit consideration of the indifference and incomparability aspect between the alternatives. The results referenced by the Promethee II and compromise programming methods reflect the preference, according to the experts, for R&D and learning in the technological innovation capacities.

The essence of the technological innovation process is the accumulation of knowledge over time. The increase of the knowledge volume is produced by different mechanisms associated with different learning modes, such as: learning derived from R&D or learning before doing (Pisano, 1990); learning by doing, which arises spontaneously in the production process (Arrow, 1962); learning by using, which is from observing the different ways in which customers use the company's products (Rosenberg, 1982); and learning by failing, from the analysis of bad decisions by top managers. These learning modes, especially the last three, have a clearly progressive nature in that it generates a continuous flow of technological innovations. But traditionally the greatest importance goes to R&D than to the other learning modes (Nieto, 2004). Based on the specialised literature (Evangelista et al., 1997) R&D has a strong impact on a company's performance. R&D is a core component of the technological innovation activities of firms (Evangelista et al., 1997). In fact, many studies on innovation use R&D as technology innovation indicators. R&D is considered a key aspect of innovative activities. Next, the degree of correlation between the dimensions of innovation capacities was determined. For this Spearman's multivariate statistical technique was used. The technique adapts to the case in question.

3.3 Phase 3: Determining the correlation of the companies' technological innovation capacity

In this section the correlations between technological innovation capacities of the companies are determined. Spearman's correlation is often used to describe the relationship between two ordinal characteristics. The data were extracted by the experts from a judgement matrix. Table 3 shows the results.

Table 3 Correlation of the technological innovation capacity dimensions of the firm

Variables: technological innovation capacity dimensions		*Technological innovation capacity in the performance of firm*								
		1	*2*	*3*	*4*	*5*	*6*	*7*	*8*	*9*
D1	R&D capacity (Guan and Ma, 2003; Burgelman et al., 2004; Yam et al., 2004)	1								
D2	Innovation decision capacity (Barton, 1984)	*0.81*	1.00							
D3	Marketing capacity (Achilladelis, and Antonajis, 2001; Guan and Ma, 2003; Yam et al., 2004; Kim et al., 2005)	0.72	*0.92*	1.00						
D4	Manufacturing capacity (Guan and Ma, 2003; Yam et al., 2004)	0.85	0.50	0.52	1.00					
D5	Capital capacity (Yam et al., 2004)	0.74	0.55	0.46	0.59	1.00				
D6	Resource allocation capacity (Lau et al., 2010)	0.25	0.27	0.14	0.15	0.70	1.00			
D7	Strategic planning capacity (Lau et al., 2010)	0.13	*(0.02)*	*(0.06)*	0.32	*(0.17)*	*(0.24)*	1.00		
D8	Learning capacity (Lau et al., 2010)	0.47	0.30	0.33	0.50	0.53	0.08	0.40	1.00	
D9	Organisational capacity (Lau et al., 2010)	0.45	0.35	0.06	0.16	0.62	0.35	*(0.10)*	0.32	1.00

Grouping the capacity dimensions, there is a strong correlation between the innovation decision capacity, R&D and marketing efforts. It is also seen that the planning capacity has no correlation with the other capacities. Planning is the company's capacity to identify internal and external strengths and weaknesses, opportunities and threats, and to formulate plans in accordance with the corporate outlook and mission. The results achieved are aligned with the state of the art that indicates a strong correlation between R&D and marketing and innovation decisions.

3.4 Phase 4: Modelling of the optimal efficiency rate of a company's technology innovation performance capacity

This phase focuses on determining the optimal efficiency rate (OERP) of the high-tech companies' technology innovation capacity using neurofuzzy modelling. It is a process whose attributes usually possess high subjectivity characteristics, in which the experience of the decision maker is very significant. Thus, within this spectrum there is the need for a tool that allows adding quantitative and qualitative variables that converge towards a single evaluation parameter (Oliveira and Cury, 2004; Von Altrock, 1997).

This model combines the neural networks and logic fuzzy technology (neurofuzzy technology). Here, this model supports the planning of technological innovation capacities of high-tech companies, as it allows to evaluate the desirable rate toward the acceptable performance of high-tech companies. The model shown here uses the model of Oliveira and Cury (2004). Based on the neurofuzzy technology, the qualitative input data are grouped to determine the comparison parameters between the alternatives. The technique is structured by combining all attributes (qualitative and quantitative variables) in inference blocks (IB) that use fuzzy-based rules and linguistic expressions, so that the preference for each alternative priority decision of the optimal rate of technological innovation performance determinants, in terms of benefits to the company, can be expressed by a range varying from 0 to 10. The neurofuzzy model (Figure 3) consists of qualitative and quantitative variables, based on information from the experts.

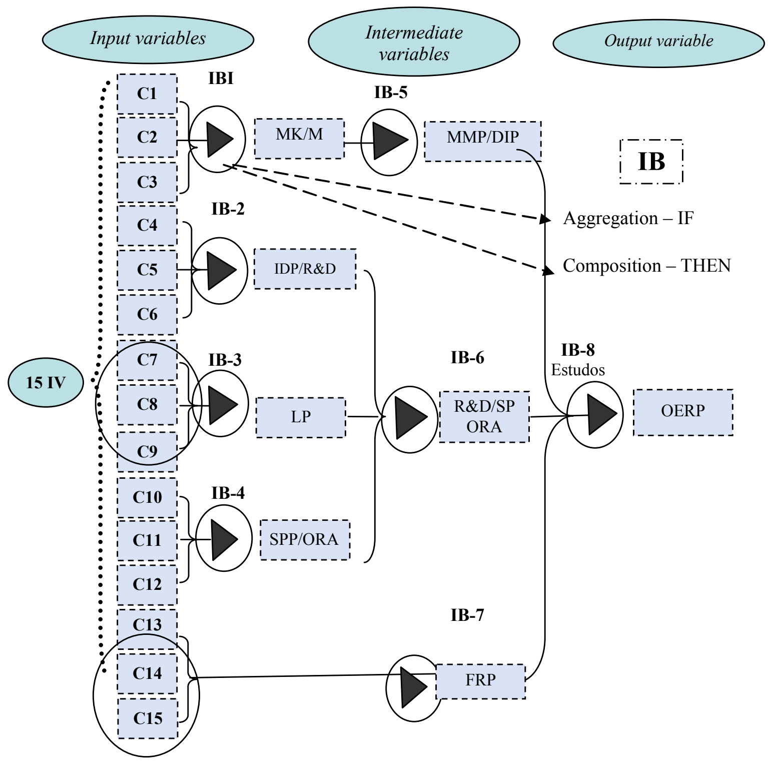
3.5 Determination of input variables

This section focuses on determining the qualitative and quantitative input variables (IV). These variables were extracted (15 variables) from the independent variables (dimensions of technological innovation capacity of the companies). The linguistic terms assigned to each IV are: high, medium and low. Accordingly, Table 1 shows the IVs in the model, which are transformed into linguistic variables with their respective degrees of conviction or certainty (DoC), with the assistance of 20 judges opining in the process. The degrees attributed by the judges are converted into linguistic expressions with their respective DoCs, based on fuzzy sets and IT rules (aggregation rules), next (composition rules).

3.6 Determination of intermediate variables and linguistic terms

The qualitative IV go through the inference fuzzy process, resulting in linguistic terms of intermediate variables (IVar). Thus, the linguistic terms assigned to IVar are: low, medium and high. The IVar were obtained from: marketing performance and manufacturing; innovation decision performance and R&D; learning performance; strategic planning performance, organisation and resource allocation. The configurations are marketing and manufacturing performance; decision innovation performance, R&D, strategic planning, organisation and resource allocation; financial return performance. The architecture proposed is composed of eight expert fuzzy system configurations, four qualitative IV that go through the fuzzy process and through the inference block, thus producing an output variable (OV), called intermediate variable (IVar).

Figure 3 Neurofuzzy model (see online version for colours)



Then, the IVars, which join the other IVar variables form a set of new IVars, thereby configuring a sequence until the last layer in the network. In the last layer of the network the OV of the neurofuzzy network is defined. This OV is then subjected to a defuzzification process to achieve the final result: optimal efficiency rate of technological innovation capacity performance of high-tech companies. In summary, the fuzzy inference occurs from the base-rules, generating the linguistic vector of the OV, obtained through the aggregation and composition steps. For example, when the experts' opinion was requested on the optimal efficiency rate for the technological innovation capacity performance of company A, the response was 8.0. Then the fuzzification (simulation) process was carried out, assigning LOW, MEDIUM and HIGH linguistic terms to the assessment degrees at a 1 to 10 scale. Degree 8, considered LOW by 0% of the experts, MEDIUM by 55% and HIGH by 45% of the experts. In summary, the expert's response enabled to determine the degree of certainty of the linguistic terms of each of the IV using the fuzzy sets. The results confirm the H2: the optimal efficiency rate depends on the combination and interaction of the innovation capacities of the high-tech companies. The generic fuzzy sets were defined for all qualitative IVars, which always exhibit three levels of linguistic terms: a lower, a medium and a higher one. After converting all IVars into its corresponding linguistic variables with their respective DoC, the fuzzy IB, composed of IF-THEN rules, are operated based on the MAX-MIN operators, obtaining a linguistic value for each IVar and OV of the model, with the linguistic terms previously defined by the judges. With the IV (features extracted from product development projects), the rules are generated. Every rule has an individual weighting factor, called certainty factor (CF), between 0 and 1, which indicates the degree of importance of each rule in the *fuzzy* rule-base. And the *fuzzy* inference occurs from the rule-base, generating the linguistic vector of OV, obtained through the aggregation and composition steps.

3.7 Determination of OV – optimal efficiency rate of technological innovation capacity

The OV of the neurofuzzy model proposed was called optimal efficiency rate of technological innovation capacity in high-tech companies. The fuzzification process determines the pertinence functions for each input variable. If the input data values are accurate, results from measurements or observations, it is necessary to structure the fuzzy sets for the IV, which is the fuzzification process. If the IV is obtained in linguistic values, the fuzzification process is not necessary. A fuzzy set A in a universe *X*, is a set of ordered pairs represented by equation (1).

$$A = \left\{ \left(\mu_A(x), x \right) \middle| x \in X \right\} \tag{1}$$

where (*x*) is the pertinence function (or degree of pertinence) of *x* in *A* and is defined as the mapping of *X* in the closed interval [0, 1], according to equation (2) (Pedrycz and Gomide, 1998).

$$\mu_A(x) : X \rightarrow [0,1] \tag{2}$$

Fuzzy inference: The fuzzy inference rule-base consists of IF-THEN rules, which are responsible for aggregating the IV and generating the OVs in linguistic terms, with their respective pertinence functions. According to Von Altrock (1997), a weighting factor is assigned to each rule that reflects their importance in the rule-base. This coefficient is called CF, and can vary in range [0, 1] and is multiplied by the result of the aggregation (IT part of inference). The fuzzy inference is structured by two components:

1 aggregation, i.e., computing the IF rules part

2 composition, the THEN part of the rules.

The DoC that determines the vectors resulting from the linguistic processes of aggregation and composition are defined with equation (3).

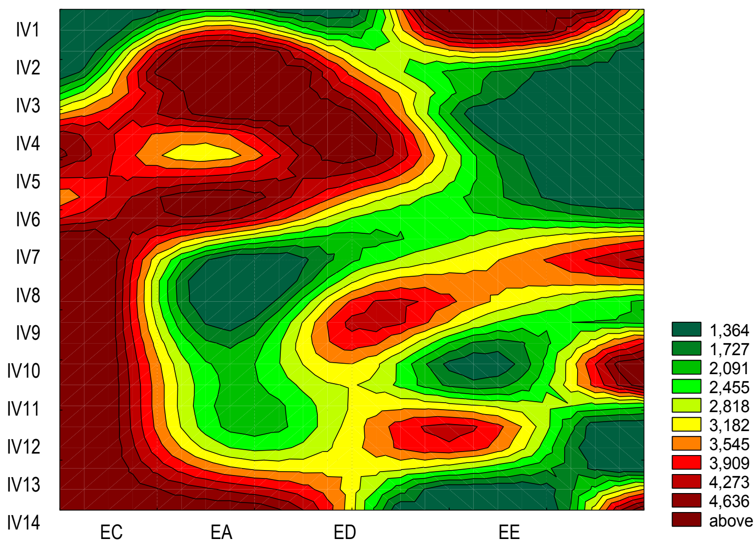
$$DoC: \begin{array}{l} \max\left[FC_1 \cdot \min\left\{ GdC_{A11}, GdC_{A12}, \ldots, GdC_{1n} \right\}, \ldots, \right. \\ \left. \qquad FCn \cdot min\left\{ GdC_{An1}, GdC_{An2}, \ldots, GdC_{Amn} \right\} \right| \end{array} \tag{3}$$

Defuzzification: for the applications involving qualitative variables, as is the case in question, a numerical value is required as a result of the system, called defuzzification. Thus, after the fuzzy inference, fuzzification is necessary, i.e., transform linguistic values into numerical values, from their pertinence functions (Von Altrock, 1997). The IT maximum centre method was popularised to determine an accurate value for the linguistic vector of OV. Based on this method, the degree of certainty of linguistic terms is defined as 'weights' associated with each of these values. The exact value of commitment (VC) is determined by considering the weights with respect to the typical values (maximum values of the pertinence functions), according to equation (4) presented below (Von Altrock, 1997; Oliveira and Cury, 2004).

$$OV = \frac{\sum_{i=1}^{n} DoC_i \cdot X_i}{\sum_{i=1}^{n} DoC_i \cdot X_i} \tag{4}$$

where DoC_i represents the DoC of the linguistic terms of the final OV and X_i indicates the end of the typical values for the linguistic terms, which correspond to the maxima of fuzzy sets that define the final OV. By way of demonstration, using assigned IT (average) hypothetical (company A) enters-IT into the calculation expression of $TPCIT_j$ with $GdCi$ of the following linguistic vector of the OV, also hypothetical: Low = 0.30, Middle = 0.49, High = 0.14. The numerical value of OERP at a 0 to 1 scale corresponds to 0.7352, resulting from the arithmetic mean of the values resulting from the defuzzification of each of the simulated 20 judges. This value corresponds to an average value for OERP. With this result (optimal efficiency rate: 0.7352) produced for a better combination and interaction of strategic innovation capacity dimensions (innovation activities) that converged toward a single parameter, it is feasible to assert that this combination of technological innovation activities of the firm at this time, can at least ensure the performance desired by the firm at that time. It is plausible that the company maintains at least this value (0.7352), which ensures the desired performance. It is also plausible to state that, to some degree, there is efficiency in the management of those planning innovation in this category of companies. To illustrate this, assuming that the study-object companies demonstrate the following optimal efficiency rates: A-0.7352; B-0.3542; C-0.8432; D-0.4983; AND-0.4782. The expected reference performance for all firms is 0.56 (hypothetical) (Figure 4). It is concluded that:

Figure 4 Optimal efficiency rate of technological innovation capacity (see online version for colours)



Companies A and C show efficiency in the combination of their innovation activity strategies, based on the performance expectations (P1: impact on the customer; P2: business results; and P3: percentage sales of innovative products). The priorities of innovation activities are dynamic and dependent on constraints and uncertainties that come from the environment at any given time. Companies B, D and F are not efficient in combining their strategies for innovation activities, since they do not meet the desired performance expectations. The environmental contingencies are crucial and essential to adapt the strategies. The modelling approach presented here enables this sophistication refinement for every contingency presented.

4 Final considerations

4.1 Conclusions and implications

The objective of this study was to contribute to an innovation planning policy for high-tech companies in Brazil. Therefore, it presents a methodology to assess the impacts of technological innovation capacity performance in this category of companies. The study strived to fill a gap in the existing literature on innovation planning from the perspective of technological innovation capacity. Thus, a set of psychometric scaling methods, multicriteria analysis and artificial intelligence was conceived, within a context of uncertainty and subjectivity. This procedure enables to reduce the subjectivity in the results achieved. The compelling presupposition assumed is acknowledging the importance of subjectivity in the decision-makers' judgement; their values, their goals, their biases, their culture, their intuition, as well as the influence of subjective factors on the perception and understanding of the variables involved.

Here, the modelling approach presented gains emphasis, such diversity of methods when combined are valuable tools with great potential and significant added value, contributing to the robustness of the modelling. The feasibility of the neurofuzzy technology, especially in the interaction of qualitative and quantitative variables used in the modelling process, is instrumental for the optimum efficiency rate of technological innovation performance for high-tech companies. Because it is a procedure in which the attributes have subjectivity characteristics, with the intervention of specialists, the neurofuzzy technology was crucial and significant to classify the qualitative and quantitative variables converged to a single parameter, the optimal efficiency rate of technological innovation performance. This facilitates decision making within a context of uncertainty. This proposal is an additional tool available to managers, which helps to greatly reduce the uncertainty of technological innovation decisions. There are of course several issues to be further explored in other such studies, and is hoped that it contributed to a plausible methodological discussion, with much still to be explored. Innovation admittedly poses significant challenges to both research and practice, requiring the need for active learning in high-tech companies. This learning capacity involves not only the development of new capabilities within a company, but also crosses borders. Interactions with other companies, other knowledge sources and experts are becoming an important and emerging focal point for technological innovation.

Of the different dimensions, the results show a predominance of R&D efforts. However, such innovation capabilities have to keep up with up-to-date changes and should be viewed as a priority of the present moment, with regards to systemic efforts guided by defining and redefining the performance of high-tech companies over time. It is plausible that building capacities occur over a continuous process and converge to the desired performance, which is in constant transformation through the new demands. Therefore, the innovation policy for companies in this category should be anchored by efficient planning. Hopefully the R&D capacities can open way, hence allowing high-tech companies to expand their existing technologies and to establish new technologies or improve the R&D functions. The R&D capacity comprises, for the most part, a significant number of researchers employed (Lefebvre et al., 1991), the success rate of R&D auto-generated products by innovative products, number of patents (OECD, 1992; Achilladelis and Antonajis, 2001), and R&D intensity (Sterlacchini, 1999; Manu and Sriram, 1996; OECD, 1992; Achilladelis and Antonajis, 2001; Yam et al, 2004).

These criteria are measured quantitatively and qualitatively. However, the innovation decision capacities refer to the capacity to enforce innovative technology decisions in the company. These capacities include the degree of R&D innovation, the collaboration intensity with other companies or R&D centres (Lefebvre et al., 1991; Achilladelis and Antonajis, 2001), the R&D capacity to share knowledge (Guan and Ma, 2003), forecasting and evaluating technological innovation (Yam et al., 2004; Burgelman et al., 2004), and business innovation initiatives (Guan and Ma, 2003). These capacities are evaluated subjectively. Marketing resources indicate a solid capacity to promote and sell products based on demand, which is primarily influenced by the market (Manu and Sriram, 1996), degree of competitiveness of new products, monitoring of market forces (Guan and Ma, 2003), marketing specialised unit (Achilladelis and Antonajis, 2001), and the percentage of exports (Sterlacchini, 1999; OECD, 1992; Guan and Ma, 2003). All these variables are subjective in nature. Secondly, the efforts are for production capacity, in which companies must transform R&D into results of product and technical improvement and product quality. Manufacturing capacities, such as advanced manufacturing technology (Guan and Ma, 2003), the level of product quality, success rate of commercialisation (Yam et al., 2004), quality level of production personnel (Yam et al., 2004) and product cycle time (Guan and Ma, 2003) are evaluated subjectively. Finally, capital capabilities that are necessary to ensure that the advance of the companies' technological capacities are mainly from fundraising capabilities, optimal allocation of capital inflow (Burgelman et al., 2004), capital intensity (Sterlacchini, 1999; Guan and Ma, 2003) and return on investment (Manu and Sriram, 1996). It is also evident that the technological innovation capacities are a dynamic list of priorities, depending on the essential and desired existing capacities that emerge over practice time, always bringing new concepts and demanding new behaviours, new content and technical implementations, thus fundamentally requiring to permanently reconfigure the new capacities for the new innovation performances. Regarding this effort, the research on such priorities should be applied permanently and periodically.

4.2 Limitations of the study and future perspectives

Of the findings of the state of the art and state of practice, it is reasonable to state that this research is vulnerable to criticism. This study includes several limitations as specified below, which also helps to identify potential areas for future studies. Firstly, the study is based on the state of the art to establish the structure and contents of the model. With this spectrum, any attempt to consolidate a reconstruction and a consistent interpretation requires, first of all, analysing the appropriate literature of events, produced by facts acquired through reliable research, i.e., extracted under conditions to obtain results that are closer to reality. And the first question about the construction or reconstruction of a model is with regards the selection, made from a profusion of events and facts that can be considered.

In the research, cross-sectional data used in this study may not be appropriate to establish fundamental relationships between variables, but as referenced by Kenny (1979), the relationships that use cross sections are satisfactory and popularly accepted in relationship tests. Furthermore, a survey was developed for Brazilian companies in a static context, which may represent a limiting factor. Therefore, it is recommended to reproduce and replicate the model in companies from other countries in order to confirm the results.

It is also recommended that the innovation capacity dimensions should be extracted from the state of the art, but strongly confirmed by the state of practice, by the judgement of other experts (from other countries), taking into account that values, beliefs, cultures and experiences are determinants in the assessment, which can overturn the effects on the results. It is also underscored that the methodologies and technical basis of this modelling should undergo evaluation by a multidisciplinary team of specialists permanently and periodically, hence proposing possible additions or adjustments to these methodologies. And also replace some of the technical implementations used herein by others, in order to provide a similar role to verify the robustness of the model.

Of the research findings, the high-tech industries undertake the ever-fast changes, intense competition and a highly uncertain and risky environment. The effect produced by technology on the development of new products is equally intensive. R&D is crucial for innovation capacity. It confirms the state of the art. Shanklin and Ryans (1984) suggest that high-tech companies anticipate potential technical and scientific capabilities that provide quick responses to the existing techniques, enabling to meet the market demands to be constructed or altered. It is reasonable to focus efforts on R&D, thereby creating an internal stock of scientific knowledge (Feinberg and Majumdar, 2001; Griliches, 1979; Hall and Mairesse, 1995), which enables to develop and introduce new products, lower production costs, more competitive prices and greater financial return (Kafouros, 2008a, 2008b). R&D has indirect effects on increasing the organisational learning, enables to understand external ideas and technologies and apply them to the ultimate business outcome (Cohen and Levinthal, 1989) and also contributes to identifying areas that are still technologically unexplored (Miller et al., 2007). This logic will be maintained, however only through opening spaces for the various strata: partners, suppliers and customers. Nevertheless, the capacity to innovate high-tech companies will have to be anchored in efficient planning policies. One can argue that Brazil's high-tech industry still has a long way to go and also has tremendous growth potential. Hopefully, Brazil can become a technological and competitive nation.

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Integrated inventory model with uniform demand for one vendor one customer

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Abstract: This article investigates the problems in inventory system and develops a model, integrated vendor-customer inventory policy for items with imperfect quality also with inspection errors and shortage cost. Quantity of delivered items to the customer is identical at each shipment. Production process is imperfect and it may produce certain number of defective items. Screening process is conducted at the customer's end, but the inspector may incorrectly classify a non-defective item as defective or incorrectly classify a defective item as non-defective. Integrated total cost of the vendor and the customer is calculated to provide the optimal solution. Each lot contains a variable number of defective items and completely backordered, shortages are permitted. The objective is to minimise the total costs. An impressive cost reduction is shows through integrated model in comparison to an independent decision, with the help of numerical examples.

Keywords: joint economic lot size; total relevant cost; absolute cost; quantity discount; inspection error; shortage cost.

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1 Introduction

To obtain an economic order quantity based on the many assumptions, for the most economical batch size in a stock or in a production facility, one assumption is that the items produced by the facility are all of a perfect quality, another is that the screening process that identifies the defective items in a lot. Then the screening process is adopted to identify the imperfect items. Also there may be some inspection errors in the imperfect screening process.

Traditional economic order quantity (EOQ) models offer a mathematical approach to determine the optimal number of items a customer should order to a supplier each time. One major implicit assumption of these models is that all the items are of perfect quality. However this is not always the case, as often a number of the items are imperfect. Porteus (1986) and Rosenblatt and Lee (1986) were among the first to study the effect of imperfect items into EOQ and economic production quantity (EPQ) models. Since then, several studies have incorporated the effect of imperfect items into different EOQ and EPQ models, most notably in Salameh and Jaber (2000), who considered a situation in which an average percentage of all items ordered are imperfect. The customer conducts an inspection of all the items to separate the imperfect items from the perfect ones. Formulating the problem, the optimal order quantity is derived. Salameh and Jaber (2000) model has been extended in several directions.

Supply chain management focuses on the material and information that flows between the facilities and their final customer; it is one of the most popular operations strategies for improving organisational competitiveness. Cao and Zhang (2010) showed that firms have been attempting to achieve greater collaborative advantages with their supply chain partners in the past few decades; this means that the vendor and the buyer should work together in a cooperative manner towards maximising their mutual benefits. Integrated inventory management has recently received a great deal of attention. Hill (1999) determined the optimal production and inventory policy for a vendor manufacturing to supply to a single buyer.

Goyal (1976) considered the joint optimisation problem of a single vendor and a single customer, in which he assumed that the vendor's production rate is infinite, on the other hand Banerjee (1986) assumed finite rate of production and developed a joint economic-lot-size (JELS) model for the products with a lot-for-lot shipment policy. He demonstrated the advantage of the JELS approach through an analysis of the cost trade-offs from the perspective of each party's optimal position. It was shown that a jointly optimal ordering policy, together with an appropriate price adjustment, could be economically beneficial for both the vendor and the customer. By relaxing the Banerjee's (1986), lot-for-lot assumption, Goyal (1988) developed a joint total relevant cost model for a single-vendor single-customer production-inventory system in which each production batch was shipped to the customer in smaller lots of equal size. Lu (1995) considered the single-vendor multi-buyer integrated inventory problem with the objective of minimising the vendor's total cost subject to the maximum costs which the buyers were prepared to incur. Aderohunmu et al. (1995) showed that a significant cost reduction could be achieved to the advantage of both the vendor and the buyer in a just in time environment.

The traditional EOQ model assumes that items produced are of perfect quality. Some researchers argue that product quality is not always perfect, but is directly affected by the reliability of the production process used. Therefore, the process may deteriorate and produce defectives or poor-quality items. Salameh and Jaber (2000) developed an economic order quantity model where a random proportion of the items in a lot are defective. Huang (2010) extended the integrated vendor-customer inventory model by accounting for imperfect-quality items. He considered the situation where the delivery quantity sent to them was identical for each shipment. Goyal and Cárdenas-Barrón (2002) used model to determine an optimal integrated vendor-customer inventory policy for an item with imperfect quality. The objective is to minimise the total joint annual costs incurred by the vendor and the customer. Wee et al. (2007) extended the approach by Salameh and Jaber (2000) to consider permissible shortage backordering and the effect of varying backordering cost values. Bacel and Jaber (2008) corrected a flaw in the Salameh and Jaber (2000) model by using the renewal reward theorem. They came up with simpler expressions for the expected profit and the order quantity. Yoo et al. (2009) proposed a profit-maximising EPQ model that incorporated both imperfect production quality and two-way imperfect inspection, that is, type I inspection error of falsely screening out a proportion of non-defects and disposing of them and type II inspection error of falsely not screening out a proportion of defects. However, due to imperfect product quality, shortages may sometimes occur. Siajadi et al. (2006) presented a new methodology to obtain the joint economic lot size in the case where multiple buyers were demanding one type of item from a single vendor.

Kumar et al. (2011) presented the economic production lot size (EPLS) model which accounts for a production system producing perfect and imperfect quality items. Also, a single period multi-item volume flexible production model for deteriorating items with stochastic demand and stochastic imperfect production. Deterioration is taken as constant. Linear holding cost is considered in his model. Mikdashi's (2012) model is one of the simplest inventory models, the classical EOQ model assumes that the quantity obtained is exactly equal to the quantity requested, so that there are no lost items. Also, the EOQ model assumes that the demand is known and fixed, and replenishment is instantaneous. Chiu et al. (2011) concerned with joint determination of the optimal lot size and optimal number of shipments for an economic production quantity (EPQ) model with the reworking of random defective items produced.

Shaw and Khan (2012) considered uncertainty is the major attribute in managing the supply chains. Developed heuristic methods to determine optimal inventory policies of facilities in a supply chain system under fuzzy stochastic environment. The total cost of the inventory system is computed using defuzzification methods. Prakash and Nithya (2012) presented an entropic fuzzy economic order quantity with imperfect quality items in a fuzzy situation by employing the type of fuzzy numbers which are triangular. The objective is to determine the optimal order lot size to maximise the total profit.

The purpose of this paper is to develop an integrated vendor-customer inventory model for items with imperfect quality considering backordering and shortage. We develop a mathematical model that integrates the vendor's and the customer's annual cost taking into consideration imperfect-quality items and shortage cost. In order to illustrate important aspect of the model numerical example is given.

2 Notations and assumptions used in the model

We consider a simple supply chain problem with a single vendor and a single customer. The customer has an annual demand rate of D units for the given product and places regular orders of fixed size Q_P. The vendor prepares for the repeating flow of orders of size $Q_P = nQ$ from the customer by producing items in batches of size Q_P and planning to have each batch delivered to the customer in n deliveries, each with a lot of Q units. The vendor fulfills the shipments of Q units with a known and fixed lead time. Since the production process is not perfect, some of the items produced may be defective. Once the customer receives the lot of Q units, a 100% screening process is conducted.

We assume the screening process and demand take place simultaneously. The screening process is also not perfect, involving type I and type II inspection errors. The objective is to minimise the total joint annual costs incurred by the vendor and the customer. Since all customers are assumed to be willing to wait for a later shipment at some known cost, shortages at the customer are allowed and backordered.

2.1 Notations

Q_P the size of a production batch of items at the vendor

Q the size of the deliveries from the vendor to the customer

B the maximum backordering quantity in units at the customer

n the number of deliveries per batch production run, a positive integer ($Q_{PR} = nQ$)

D the annual demand of the customer

PR the annual production rate ($PR > D$) at the vendor

Sv the setup cost per production run for the vendor

S_B the ordering cost per order for the customer

X the screening (inspection) rate

P the probability that an item produced is defective

$f(P)$ the probability density function of P

e_1 the probability of a type I error (classifying a non-defective item as defective)

$f(e_1)$ the probability density function of e_1

e_2 the probability of a type II error (classifying a defective item as non-defective)

$f(e_2)$ the probability density function of e_2

c_i the customer's inspection cost per unit

c_w the vendor's unit cost for producing a defective item

c_{aB} the customer's cost of a post-sale defective item

c_{av} the vendor's cost of a post-sale defective item

c_a the cost of accepting a defective item ($c_a = c_{aB} + c_{av}$)

c_r the cost of rejecting a non-defective item

v the vendor's unit warranty cost per defective item for the customer

d the screening cost per unit

b the backordering cost per unit per year at the customer

g the probability that an item produced is defective

$f(g)$ the probability density function of g

hv the holding cost per unit per year for the vendor

h_B the holding cost per unit per year for the customer

F the freight (transportation) cost per shipment from the vendor to the customer

T time interval between successive shipments of Q units

T_1 period during which the vendor produces

T_2 period during which the vendor supplies from inventory

Tc cycle time = $T_1 + T_2 = nT$

2.2 Assumptions

1. The demand rate is known, constant, and continuous.
2. The lead time is known and constant.
3. The production processes are imperfect and may produce defective items. The defective percentage γ has a probability density function $f(\gamma)$. To ensure that the vendor has enough production capacity to produce the customer's annual demand, it is assumed that $E(\gamma) < 1–D/P$.
4. The inspection process is also imperfect. The probability of classifying a non-defective item as defective is e_1 with a probability density function $f(e_1)$.
5. The probability of classifying a defective item as non-defective is e_2 with a probability density function $f(e_2)$.
6. The customer returns all items classified as defective and those returned from the customers to the vendor at the end of the 100% screening process, and receives a full price refund from the vendor. Thus, a defective item incurs a cost of c_w for the vendor. The vendor will sell the returned items at a discounted price to a secondary market. Therefore, c_r (the cost of rejecting a non-defective item) is the difference between the regular and the discounted prices.
7. Customers who buy the defective items will detect the quality problem and return them to the customer and receive a good (replaced) item from the customer. Both the vendor and the customer incur a post-sale failure cost (e.g., loss of good will) for the items returned from the market.
8. Shortage is completely backordered.
9. A single product is considered.
10. There is a single vendor and a single customer.

3 Mathematical models

The customer's cost per cycle: consider a lot size Q being delivered to the customer. It is assumed that 100% inspection is done on the lot at the beginning of each cycle. Each lot contains a percentage P of defective items at the probability density function $f(P)$.

After screening the items, an inspector may incorrectly classify a non-defective item as defective with probability e_1, and the probability density function is $f(e_1)$, or the inspector may identify a defective item as non-defective with probability e_2 and the probability density function is $f(e_2)$. It is assumed that the customer returns all the items classified as defective by the inspector and the items returned from the market to the vendor as a single batch at the end of the screening process.

For each item being returned from the market, the customer and the vendor incur a post-sale failure cost (such as loss of good will) C_{aB} and C_{aV} respectively. If the vendor and the customer do not work together in a cooperative manner towards maximising their mutual benefits, and the customer makes his own decision independent of the vendor, then the vendor will produce and deliver the items to the customer on a lot for lot basis.

So, by definition, we have

$$B_1 = Q.(1-P)e_1 + Q.P(1-e_2) \tag{1}$$

and

$$B_2 = Q.P.\, e_2 \tag{2}$$

Let D^1 be the effective demand then

$$D^1 = D + \frac{B_2}{T} \text{ (regular demand and the returned item) } s$$

So, the cycle length of each delivery of size Q is $T = \dfrac{Q - B_1}{D^1}$

$$\therefore T = \frac{Q - B_1}{D} + \frac{B_2}{T}$$

$$T\left(D + \frac{B_2}{T}\right) = (Q - B_1)$$

$$T = \frac{Q - B_1 - B_2}{D}$$

Replacing the values of B_1 and B_2 according to the equations (1) and (2)

$$T = \frac{Q - [Q(1-P)e_1 + QP(1-e_2)] - QPe_2}{D} = \frac{Q(1-e_1) + QP(e_1 - 1)}{D} = \frac{Q(1-e_1)(1-P)}{D}$$

Holding or delivery cost is

$$H_c = h_B\left\{B_1 \frac{Q}{x}\right\} + \frac{(Q-B_1)T}{2} + h_B\left(\frac{B_2 T}{2}\right)$$

According to the value of B_1 and B_2

$$H_c = h_B\left\{Q(1-P)e_1 + Q.P(1-e_2)\frac{Q}{x} + \frac{(Q-B_1)T}{2}\right\} + h_B\left(\frac{B_2T}{2}\right)$$

$$\begin{aligned}&\therefore h_B\left[\begin{aligned}&Q(1-P)e_1 + Q.P(1-e_2)\frac{Q}{x} + \frac{1}{2D}\{Q - Q(1-P)e_1\\&+Q.P(1-e2)\}Q(1-P)(1-e_1)\}\end{aligned}\right]\\&+h_B\left\{\left(\frac{1}{2D}Q.P.e_2.Q(1-P\right)(1-e_1)\right\}\end{aligned} \tag{3}$$

From equation (3)

$$\therefore h_b\left[\begin{aligned}&\frac{Q^2}{x}\{(1-P)e_1 + P(1-e_2)\} + \frac{Q^2}{2D}\\&\left[\{1-(e_1+P) + P(e_1+2e_2)\}(1-P)(1-e_1)\right]\end{aligned}\right] \tag{4}$$

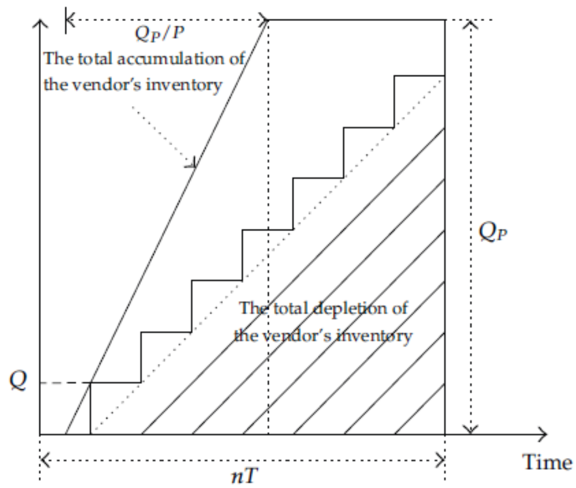
As shortages are allowed, B_2 is the no. of items that are returned from the market in each delivery of Q units, so the B_2 units are shortages at each delivery.

$$\therefore \textit{Shortage cost} = \frac{1}{2}b.n.\frac{(B_2)^2}{D} = \frac{1}{2}b.n.\frac{(QPe_2)^2}{D}$$

So, the customer's inventory cost per cycle consists of costs due to placing an order, transportation, inspection and post sale failure costs, screening, holding and backordering (shortage), the customer will return the defective items to the vendor,

$$\begin{aligned}&\therefore TC_B(n,Q,B) = S_B + nF + nC_iQ + nC_{aB}Q.Pe_2 + nh_B\left[\frac{Q^2}{x}\{(1-P)e_1 + P(1-e_2)\}\right]\\&+\frac{Q^2}{2D}[\{1-e_1+P) + P(e_1+2e_2)\}(1-P)(1-e_1)] + \frac{1}{2}b.n.\frac{(QPe_2)^2}{D}\end{aligned} \tag{5}$$

Figure 1 Behaviour of the inventory over time for the vendor and the customer



For the non-defective items, the maximum inventory level is $Q - B_1 - B_2$ and the minimum inventory level is 0, so the average inventory level is $\frac{Q - B_1 - B_2}{2}$.

Since we assume that the customer will return all defective items to the vendor upon receipt of the next lot.

$T = \frac{Q - B_1 - B_2}{2}$ the customers holding cost per cycle is

$$h_B \left\{ B_1 T_1 + \frac{(Q - B_1)T}{2} \right\} + hB \left\{ \frac{B_2 T}{2} \right\}$$

The vendor's cost per cycle:

Holding cost per cycle = h_v {bold area – shaded area}

$$= h_v \left\{ \left[nQ\left(\frac{Q}{PR}\right) + (n-1)T - \frac{nQ\left(\frac{nQ}{PR}\right)}{2} \right] - T[Q + 2Q + \ldots + (n-1)Q] \right\}$$

$$= h_v \left\{ \begin{array}{l} \left[nQ\left(\frac{Q}{PR}\right) + (n-1)\frac{Q(1-P)(1-e_1)}{D} - \frac{nQ\left(\frac{nQ}{PR}\right)}{2} \right] \\ - \frac{Q(1-P)(1-e_1)}{D}[Q + 2Q + \ldots + (n-1)Q] \end{array} \right\} \tag{6}$$

So total cost of vendor's per cycle after adding the costs of setup, warranty, and type I and type II errors,

$$\begin{aligned} TC_v(n,Q) &= S_v + nC_w QP + nC_p(1-P)e_1 + nC_{av}QPe_2 \\ &\quad + h_v \left\{ \frac{nQ^2}{PR} - \frac{n^2Q^2}{2PR} + \frac{n(n-1)Q^2(1-P)(1-e_1)}{2D} \right\} \end{aligned} \tag{7}$$

The total cost of vendor-customer integrated cost per-cycle is,

$$\begin{aligned} &TC_c(n,Q,B) = TC_v(n,Q) + TC_B(n,Q,B) \\ &= S_B + nF + nC_iQ + nC_{aB}QPe_2 + nh_B \left\{ \frac{Q^2}{x}[(1-P)e_1 + P(1-e_1)] \right\} \\ &+ \frac{Q^2}{2D}[\{1 - (e_1 + P) + P(e_1 + 2e_2)\} \\ &(1-P)(1-e_1)] + \frac{1}{2}b.n.\frac{(Q.P.e_2)^2}{D} + S_v + nC_wQP + nC_p(1-P)e_1 + nC_{av}QPe_2 \\ &+ h_v \left\{ \frac{nQ^2}{PR} - \frac{n^2Q^2}{2PR} + \frac{n(n-1)Q^2(1-P)(1-e_1)}{2D} \right\} \end{aligned} \tag{8}$$

Since $T_c = n.\dfrac{Q(1-P)(1-e_1)}{D}$

$$E[T_c] = \frac{nQ(1-E[P])(1-E[e_1])}{D} \tag{9}$$

Using the renewal reward theorem, the expected total annual cost of the vendor and the customer is

$$\begin{aligned}
ETC(n,Q) &= \frac{E[TC_c(n,Q)}{E[T_c]} \\
&= \frac{(S_v + S_B + nF)D}{n.Q.([1-E[P])(1-E[e_1])} + \frac{\begin{array}{l} D(C_i + C_w E[P] + C_a E[P]E[e_2] \\ +C_v(1-E[P]E[e_1]) \end{array}}{(1-E[P])(1-E[e_1])} \\
&\quad + h_B Q\left\{\frac{D\{(1-E[P])E[e_1) + E[P](1-E[e_1]\}}{x(1-E[P])(1-E[e_1])}\right\} \\
&\quad + \frac{E[A]}{2(1-E[P])(1-E[e_1]} + \frac{1}{2D} b.n.Q^2(E[P]E[e_2])^2 \\
&\quad + h_v\left[\begin{array}{l} \dfrac{QD}{PR\{(1-E[P])(1-E[e_1]\}} - \dfrac{nQD}{2PR\{(1-E[P])(1-E[e_1])\}} \\ + \dfrac{(n-1)Q}{2} \end{array}\right]
\end{aligned} \tag{10}$$

where

$$\begin{aligned}
A &= \{1-(e_1+P) + P(e_1+2e_2)\}(1-P)(1-e_1) \\
&= 1-2(P+e_1) + 4Pe_1 + 2Pe_2(1-e_1) + PE(1-2e_1-2e_2+2e_1e_2+e_1^2) + e_1^2(1-2P)
\end{aligned}$$

and

$$\begin{aligned}
E[A] &= 1-2(E[P]+E[e_1]) + 4E[P]E[e_1] + 2E[P]E[e_2](1-E[e_1]) + \\
&\quad E[PE](1-2E[e_1]-2E[e_2]+2E[e_1]E[e_2]+E[e_1^2]+E[e_1^2](1-2E[P]))
\end{aligned}$$

Using the renewal reward theorem, the expected total annual cost of the vendor and the customer is

$$\begin{aligned}
ETC(n,Q,B) &= \frac{(S_v + S_B + nF)D}{n.Q.([1-E[P])(1-E[e_1])} + \frac{\begin{array}{l} D(C_i + C_w E[P] + C_a E[P]E[e_2] \\ +C_v(1-E[P]E[e_1]) \end{array}}{(1-E[P])(1-E[e_1])} \\
\frac{E[TC(n,Q,B)]}{E[T_c]} &= h_B Q\left\{\frac{D\{(1-E[P])E[e_1) + E[P](1-E[e_1]\}}{x(1-E[P])(1-E[e_1])}\right\} \\
&\quad + \frac{E[A]}{2(1-E[P])(1-E[e_1]} + \frac{1}{2}\frac{b.n.Q^2(E[P]E[e_2])^2}{(1-E[P](1-E[e_1])}
\end{aligned} \tag{11}$$

$$+h_v\left[\frac{QD}{PR\{(1-E[P])(1-E[e_1]\}}-\frac{nQD}{2PR\{(1-E[P])(1-E[e_1])\}}+\frac{(n-1)Q}{2}\right]$$

$$\frac{\partial ETC(n,Q,B)}{\partial Q}=\frac{(S_v+S_B+nF)D}{n.Q^2.([1-E[P])(1-E[e_1])}+h_B\left\{\frac{D\{(1-E[P])E[e_1) +E[P](1-E[e_2]\}}{x(1-E[P])(1-E[e_1])}\right\}$$

$$+\frac{E[A]}{2(1-E[P])(1-E[e_1]}+\frac{1}{2}\frac{b(E[P]E[e_2])^2}{(1-E[P](1-E[e_1])} \tag{12}$$

$$+h_v\left[\frac{D}{PR\{(1-E[P])(1-E[e_1]\}}-\frac{nD}{2PR\{(1-E[P])(1-E[e_1])\}}+\frac{(n-1)}{2}\right]$$

$$\frac{\partial ETC(n,Q,B)}{\partial Q}=0$$

Taking the second derivative, we have

$$\frac{\partial^2 ETC(n,Q,B)}{\partial Q^2}=\frac{2(S_v+S_B+nF)D}{n.Q^2.([1-E[P])(1-E[e_1])}$$

Here, $E\,[P] < 1$ and $E\,[e_1] < 1$, we have $\frac{\partial^2 ETC(n, Q, B)}{\partial Q^2} > 0$.

Which implies that a particular value of n, the total integrated annual cost is a convex function and there exists a unique value of Q that minimises equation (11) which is given as?

$$\frac{(S_v+S_B+nF)D}{n.Q^2.([1-E[P])(1-E[e_1])}=h_B\left\{\frac{D\{(1-E[P])E[e_1)+E[P](1-E[e_2]\}}{x(1-E[P])(1-E[e_1])}+\frac{E[A]}{2(1-E[P])(1-E[e_1]}\right\}$$

$$+\frac{1}{2}\frac{b(E[P]E[e_2])^2}{(1-E[P](1-E[e_1])}+h_v\left[\frac{D}{PR\{(1-E[P])(1-E[e_1]\}}-\frac{nD}{2PR\{(1-E[P])(1-E[e_1])\}}+\frac{(n-1)}{2}\right]$$

$$\frac{(S_v + S_B + nF)D}{n.Q^2} = h_B \left\{ \frac{D}{x} \{1 - E[P])E[e_1] + E[P](1 - E[e_2] + \frac{1}{2} E[A]\} \right\}$$
$$+ \frac{1}{2} b(E[p]E[e_2]^2$$
$$h_v \left\{ \frac{D}{PR} - \frac{nD}{2PR} + \frac{n-1}{2}(1 - E[P])(1 - E[e_1]) \right\}$$

$$Q = \sqrt{\frac{2(S_v + S_B + nF)D}{n\left[\begin{array}{l} h_B \left\{ \frac{2D}{x} \{(1 - E[P]E[e_1] + E[P](1 - E[e_2])\} + E[A] \right\} + b(E[P]E[e_2])^2 \\ +h_v \left\{ \frac{(2-n)D}{PR} + (n-1)(1 - E[P])(1 - E[e_1] \right\} \end{array}\right]}}$$

$$\therefore Q^* = \sqrt{\frac{2(S_v + S_B + nF)D}{n\left[\begin{array}{l} h_B \left\{ \frac{2D}{x} \{(1 - E[P]E[e_1] + E[P](1 - E[e_2])\} + E[A] \right\} \\ +b(E[P]E[e_2])^2 \\ +h_v \left\{ \frac{(2-n)D}{PR} + (n-1)(1 - E[P])(1 - E[e_1] \right\} \end{array}\right]}} \tag{13}$$

3.1 The customer's independent optional solution

If the vendor and the customer do not work together in a cooperative manner to maximise total benefits, and customer makes his own decisions, then customer's expected annual cost is

$$\begin{aligned} ETC_B = (Q.B) &= \frac{E(TC_B(n.Q.B))}{E(T)} = \frac{(SB + F)D}{Q(1 - E[P])(1 - E[e_1])} \\ &+ \frac{D(C_i + C_{aB} E[P]E[e_2])}{(1 - E[P](1 - E[e_1])} \\ &+ h_B Q \left\{ \frac{D((1 - E[P])E[e_1] + E[P](1 - E[e_2]))}{x((1 - E[P](1 - E[e_1]))} + \frac{E[A]}{2(1 - E[P](1 - E[e_1])} \right\} \\ &\frac{1}{2} \frac{bQ(E[P]E[e_2]^2}{(1 - E[P](1 - E[e_1])} \end{aligned} \tag{14}$$

Taking the first derivative Q, of ETC_B (Q, B) with respect to Q, we have

$$\frac{ETC_B(Q.B)}{\partial Q} = -\frac{(S_B+F)D}{Q^2(1-E[P])(1-E[e_1])} + h_B\left\{\begin{array}{l}\dfrac{D((1-E[P])E[e_1]+E[P](1-E[e_2]))}{x((1-E[P](1-E[e_1]))} \\ +\dfrac{E[A]}{2(1-E[P](1-E[e_1])}\end{array}\right\} + \frac{1}{2}\frac{b(E[P]E[e_2]^2}{(1-E[P](1-E[e_1])} \tag{15}$$

$$\frac{(S_B+F)}{Q^2(1-E[P])(1-E[e_1])} = h_B\left\{\begin{array}{l}\dfrac{D((1-E[P])E[e_1]+E[P](1-E[e_2]))}{x((1-E[P](1-E[e_1]))} \\ +\dfrac{E[A]}{2(1-E[P](1-E[e_1])}\end{array}\right\} + \frac{1}{2}\frac{b(E[P]E[e_2]^2}{(1-E[P](1-E[e_1])}$$

$$\therefore \frac{(S_B+F)}{Q^2} = h_B\left\{\frac{D}{x}((1-E[P])E[e_1]+E[P](1-E[e_2])) + \frac{E[A]}{2}\right\} + \frac{1}{2}b(E[P]E[e_2]^2$$

$$Q_B = \sqrt{\frac{(S_B+F)D}{h_B\left\{\frac{D}{x}((1-E[P])E[e_1]+E[P](1-E[e_2])) + \frac{E[A]}{2}\right\} + \frac{1}{2}b(E[P]E[e_2]^2}}$$

$$Q_B^* = \sqrt{\frac{2(S_B+F)D}{h_B\left\{\frac{2D}{x}((1-E[P])E[e_1]+E[P](1-E[e_2])) + E[A]\right\} + b(E[P]E[e_2]^2}} \tag{16}$$

The vendor's expected annual cost is given as $ETC_v(n,Q) = \dfrac{E[TC_v(nQ)]}{E[T]}$

$$TC_v(n,Q) = S_v + nC_wQ_v + nC_vQ(1-P)e_1 + nC_{av}Q_ve_2 + hv\left\{\frac{nQ^2}{PR} - \frac{n^2Q^2}{2PR} + \frac{n(n-1)Q^2(1-P)1-e_1)}{2D}\right\}$$

$$\therefore ETC_v(n,Q) = \frac{E[TC_v(n,Q)]}{E(T_c)} = \frac{S_vD}{Q(1-E[P](1-E[e_1])} + \frac{D\{C_wE[p]+C_v(1-E[P]E[e_1])+C_{av}E[P]E[e_2]\}}{(1-E[P](1-E[e1])} + h_vQ\left\{\frac{D}{P(1-E[P])(1-E[e_1])} - \frac{nD}{2P(1-E[P])(1-E[e_1])} + \frac{n-1}{2}\right\}$$

$$\frac{ETC_v(n,Q)}{\partial Q} = -\frac{S_v D}{Q^2(1-E[P](1-E[e_1])}$$
$$+h_v\left\{\frac{D}{P(1-E[P])(1-E[e_1])} - \frac{nD}{2P(1-E[P])(1-E[e_1])} + \frac{n-1}{2}\right\}$$

$$\frac{S_v D}{Q^2(1-E[P](1-E[e_1])} = h_v\left\{\frac{2D-nD+P(1-E[P])(1-E[e_1])}{2P(1-E[P])(1-E[e_1])}\right\}$$
$$\frac{S_v D}{Q^2} = h_v\left\{\frac{(2-n)D+PR(1-E[P](1-E[e_1])}{2PR}\right\} \tag{17}$$

$$Q^* = \sqrt{\frac{2(S_v D)PR}{h_v\{(2-n)D+PR(1-E[P](1-E[e_1])\}}} \tag{18}$$

4 Numerical example and sensitivity analysis

Consider an integrated vendor-customer cooperative inventory model with the following data, optimal solutions of n, PR = 160,000, D = 50,000, x = 175,200, S_v = 300, S_B =100, h_v = 2, h_B = 5, F = 25, c_i = 0.5, c_w = 50, c_r = 100, c_{aB} =200, c_{av} = 300, β = λ = η = 0.04, b = 10.

Due to the property of uncertainty and the lack of sufficient data for the defective rate, proper distribution of defective rate cannot be determined. Therefore, here followed the previous researchers such as Bacel and Jaber (2008) and Salameh and Jaber (2000), by employing the uniform distribution as the form of defective rate.

If the defective percentage and inspection errors follow a uniform distribution with

$$f(\gamma) = \begin{cases} \frac{1}{\beta} & 0 \le \gamma \le \beta \\ 0 & otherwise \end{cases} \quad f(e_1) = \begin{cases} \frac{1}{\lambda} & 0 \le e_1 \le \lambda \\ 0 & otherwise \end{cases} \quad f(e_2) = \begin{cases} \frac{1}{\eta} & 0 \le e_2 \le \eta \\ 0 & otherwise \end{cases}$$

Then

$$E[\gamma] = \int_0^\beta f(\gamma)d\gamma = \int_0^\beta \frac{\gamma}{\beta}d\gamma = \frac{\beta}{2}, E[\gamma^2] = \int_0^\beta (\gamma^2)f(\gamma)d\gamma = \int_0^\beta \frac{\gamma^2}{\beta}d\gamma = \frac{\beta^2}{3},$$
$$E[e_1] = \frac{\lambda}{2}, E[e_1^2] = \frac{\lambda^2}{2} \text{ and } E[e_1] = \frac{\eta}{2}, E[e_2^2] = \frac{\lambda^2}{2}$$

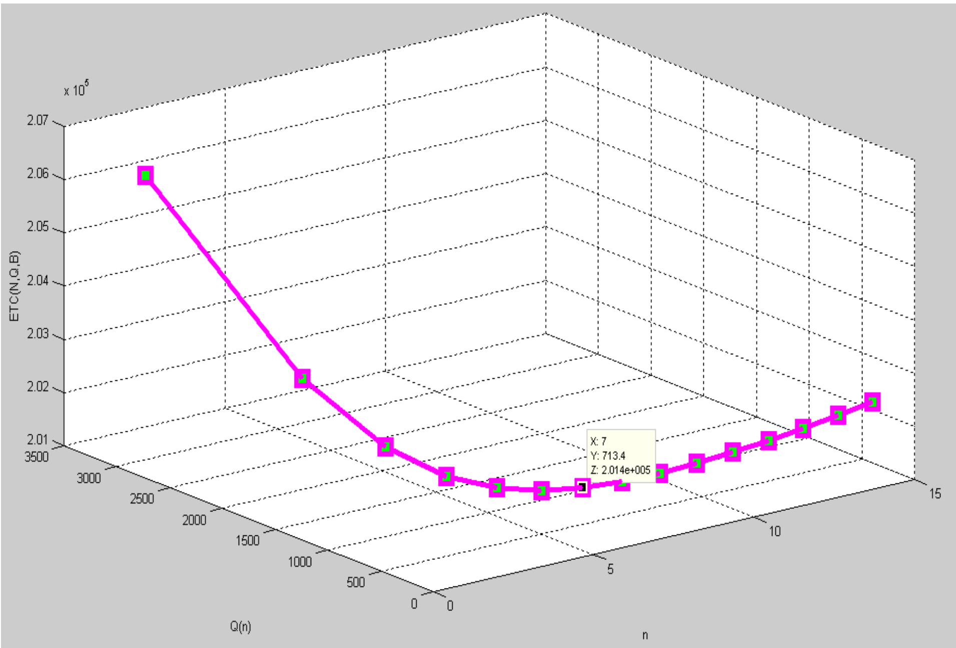
Specifically, if β = λ = η = 0.04, now obtain the expected total annual cost of the vendor and the customer as a function of n and Q.

According to Table 1, the optimal solution is n^* = 7, Q^* = 713 and the minimum total expected annual cost is 201,416.2512. Compared with Lin (2008) and the number of delivery of this model is the same as that in Lin (2008).

Table 1 Optimal solutions of lot size

N	*Q(n)*	*ETC(N,Q,B)*	*n*	*Q(n)*	*ETC(N,Q,B)*
1	3,034.012834	206,294.965166	9	589.501249	201,503.164457
2	1,855.143383	203,282.181011	10	544.745421	201,583.488419
3	1,368.165102	202,229.956883	11	507.504209	201,678.763594
4	1,097.413164	201,755.435085	12	475.998648	201,784.737854
5	923.931228	201,530.584274	13	448.972678	*201,898.465112*
6	802.863267	201,435.646256	14	425.513813	202,017.848636
7*	713.361631	201,416.251202*	15	404.942955	202,141.362691
8	644.37879	201,444.133887			

Figure 2 The expected total annual cost of the vendor and the customer (see online version for colours)



The sensitivity analysis on the defective percentage, which is uniformly distributed between 0 and β, it is noted when β increases the optimal size of the deliveries first increases until it reaches its maximum value and then begins to decrease. The larger the value β the greater the cost reduction of the integrated model in comparison to an independent decision by the customer is.

Figure 3 Graphical representations of expected total cost (see online version for colours)

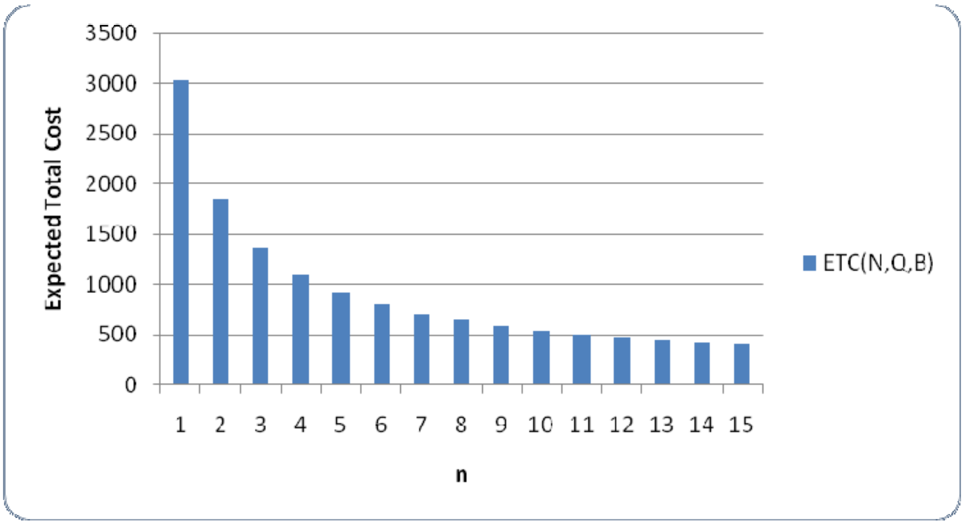


Table 2 Optimal solution when the defective percentage is uniformly distributed

Beta	*Q(B*)*	*ETCB(QB*)*	*ETCV(QB*)*	*n**	*Q*(n)*	*ETC(n,Q*(n))*	*Cost reduction*
0.04	1,645.424438	34,247.097656	171,705.578125	7	713.361631	201,416.251202	4,536.42455
0.08	1,678.622437	39,183.269531	232,495.140625	7	722.735739	267,109.365167	4,569.04503
0.12	1,712.924927	44,332.203125	295,873.78125	7	732.371783	335,597.869868	4,608.11452
0.16	1,748.368042	49,707.929687	362,010.53125	7	742.281385	407,064.070391	4,653.39058
0.2	1,784.986816	55,325.710937	431,089.40625	7	752.476893	481,706.490752	4,708.62643
0.24	1,822.815063	61,202.230469	503,311.15625	7	762.971442	559,741.673812	4,771.71286
0.28	1,861.884033	67,355.695312	578,895.1875	7	773.778989	641,406.289261	4,844.59361
0.4	1,986.804077	87,687.632812	828,344.1875	8	728.224441	910,910.51877	5,121.30161

Figure 4 Graphical representations of the optimal values (see online version for colours)

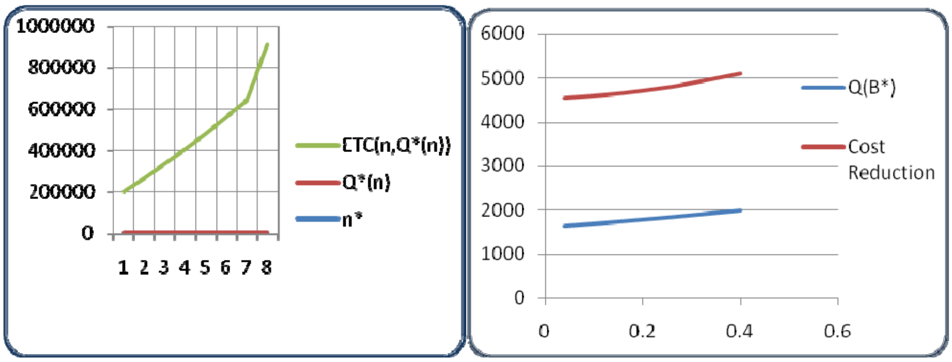


Table 2 shows the sensitivity analysis on the defective percentage γ, which is uniformly distributed between 0 and β. Here from Table 2, found that when β increases, the maximum backordering quantity decreases. The larger the β value, the greater the cost reduction of the integrated model in comparison to an independent decision by the customer. From the numerical examples, it is clear that the integrated model results in an impressive cost reduction in comparison to an independent decision by the customer.

5 Conclusions

The model for integrated vendor-customer production-inventory considering imperfect quality and inspection errors. The objective is to minimise the total joint annual costs. By considering the policy in which the delivery quantity to the customer is identical at each delivery. There is chance of deliver of defective items from the vendor to the customer. So, customer is conducting screening process of the lot, 100% inspection is done on the received items, but the screening process is also not perfect. The inspector may incorrectly classify a non-defective item as defective (a type I inspection error), or incorrectly classify a defective item as non defective (a type II inspection error). The expected total integrated annual cost of the vendor and the customer is derived and a solution procedure is provided to find the optimal solution that minimises the expected total integrated annual cost. Numerical examples show that the integrated model gives an impressive cost reduction in comparison to an independent decision by the customer.

In this paper, the no. of defective items are consider as shortages, shortages are completely backordered and shortage cost is consider for calculating the total cost of customer. The vendor reworks the defective items and converts the defective items into good quality products to satisfy the customer's demand.

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Holistic modelling, simulation and visualisation of demand and supply chains

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Abstract: The evolution of the economic and technological contexts pressure businesses toward transforming their demand and supply chains to become more customer-centric, collaborative, innovation enabling, agile and personalised. Simulation models are needed to contrast actual vs. proposed chains, analyse the dynamic performance of these chains, and understand their overall behaviour in specific contexts. This paper proposes a holistic agent-oriented approach for modelling, simulation and visualisation of such demand and supply chains. The simulation platform for extended enterprises (SPEE) developed exploits multiple concurrent viewers that can both illustrate global multi-perspective insights into the supply chain as well as tunnel down to highly detailed information. This allows decision makers to embed themselves into the simulation and obtain the holistic visualisation needed to support their decisions.

Keywords: demand and supply chain design; holistic modelling and simulation; agent-oriented modelling and simulation; client modelling.

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Jonathan Loubier studied Computer Science at college and university levels before becoming a professional programmer/analyst, specialising in simulation platforms.

1 Introduction

To maintain a competitive position, businesses are challenged to transform their demand and supply chain so that it becomes more customer-centric, collaborative, agile, resilient, personalised and innovation enabling while sustaining profitability. Each of these adjectives is demanding and their combination is tougher, for example requiring businesses to profitably delight customers through product and service innovation and customisation while sustaining high delivery velocity and reliability.

Once businesses decide to address the challenge, they begin to analyse their current demand and supply chain to identify the transformations that could be implemented in order to meet the new demands and expectations. However, these transformation projects often affect the core business processes and involve considerable investments with no guarantee of success. Decision makers are all too aware of the stories where firms went through with a transformation project only to face endless obstacles throughout the supply chain that either reduced or cancelled out the expected profit. They are therefore hesitant to endorse these major transformations without higher assurance of success. Indeed, on the surface, proposed demand and supply chain transformations often appear ideal with their combination of customer centricity, agility, personalisation and innovation capabilities as well as collaborative behaviour. Yet the realisation of the implied transformations raises a number of questions. Will the change be really worth the effort? What will be the impact on the key stakeholders? What are the risks entailed by the change? What will be the dynamic behaviour of the proposed demand and supply chain? How will the business manage and control this new network?

Simulation has long been identified as having the potential to answer such questions and help better design and assess demand and supply chain transformations. Yet in reality, simulation models are generally both highly detailed and focused on specific facets, or much more aggregate when attempting to cover the overall chain spectrum. This has, up to now, drastically limited their applicability in industry (Jahangirian et al., 2010). This paper proposes a holistic approach to modelling and simulating demand and supply chains that has the potential to unlock the compromise between modelling breadth and depth, thus making it possible to achieve the envisioned potential of simulation in designing and assessing transformations. The paper presents a novel agent-based approach for modelling demand and supply chains that has the potential to better manage the traditional trade-off between macro and micro modelling.

This paper is structured as follows. Starting with a literature review, Section 2 positions and describes the research contribution. Section 3 details the agent-oriented modelling approach through a case study. Section 4 emphasises deep holistic visualisation, illustrated using the simulation platform for the case study. Section 5 provides conclusive remarks.

2 Toward holistic simulations of demand and supply chains

Supply chain (SC) simulation research is constantly gaining in popularity since it is recognised as the most realistic way of investigating the impact of transformations without having to implement pilots (Terzi and Cavalieri, 2004). Applications have been numerous, in (Albino et al., 2007) simulation is used to analyse the benefits of supply chain cooperation in industrial districts, and in (Badell et al., 2007) the simulation is used for concurrently modelling operational and financial aspects of a SC. SC simulation research has methodologically evolved in the last 15 years. Baggachi et al. (1998) describe SC modelling principles and illustrate the architecture of a SC simulator. Ingalls and Kasales (1999) show the benefit of using simulations to analyse dynamic SC performance, in contrast with an optimisation modelling approach such as the one proposed in Silva et al. (2009). Jain et al. (2001) describe an abstraction process for developing a SC simulation model while Rossetti and Chan (2003) identify generic model elements. Biswas and Narahari (2004) propose using object-oriented modelling and an object library of SC elements, enabling the combination of optimisation and simulation. Chatfield et al. (2006) propose an object-oriented simulation architecture exploiting an XML based information exchange language termed the supply chain modelling language. Reiner (2005) proposes the tandem use of discrete-event simulation and system dynamics simulation to evaluate the full impact of process improvements in SC.

Similarly, agent-based SC simulation is also becoming more popular. The general agent-oriented modelling and simulation approach allows for a system to be represented by individuals, or agents, and their interactions with other agents. Each one has an identity with a specific role and behaviour. These individuals evolve and act without any control or external intervention (autonomy), perceive their environment and respond to its changes (reactivity), initiate behaviours according to internal goals (pro-activity) and interact (sociability), (Wooldridge and Jennings, 1995). The properties characterising the multi-agent system approach for modelling socio-technical systems make it a natural prospect for studying and representing the behaviour of the different entities that constitute the demand and supply chain (Labarthe et al., 2006; Lemieux et al., 2009). Mele et al. (2006) propose an agent-oriented simulation-based optimisation framework to help decision-making at the operational and tactical levels in supply chain networks. Kim and Cho (2010) propose agent negotiation to determine an optimal solution for order allocation in a multi-member supply chain. Persson and Araldi (2009) use a SCOR template to develop a discrete-event simulation to analyse the dynamics of supply chains. Li and Chandra (2007) propose an integration framework that models complex network structures and uses dependency modelling and information theory to consider knowledge gained from new technologies in the decision-making process. Santa-Eulalia et al. (2011) propose a literature review of recent methodological frameworks for agent-based SC planning. Noticing the lack of an efficient methodological framework in this domain, Santa-Eulalia et al. (2012) propose the FORAC architecture for modelling agent-based simulation for SC planning to aid simulation analysts define the requirements of their simulation scenarios.

Even though gains have been marked, inherent difficulties in modelling and simulating demand and SC have been constant application hurdles:

1. the number and heterogeneity of the network's entities
2. the complexity of the interactions
3. the influence of the environment
4. the importance of smart planning and decision making
5. the diversity of organisation structures.

Tackling and circumventing these difficulties is rooted in all published SC simulation literature, being the source of significant representativeness compromises. In most reported SC simulation research, demand is an input, usually represented by a stochastic distribution. However, in a customer-centric and demand-driven context, such approximation and aggregation become a major limitation. Demand stems from clients that have distinct profiles and, consequently, different requirements. Explicitly modelling the client becomes a key factor in being able to assess the potential value of demand and SC capable of addressing the personalised needs of individual clients.

In general there is a constant compromise between modelling depth and modelling breadth. When focused on a specific part of the business, models are usually quite detailed. However, the larger the scope of the simulation, the more superficial becomes the model, using more aggregate data. Businesses are now trying to evaluate large scope projects that will affect most actors in their SC. This would allow them to test any transformation project. There is thus a need to push the current thoroughness limits to increase the modelling and simulation capability for concurrent breadth and depth, in order to enable the development of detailed simulation models that provide holistic as well as focused analysis capabilities. Holistic modelling of complex demand and supply chains that combines fine granularity and global comprehensiveness is beyond near future capabilities. Four main factors converge to allow this migration:

- Conceptually, the combination of discrete-event, object and agent oriented modelling and simulation frameworks offering a sound conceptual framework for mastering the complexity, scope and scale underpinning holistic modelling of demand and supply chains.
- Methodologically, developing agent-oriented models and simulations of demand and SC based on a structured three-tiered domain-conceptual-operational approach to develop models, reduces the learning required to generate such models, then structures and speeds up their development (Labarthe et al., 2007; Santa-Eulalia et al., 2012).
- Technologically, advances in computer power and in clustering and networking capabilities, coupled with availability of distributed simulation architectures and protocols; provide the infrastructure for simulation platforms to achieve the computing performance necessary to sustain holistic simulation.
- From an information requirements perspective, there is a huge availability of data stored in databases, which can be automatically accessed and exploited. Also, there

is a growing body of knowledge workers in organisations with whom model developers can interact for adequate modelling and parameter estimation.

This paper does not address the technical issues underlying the realisation of holistic simulations. There currently exists two fundamental ways to generate the computational power to execute the models. The first is using a computational cluster composed of multiple processors which are virtually exploited as a single entity by the software. The second is using a distributed network of processors, assigning organisational units and agents to specific processors in the network. The platform developed by the authors illustrates currently achievable performance for supporting holistic modelling and simulation according to the second approach.

3 Holistic modelling of demand and supply chains

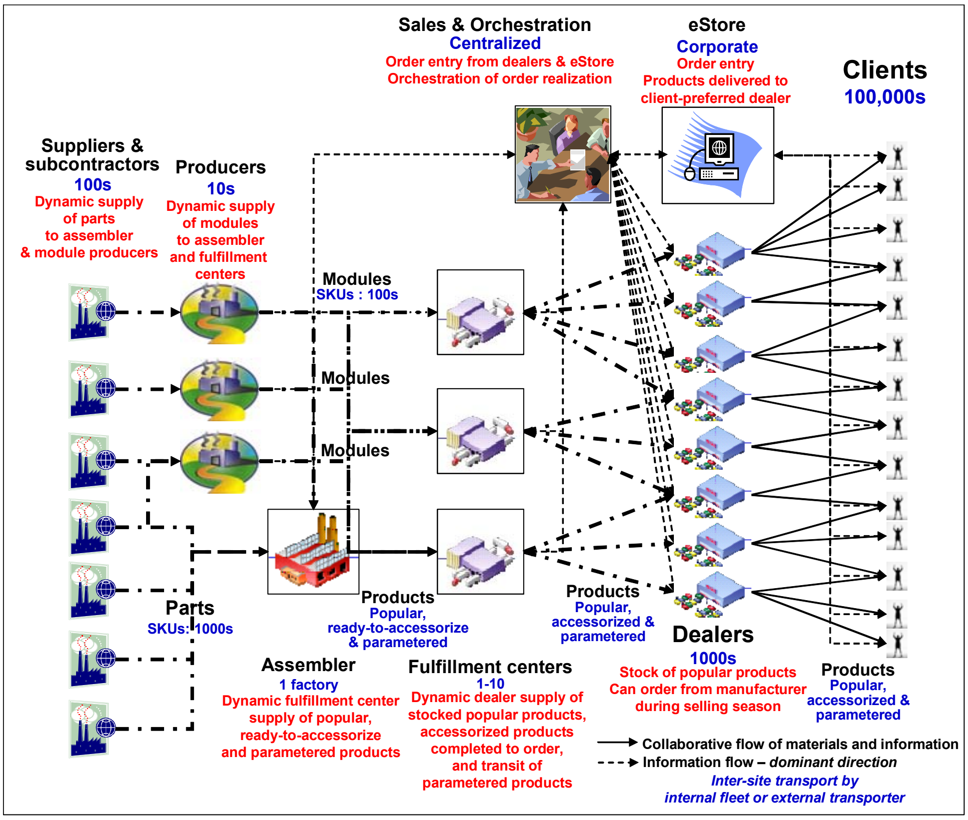
This section describes how a demand and supply chain can be modelled using an agent-based approach as previously defined in the literature review. The next sub-section illustrates the essence of demand and supply chain transformations where the first key decision maker is the client. The scale, scope and complexity of the proposed transformation are such that its feasibility and value are both important and tough to assess.

3.1 Demand and supply chain transformation

Figure 1 represents an alternative of demand and supply chains for a recreational vehicle business which designs, manufactures and sells snowmobiles on the North American market (Montreuil, 2005). By opposition, in a mass production and distribution oriented demand and supply chain the manufacturer offers the market a mix of standard snowmobile models, internally labelled as stock keeping units. Potential clients of the supply chain are individual people wanting to purchase a snowmobile from one of the independently owned dealers that are part of the manufacturer's retail network. The manufacturer forces dealers to place a single yearly order in April, long prior to the main selling season starting in September and finishing at the end of winter. It offers no in-season reordering possibilities to the dealers. Provided the orders from all dealers, it sets the production schedule for its single assembly plant. It aims to minimise setup and manpower variation costs, so that all vehicles are produced and delivered between mid-summer and mid-December. The mass production and distribution oriented demand and supply chain is attractive to the assembly plant and the suppliers, it pushes the market risk to the dealers and limits clients to selecting from their dealer's stock which is depleting as the season progresses, forcing ever increasing compromises leading to lost sales and substitution sales.

The proposed transformation shifts away from strictly offering standard products, towards a much more personalised approach, offering a combination of popular products, accessorised products and parameterised products (Montreuil and Poulin, 2005). The proposed alternative, claimed to be personalised, customer-centric, collaborative and agile. Dealers are now allowed to order whenever they want instead of once several months prior to the main selling season. The business aims for one-day, three-day and ten-day delivery of popular, accessorised and parameterised products to dealers anytime during the selling season. In order to achieve the intended customer-centricity and agility, investments need to be made into the product realisation network. Setup times have to be reduced, allowing mixed-model unitary flow through the main assembly plant. This plant has to feed a network of distributed fulfilment centres that can accessorise products from ready-to-accessorise products based on customer orders. Finally, collaborative practices have to be implemented within the supplier network to enable their required agility. The business also switches from mainly receiving parts from suppliers to receiving modules.

Figure 1 A customer-centric, collaborative and agile demand and supply chain (see online version for colours)

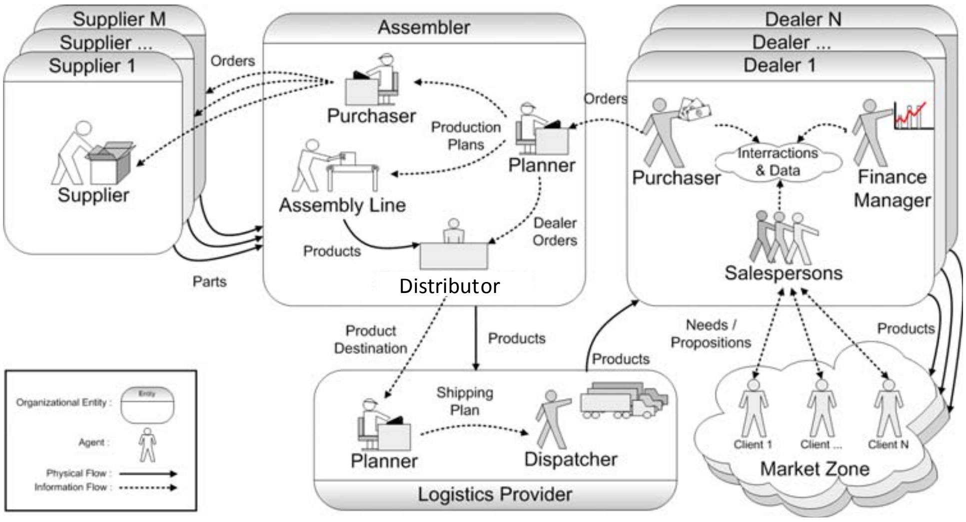


3.2 Case study model

The recreational vehicle manufacturer case introduced in Section 2 is used for illustrating the analysis capabilities of the proposed approach. In this section, the description focuses on modelling the current demand and supply chain and its agents, as shown in Figure 2, at a level making it comprehensible how one would then proceed to model the alternative customer-centric supply chain.

Figure 2 shows the existing relationships between the main types of entities in the illustrative network. To simulate the demand, each client is modelled as an individual agent. The implemented model involves an assembler, a logistics provider, 500 dealers and about 50,000 clients spread throughout the North American snow belt, as well as 250 suppliers from around the world, for a total of nearly 53,000 agents. The main agents are described in the following subsections, with an emphasis on their fundamental nature, their behaviour and their interactions in the overall agent community.

Figure 2 Case study model – agents and their interactions



3.3 Client modelling

The clients in this case are people wishing to purchase a snowmobile. Each one is modelled as an individual agent. They are each provided with an identity, a personality, a demand profile and behavioural capabilities relative to their shopping process. To define their identity, each client has a name, address and personality characteristics. These are matched with overall statistical distributions about client population and demand. For example, the expected number of clients in a country, state or region is relative to the overall stochastic demand in these geographical zones. Demand profiling of each client is achieved through three specific profiling facets: time, budget and product fit. The shopping process of each client is time delimited by a shopping start time, a target purchasing time and a latest shopping time. Each client is also provided with a budget: target spending on the product and maximal allowed spending. This budget is stochastically correlated with his product fit profile. Each client is provided with personality characteristics influencing his decisions throughout the shopping process. First is his willingness to shop around, here expressed as a combination of the geographical perimeter around his address within which he is willing to shop for a product and the maximum number of dealer visits he is willing to do. Second is his tolerance to delivery delays, here expressed as the maximum time he is willing to wait for delivery of a product not available at a dealer at purchase time. Third is his tolerance to dissatisfaction due to product substitution, here expressed as a minimum satisfaction threshold below which he will not buy an alternate product instead of his unavailable favourite. Fourth is his immediate purchase impulsivity, here expressed as a maximum satisfaction threshold above which he will immediately purchase the offered product.

Each snowmobile offered by the business in its product mix is here a specific combination among the following features: ten platforms, thirteen motors, three suspension types, two types of tracks, three types of seats and four vehicle colours. For example, the ten platforms are child, cruiser, deluxe cruiser, family, ice racing, jumping, labour, mountain, performance and super performance. Theoretically, 9,360 combinations could be offered by the company. Among these, several are infeasible. For example, one cannot put the biggest engines on a child platform. However, being a mass producer and distributor, the business has limited itself to offering only 126 standard combinations among the potential feasible combinations. The client, when first entering his shopping process, does not think in terms of specific snowmobile models. In fact, through his product fit profile, the client agent focuses on the following attributes, weighted by relative importance: performance, manoeuvrability, durability, comfort, security, economy and appearance. Each feature, such as the platform and the engine, has an impact on the relative fit to each feature. For example, a small engine will contribute poorly to the performance attribute, yet will score high in terms of economy. The combination of features in a given model allows the computation of the relative fit of the model for each attribute. By using the specific client weights, the model fit for each client is calculated as a satisfaction level between 0 and 1. The theoretical ideal fit has a satisfaction index of one. The feasible ideal fit may have a satisfaction index lower than one and may not be offered by the business. The best fit corresponds to the model, offered by the business, which gives the highest satisfaction level. The agent behaviour is characterised and defined by using probabilistic distributions as introduced in Cloutier et al. (2010) and Montreuil et al. (2013) and the agent interactions are presented in Figure 2.

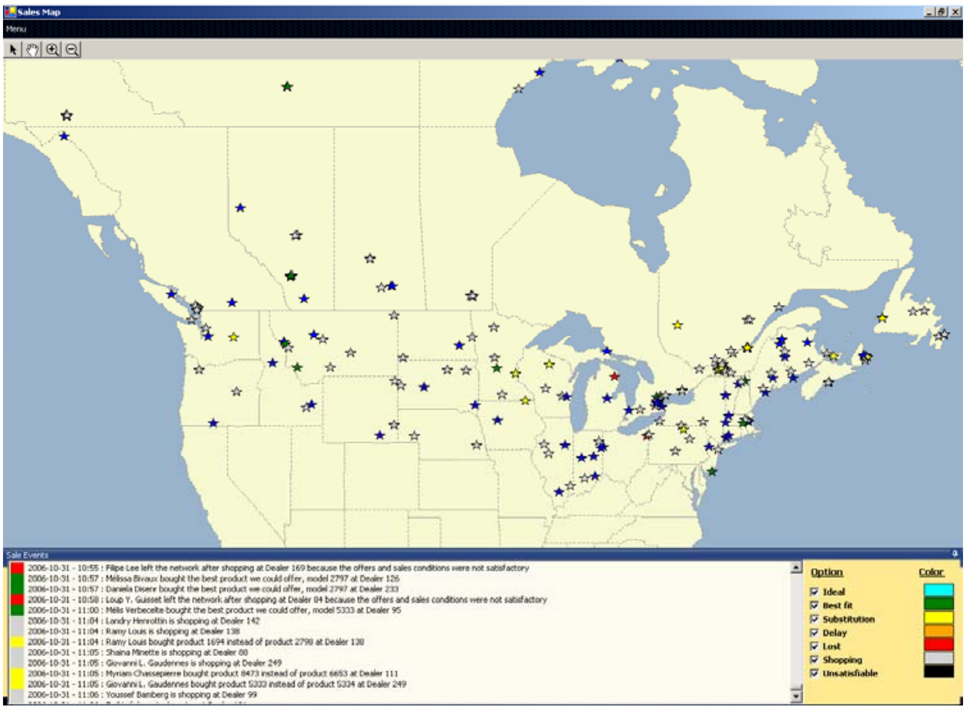
From a behavioural perspective, each client visit to a dealership is explicitly modelled, including the client's interaction with a salesperson. During such a visit, the salesperson discusses with the client, assessing his needs as best as possible. Based on this assessment and product availability, the salesperson offers a product to the client, at a specific price and delivery time. Given this offer, the client evaluates his degree of satisfaction for the product by taking into account

1 the difference between his budget and the sales price
2 the product fit, based on the match between the desired attributes and those of the model proposed
3 the dealer's proficiency (ex: welcome, showroom and suitability of the products).

If the satisfaction towards the proposed offer is greater than the client's maximum satisfaction threshold, he buys the product immediately even if he had planned to visit more dealers before making a decision. If the satisfaction towards this offer is less than the maximum satisfaction threshold but greater than the client's minimum satisfaction threshold, he will put it in his potential buying list and continue visiting dealers. Once the client has reached his intended number of dealer visits or the limit of his intended shopping period, he will seek to purchase the offer with the highest satisfaction rate. He will visit the dealer who made the best offer in order to purchase the product. If the product has already been sold, he will seek to purchase the next highest offer in his list. If there are no more offers in his potential buying list, he will leave the market zone without making a purchase. Thus, at anytime the state of any client belongs to one of the eight following categories:

- Ideal fit – *Blue* – he bought and received the model fitting his needs
- Best fit – *Green* – he bought and received the model in the product mix that best fit his needs
- Substitute – *Yellow* – he bought and received a substitute model
- Delay – *Orange* – he bought a best fitting model and accepted a significant delivery delay
- Shopping – *White* – he is still undecided and pursues the shopping process
- Inactive – *Blue* – he is not yet actively shopping
- Lost – *Red* – he decided not to buy the offered models
- No fit – *Black* – he stopped shopping since there was no model even remotely satisfying his needs.

Figure 3 Client events map (see online version for colours)



3.4 Modelling the dealer network

The dealer's employees are modelled individually (a finance agent, a purchasing agent and one or more sales agents). Each salesperson in a dealership has an individual profile specifying his perceptivity, his service inclination, and his client centricity. From worst to best, these three profiling parameters range from zero to one. Perceptivity affects his capability to listen and assess the real client needs, to find the best-fit product for the client and, if it is not available, the best substitute products. At worst he considers only products in the showroom as potential offers to clients. At best he considers the entire available inventory and incoming products, as well as potential transfers from other dealers or the business (when allowed in the scenario). His client centricity indicates whether at best he focuses his offer selection process on optimising client satisfaction or, at worst, he always aims toward offering the highest margin product he feels acceptable to the client.

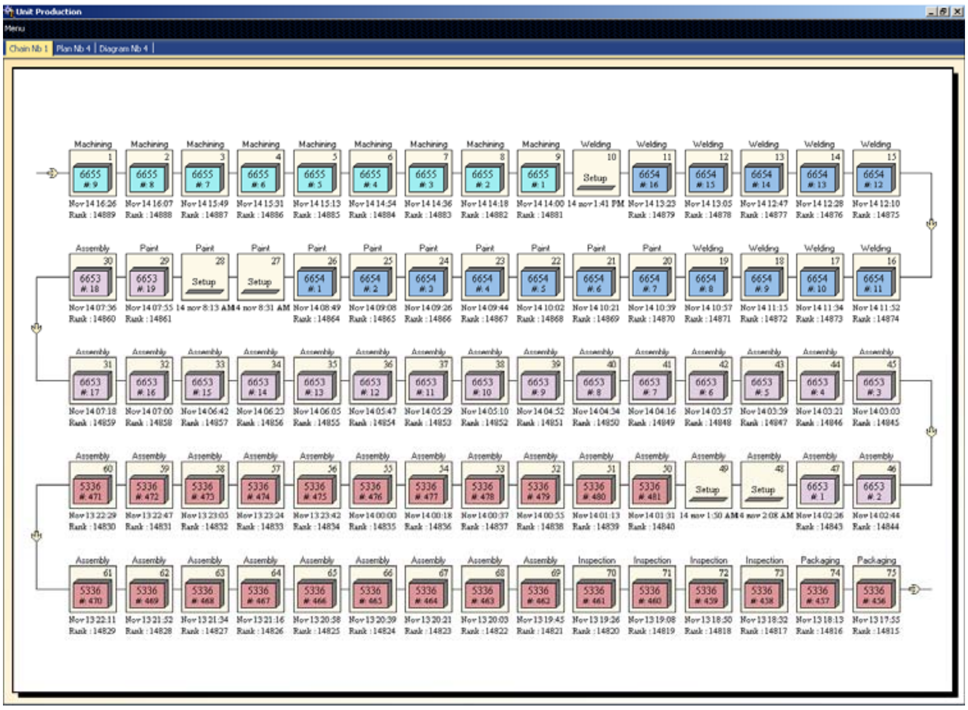
The dealer's purchasing agent calculates the sales forecasts using a yearly moving average and considers the company-wide market analysis. The executive manager translates this forecast into a purchasing decision on the overall number of vehicles, thus multiplying the forecast by a risk orientation factor to get the purchasing quantity. Then the purchasing agent decides the mix of models to be purchased and when he wants them delivered, first for filling the showroom, then to allow for a steady incoming flow of snowmobiles ahead of the expected demand to avoid in-season shortages. The dealer's finance agent sees to the accounting, pays the received products to the manufacturer and finances purchases whenever required. Beyond overall purchasing authority, the executive agent also sets the number of sales agents as well as the number of products in the showroom.

3.5 Modelling the assembler

The assembler's production facility is explicitly represented with its assembly line composed of 75 workstations, each executing a set of operations depending on the product being assembled. The products move through the line at fixed intervals set by the takt time. When switching from producing one model to another, each workstation has a setup time. This setup requires at least one time slot to be left vacant in the line, allowing the station's resources, tools and equipment to be adjusted or replaced by those needed for the next model. Figure 4 provides a view of the assembly line which dynamically details the tasks assigned to each workstation and the model unit it is currently working on. For example, workstation 47 is assembling the first product unit of model 6653. Each product unit is identified through a unique serial number and has its instantiated bill of materials and technical characteristics. As summarised in Figure 2, the model of the assembler currently includes four agents: a planner, an assembly line supervisor, a distributor and a purchaser. The planner agent receives the dealers' orders which specify the quantity for each model as well as the requested delivery dates. He optimises the assembly schedule, heuristically minimising setup times and setup costs as well as manpower change costs that occur when changing from one model to another on the assembly line (Montreuil, 2005).

The planner agent transmits his assembly schedule to the purchaser agent who validates the feasibility of having all the necessary parts available at the required time. Each model is composed of about 400 parts which are ordered from 250 suppliers. For each part-supplier combination, the purchaser tracks the supply costs, quality, constraints, delivery speed and reliability. The purchaser informs the planner of the availability constraints, if any, and the latter adjusts the schedule accordingly. The planner agent sends the final schedule to the purchaser agent who then dynamically launches orders to suppliers so as to minimise the risks of being out-of-stock while keeping inventory levels as low as possible. The assembly line supervisor agent receives the assembly plan from the planner agent and has access to parts inventory and delivery information. The agent's responsibility is to make sure that the line actually follows the plan, enacting the setups, the resource moves and material delivery to workstations, and reacting to breakdowns. He locally adjusts the plan if necessary to insure feasibility. If local adjustment fails, he refers back to the planner. The distributor agent distributes completed products to the dealer network. He monitors the inventory level of each dealer, their order list with the desired dates, and dynamically assigns products to specific dealers. This assignment is forwarded to the logistics provider who deals with the actual truck-trailer deliveries of vehicles to dealers.

Figure 4 Assembly line state view (see online version for colours)



3.6 *Modelling the supplier network*

The supplier network considered includes 250 suppliers. Geographically, some are in the same locality as the business, while others differ in terms of region, country or continent. Each supplier is currently modelled in an aggregate manner through its supplier profile. It is assigned a set of parts/modules to supply. For each of them, the profile sets whether production capacity is to be explicitly modelled or not, and if the item is stocked by the supplier or strictly made to order. If capacity is an issue, then the maximum production rate is specified, otherwise an availability lead time distribution is specified. When stocking is allowed, then the profile sets whether the inventory itself is to be modelled or if a stock availability distribution is to be used. Minimum order quantity, order bucket size, parts pricing structure and a stochastic quality distribution are specified in the profile. Currently, transportation of parts to the assembler is the supplier's responsibility.

In line with the supplier location, the profile sets transportation costs, delays and reliability. The supplier agent receives the orders from the business purchaser agent, informs him of delivery information and provides him with updates when significant deviations from expected delivery dates are building up.

4 Holistic visualisation of simulated demand and supply chains

The scale, scope and complexity of the generated models are such that if holistic visualisation is not designed carefully and made available to users, they will not be in a position to perceive what is going on during the simulation, to observe and understand the evolving dynamics, to identify the key factors at stake and to compare alternatives subject to similar scenarios. Users must be able to dynamically interact with the running simulation instead of being stuck with limited interaction before and after simulation runs. Extracting and displaying key information is therefore vital. Holistic visualisation capabilities aim for the simulation to become a goldmine of information for decision makers in each of the organisational entities whether for operational, tactical or strategic analyses. Holistic visualisation exploits multiple concurrent viewers that can both illustrate global multi-perspective insights into the demand and supply chain as well as tunnel down to highly detailed information. The goal is to allow decision makers to embed themselves into the simulation and develop the holistic frame of mind and knowledge needed to support their decisions.

Holistic visualisation involves the dynamic concurrent display of significant views of the simulated demand and supply chain. To make this happen, the simulation platform must imbed a number of ready-to-use, highly informative, visualisation interfaces and capabilities to develop personalised interfaces. The viewers can be dedicated to specific facets and actors of the demand and supply chain, allowing their examination from various perspectives such as sales, finance, production, inventory, transportation and supply. They must track key performance indicators and status indicators. They also must allow deep-focused examination of operational issues such as traceability of products, messages, decisions and events. The interfaces must allow both synthetic observation and focused data mining. The platform must allow multiple screens and projectors to concurrently display the dynamically evolving views, allowing decision makers to grasp the entire dynamics visually. Overall they aim to provide strategic decision makers with a dynamic holistic view of the business.

In order to fully exploit holistic visualisation, the simulation speed must be adjustable by the users so that decision makers can dynamically follow what is happening over the entire demand and supply chain through the multiple viewers. For example, a year of operation can be set to be simulated in an hour, then slowed significantly to examine in detail specific dynamics occurring at some time in the simulation, or speeded up when only the final results are desired for performance comparisons. Using the case study, the following sections respectively focus on the demand chain and supply chain to demonstrate clearly what holistic visualisation entails. By introducing a number of holistic views they also emphasise the necessity to research what a user must be able to see to develop a holistic frame of mind and knowledge.

4.1 Holistic demand chain visualisation

Visualising the simulated demand chain naturally starts with client centric views. There are a variety of views possible. It is important to conceptualise and enable views that help users develop a client-centric holistic perspective and understanding. Three types of such views are introduced in this paper. The first is depicted in Figure 3: *the client events map*. This map dynamically provides a feel for the shopping dynamics occurring throughout the dealer network. Each dealer is assigned the perceived state colour of the last client having concluded a visit, and reverts to dark blue after a user specified time without client events. It allows mining the specifics of each visit. While the client events map focuses on the flow of individual interactions between a dealer and a client, the second view types aim to provide a macroscopic client centric perspective to the user. Figure 5 provides an example of the second view type, *the active client state graph*. For each week since the beginning of the simulation, the graph shows the number of clients in each state as perceived from the entire business perspective. Here the clients in the shopping state have been removed from the displayed graph to concentrate strictly on transactions concluded positively or negatively in each week. These shopping-state clients globally represent, on average, 82% of the active clients per week up to the snapshot date. The graph shows that 38.7% of the transactions have failed, resulting in lost sales, with a quite negligible 0.01% of no-fit states. Then respectively 20.3%, 40.7% and 0.3% have resulted in best-fit, substitute and delay clients. So, roughly one client out of five purchased the offered product best fitting what he wanted, two settled for a substitute model while the last two were lost. The graph clearly shows that the percentage of lost sales increases as the selling season progresses, the dealers having less and less product availability for satisfying client demand. It also shows that even early in the season a large amount of substitutions are occurring, due to misfits in terms of dealer availability versus the actual demand. Dynamic data mining of such graphs can be revealing: various time granularities (day, week, month, quarter, year), various geographical zones (world, country, state, site), various organisational entities (business, specific dealer), and various zooming on specific models or model features.

In the studied case, the dealer network is the second key element of the demand chain. The client events map, the active client state graph and the substitution matrix views can all be used for dealer network visualisation by focusing on the dealer side of the client-dealer interaction. Dealers are here independent businesses and an important reality for them is their financial performance. Taking a network perspective, a *financial dealer map* tracks the financial performance of the dealer network.

The user can always mine the map by clicking on a dealer to visualise the financial state of each dealer relative to its business with the enterprise. The *dealer financial cockpit view* shown in Figure 6 shows a dealer's live financial graphs relating to his snowmobile business by illustrating monthly states of inventory, sales, cost of goods sold, gross margin and liquidities. It also plots the dynamic evolution of cash flow, gross margin ratio and inventory. By providing three years of historical results, it allows the observation of repeating overall behaviours. For example, the dealer buys and receives products in advance during the season, resulting in inventory surges which are slowly depleted. The rightmost portion of the cash flow graph illustrates the risks of rapid negative cash flows if the currently purchased products are not sold to customers as expected.

Figure 5 Active client state graph (see online version for colours)

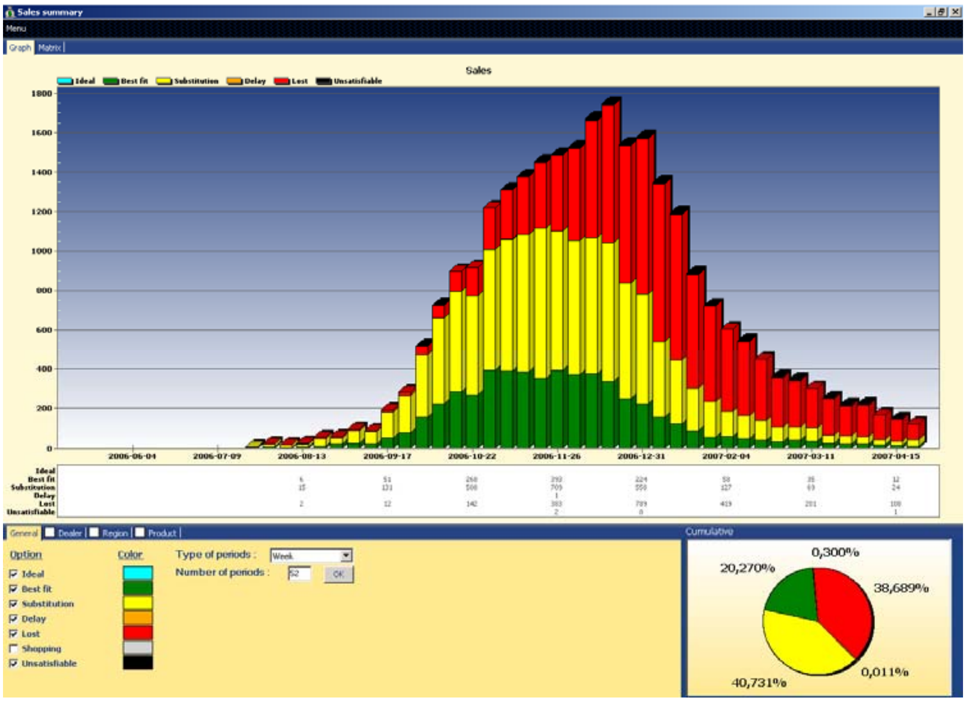
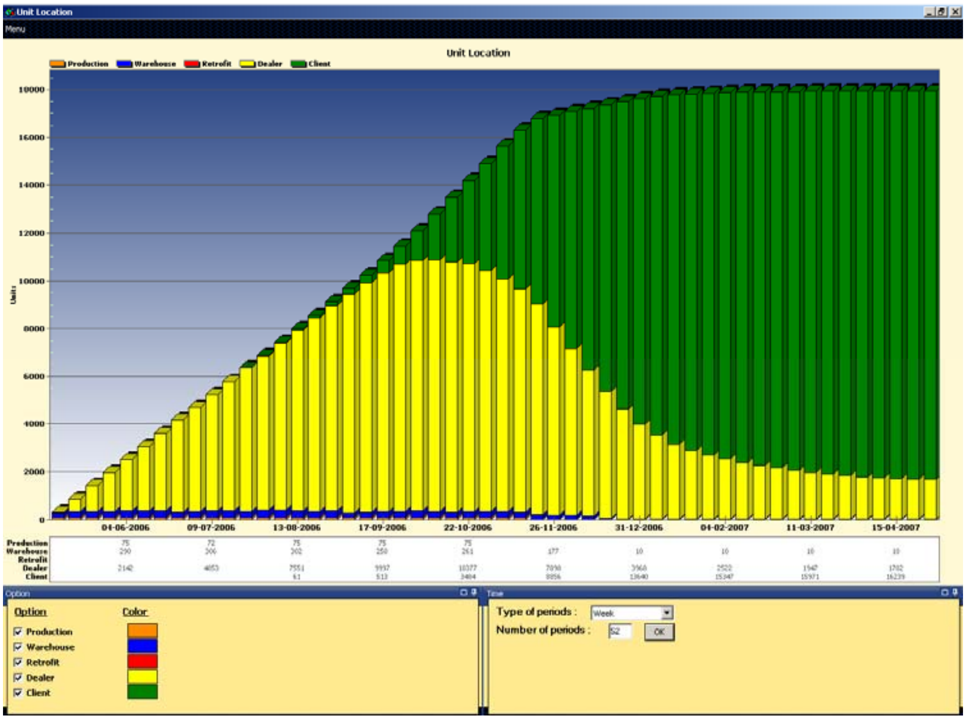


Figure 6 Dealer financial cockpit (see online version for colours)

4.2 Holistic supply chain visualisation

The current supply chains as a whole works to assemble and deliver the snowmobiles ordered by dealers so that they can build their stock and have vehicles to offer clients during the selling season. It also works to insure supply of the assembler with parts necessary for vehicle assembly. Holistic visualisation of the simulated supply chain is necessary for users to be in a position to dynamically grasp what is happening as the simulation unfolds. The product deployment graph shown in Figure 7 plots the number of products present in each type of site in the supply chain. The image here clearly shows that the current supply chain is presently using a channel stuffing strategy since there are very few units in production and in the distribution centre. In the early portion of the season, the dealers have to support the majority of the inventory and have just started selling.

Figure 7 Supply chain product deployment graph (see online version for colours)



5 Conclusions

This paper presented a holistic approach for developing and simulating demand and supply chains models. The approach relies on the modelling of a community of agents closely mimicking decision processes, with fine granularity and comprehensiveness, the various decision making actors in the modelled supply chain. The simulation of the modelled chain then exploits multiple concurrent viewers that can both illustrate global multi-perspective insights and tunnel down to highly detailed information of the supply chain. This allows decision makers to embed themselves into the simulation and obtain the deep and wide holistic visualisation needed to support their decisions.

The paper has demonstrated that it is currently possible to increase the capability for concurrent breadth and depth of simulation of demand and supply chains, pushing the actually perceived limitations in the compromise between breadth and depth. To support this holism migration, the research presented builds on recent technological, conceptual, methodological and informational breakthroughs achieved by the scientific and professional communities, and then contributes by introducing holistic modelling and holistic visualisation approaches. The paper has exploited a case study to transmit the essentials of its contribution.

Although the paper has focused on modelling and simulation of demand and supply chains, it is important to recognise that a modelling and simulation platform is necessary for enabling such an approach. Such a platform must be able to support the modelling of cases by exploiting libraries of agents and objects, to allow the management and analysis of informational input and output, to computationally execute simulation experiments, and to stimulate overall interaction with the users through holistic viewer libraries and development capabilities. Due to efforts necessary to develop and maintain holistic demand and supply chains, such a platform must become a multipurpose tool enabling the use of persistent simulation models for multiple objectives and experiments rather than a single focused experiment meeting a specific punctual objective. The platform must be capable of being used for recreating past activities and analysing past performance, and for contrasting how an altered chain would have performed under the same demand and external events. It must also be capable of allowing elegant and efficient creation of alternate future demand and event scenarios for investigating the expected performance and robustness of the current chain and proposed alternatives. Screenshots from actual simulations executed on the SPEE platform have been thoroughly exploited throughout the paper to clearly emphasise that instrumental research and development has made holistic modelling, simulation and visualisation of demand and supply chains a reality.

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Modelling and analysis of coordination of a three-level supply chain with use of price discount along with delay in payment

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Abstract: Coordination improves the performance of a supply chain system. Two popular coordination mechanisms are 'price discount' and 'delay in payment'. The effect of these two mechanisms individually on supply chain performance has already been reported in literature. In this work, the two mechanisms 'price discount' and 'delay in payment' are used simultaneously to coordinate a three-level supply chain system. The problem has been modelled mathematically and solved. The result obtained in the case is compared with that obtained when using 'price discount' alone. It is seen that use of 'price discount' along with 'delay in payment' enhances the supply chain profit significantly compared to the case of price discounts alone.

Keywords: supply chain; coordination; mechanism; price discounts; delay in payments; profit.

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This paper is a revised and expanded version of a paper entitled ‘Modeling & analysis of three level supply chain coordination: price discounts in conjunction with delay in payments as mechanisms’ presented at the International Conference on ‘Advances in Supply Chain and Manufacturing Management’, Department of Industrial Engineering and Management, Indian Institute of Technology, Kharagpur, West Bengal, India, 16–18 December 2011.

1 Introduction

Increasing importance is being given now to coordination in supply chain (SC) management so as to improve the performance. Arshinder et al. (2008) have in their review paper discussed studies about the SC coordination, which include empirical studies with different coordination mechanisms. Some important SC coordination issues dealt in the literature are in the areas of operation (Lallement and Ait-Seddik, 2012), pricing (Bernstein et al., 2006), information system (Esmaeili and Zeephongsekul, 2010), disruptions (Skipper and Hanna, 2009) and technology (Sanders, 2008). Under operations, the issues addressed in the recent studies are order quantity, fuzziness, capacity, replenishment and inventory.

The problem of equitable SC surplus sharing among SC partners (Yao et al., 2008; Jain et al., 2006) has also received attention of researchers. An interesting study to identify the factors that affect the supplier’s satisfaction in buyer-supplier relationships and explore their relationships with supplier’s satisfaction has been reported by Meena et al. (2012).

Pricing is a key issue as it normally decides the customer demand. Price dependent demand, pricing and contracts, uncertainty and pricing schemes are some of the areas found addressed in the recent works. Mechanisms such as quantity discounts and delays in payments are commonly used to enhance the coordination among the SC members.

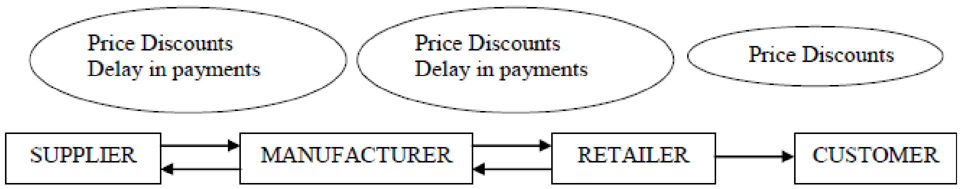
But, coordination through simple discount policy may not be an efficient solution when the system involves high degree of uncertainty. So, in such cases, multi pricing schedules to adopt global pricing policy is suggested in literature. Some models that are reported include, Integrated inventory model with permissible delay in payments for determining the optimal replenishment time interval and frequency by Chen and Kang (2007), quantity discount model to resolve practical challenges associated with implementing quantity discount policies by Shin and Benton (2007) and coordination of ordering and pricing decisions in a two stage distribution system with price sensitive demand through short-term discounting by Hsieh et al. (2010). There are studies under deterministic parameters such as coordination of two-level SC using delay in payments as coordination mechanism by Jaber and Osman (2006) and coordination of three-level SC with price dependent demand using price discounts as mechanism by Jaber et al. (2006). Both studies found that these mechanisms can coordinate the order quantities among the SC levels and minimise the cost to enhance the performance of the SC system. Ryu and Yucesan (2010) used a news vendor model and a fuzzy approach to quantify the cost of this misalignment and to assess the impact of various coordination policies. Coordination is also possible for a SC in which manufactures operation undergoes learning-based continuous improvement. Jaber et al. (2010) studied a system characterised by enhancing capacity utilisation, reduction in setup time and improved product quality. The study conducted by Kelle et al. (2007) focused on the inventory-related costs that can be influenced by adjusting the ordering, setup, and delivery policy to the random yield which represents the condition still prevailing in several industries. This study shows that not the average yields but the yields uncertainty plays the critical role mainly in providing an appropriate service level but also in finding the optimal shipment and setup policy. A recent study in the area of production-inventory system of a SC consisting of formulation of an integrated model for a three-stage multi-firm SC based on an integer multiplier at each stage, lot streaming allowed for all suppliers and manufactures and complete backordering allowed for some/all retailers (Leung, 2012). This has been solved using the methods of complete squares and perfect squares. Review of literature revealed that SC coordination mechanisms of ‘price discount’ and ‘delay in payment’ have been used separately and both are seen to improve performance measure of SC profit. But, the combined use of these mechanisms in a single system has not been reported and is worth investigating. In this paper, the effect of the usage of these two mechanisms simultaneously on the SC profit of a three-level SC system taken from Jaber et al. (2006) has been studied. The above problem has been then modelled and solved mathematically.

2 Mathematical modelling

The three-level SC used in this study consists of one supplier, one manufacturer and one retailer as shown in Figure 1. In this case, annual customer demand is known and retailer places the order according to its economic order quantity. As the demand is assumed to be price elastic, the retailer provides an optimal discount to the customer to increase the demand. Similarly, each player provides optimal discounts to their buyer in the SC to increase the demand and thereby the order quantity. At the same time, the supplier and manufacturer provides the delay in payments to their buyers due to which the holding cost of manufacturer and retailer decreases and thereby their order quantity increases.

With permissible delay in payment, the retailer and the manufacturer has the opportunity to invest the unpaid balance for the period of delay in payment. The overall objective of implementation of these mechanisms (quantity discount and delay in payment) simultaneously is to enhance the volume of business and to improve the coordination among the SC members and hence to improve the SC profit. Figure 1 shows the structure of the three-level SC and the strategic coordination mechanisms being implemented.

Figure 1 Three-level SC applying two coordination mechanisms simultaneously



Notes: Manufacturer's order quantity (Q_m), retailer's order quantity (Q_r), customer demand (D), strategic coordination mechanisms: price discounts and delay in payments.

In this work, we propose the modelling and analysis of three-level SC coordination with price discount along with delay in payment as mechanisms. The type of price discount used is 'all unit price discounts'. The performance is measured by taking the sum of the profits of the three players in the SC. In this case, both the 'all unit price discount' and 'delay in payment' are used to coordinate the order quantities among the SC levels.

This section is for mathematical modelling of a three-level SC profit function. Subsection 2.1 present assumptions, Subsection 2.2 present notations used in this modelling. Subsections 3.1 to 3.3 presents individual profit functions for the retailer, manufacturer and supplier, respectively. Then, Subsection 3.4 presents the mathematical profit model for the three-level SC with coordination using price discounts along with delay in payments as mechanisms. Finally, Section 4 presents numerical results; Section 5 presents sensitivity analysis and Section 6 presents summary and scope of further research.

2.1 Assumptions

Single supplier, single manufacturer and single retailer, single product case, no shortages to occur, zero lead time, perfect quality items, infinite planning horizon, price elastic demand, cost parameters do not vary over time, each player is financially capable of settling his/her balance with the preceding player at any point in time in a single payment, linear storage cost per unit time.

2.2 Notations

i a subscript identifying a specific player in a SC; $i = s, m, r$ (s = supplier, m = manufacturer, r = retailer)

A_i order cost for player i

h_i holding cost for player i

s_i storage cost for player i

c_i procurement cost for player i

k_i return on investment (ROI)/interest to be paid for player i.

Actual demand $D = D_0 + D_i \times d_r$, d_i = discount given by the player i. Where

D_0 initial demand

D_1 elasticity of demand

p_i selling price for each player i

t_{ij} interest free permissible delay in payments period permitted by player 'i' to player 'j' = t_{sm} and t_{mr}

τ_{ij} maximum possible delay in payments period taken by player 'i' from player 'j' τ_{rm} and τ_{ms}, if $\tau_{ij} > t_{ij}$, the player 'j' charges interest on player i for the period of $\tau - t$ where $j = m$, $r\ I \neq j$

Q_i quantity ordered by player $i = s$, m, r

T_i inventory cycle time for player,

$$T_r = \frac{Q_r}{D}, T_m = \frac{\lambda_m \times Q_r}{S}, T_s = \frac{\lambda_m \times \lambda_s \times Q_r}{D}$$

λ_i an integer lot sizing multiplier which when multiplied with the orders received at a SC stage/level gives the order quantity to be placed with the immediate up stream level means an integer multiplier to set the order quantity of player i' to that of player 'j' where $i \neq j$ and $\lambda_i = 1, 2, \ldots\ldots$ For example, $Q_m = \lambda_m \times Q_r$ and $Q_s = \lambda_s \times Q_m = \lambda_s \times \lambda_m \times Q_r$.

3 Analysis

Using the model developed and explained in the previous section, analysis has been carried out here. First, the profit functions of each of the three players are derived and this is then used to formulate the profit function for the SC. The effect of the two coordination mechanisms used has been incorporated in the profit function calculations which are given below.

3.1 Profit function for retailer

A retailer orders Q_r units from a manufacturer at a unit cost of c_r and ordering cost of A_r. The manufacturer offers the retailer an incentive to make payment by t_{mr} units of time, $t_{mr} \geq 0$, after the shipment is received by the retailer and also gives an all-unit price discount of d_m on the ordered quantity. This is to entice the retailer to order large quantities than their economic order quantity. The retailer in turn provides a discount d_r to the customer to increase the customer demand which is price elastic. The difference between sales revenue earned by the retailer, $Q_r p_r$ and the net cost for the retailer gives the profit of the retailer.

Figure 2 Illustrates the behaviour of inventory in the retailer's cycle

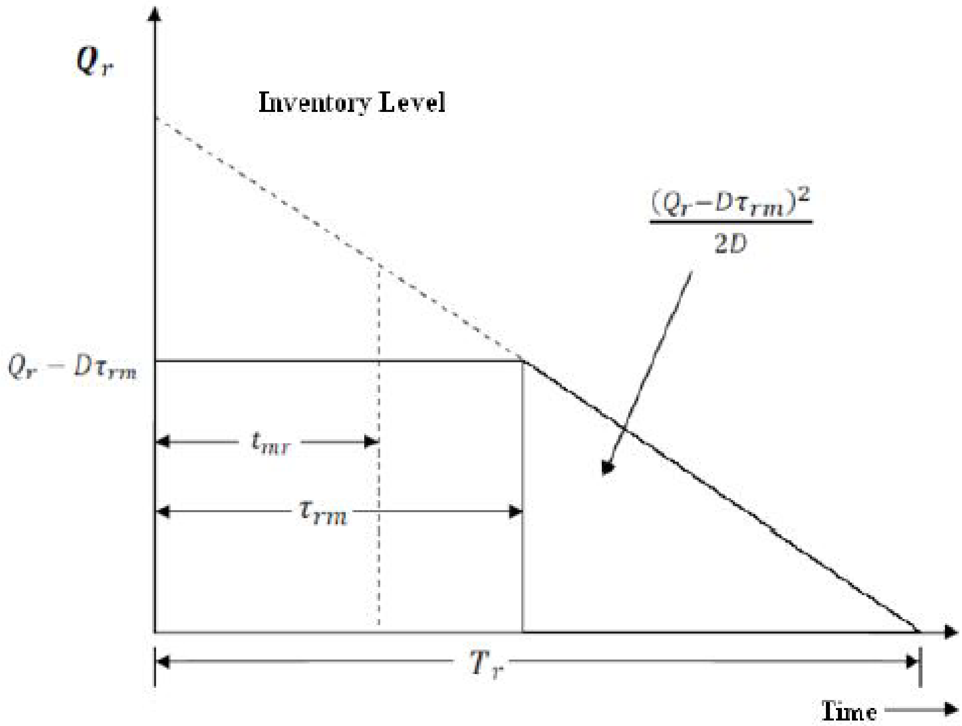


Figure 2 illustrates the retailer's inventory cycle. As the demand is linear throughout the cycle, the average inventory per cycle is equal to $\frac{1}{2} \times Q_r \times T_r$. The holding cost per cycle is computed by multiplying the average inventory per cycle with holding cost h_r. So, the holding cost is $\frac{h_r Q_r^2}{2D}$. This being the case, it is assumed that delay in payment is possible in three ways. The first one is that permitted interest free delay in payments period for the retailer by the manufacturer, t_{mr} is less than or equal to retailer's (buyer) inventory cycle time, T_r and no more extension is allowed after permitted delay in payment period. In the second case, extension is allowed but interest has to be paid for the period after the permitted period till the payment is done. The allowable extended delay in payments τ_{rm} with interest can be less than or equal to the retailer inventory cycle time T_r. In the third case also, extension is possible by paying interest to the manufacturer for the period after the permitted period till the payment is done and the allowable extended delay in payments τ_{rm} with interest can be greater than or equal to retailer's inventory cycle time, T_r. In the second and third cases, the interest free permitted delay in payment period is less than or equal to retailer's inventory cycle time T_r as in first case. The retailer must settle the purchase cost, $c_r Q_r$, with the manufacturer either by the time t_{mr} or by time τ_{rm}. Thus, if the retailer avails delay in payment, retailer's holding cost per cycle is reduced from $\frac{h_r Q_r^2}{2D}$ to either $\frac{h_r(Q_r - D \times t_{mr})^2}{2D}$ (case 1) or $\frac{h_r(Q_r - D \times \tau_{mr})^2}{2D}$ (case 2) or 'Zero' (case 3). The holding cost is zero for the case 3 as the payment is done by the retailer to manufacturer only after the retailers inventory cycle time. The retailer incurs storage cost per cycle as $\frac{s_r Q_r^2}{2D}$.

With permissible delay in payment, the retailer has the opportunity to invest the unpaid purchase cost $c_r Q_r$, for a period t_{mr} at a return rate of k_r. When the return rate for the retailer exceeds that for the manufacturer, $k_r > k_m$, it might be advantageous for the retailer to make payment by the time τ_{rm}.

Assuming a continuous compounding rate of return, the term $c_r \times Q_t \times \{e^{(k_m \times (\tau_{rm} - t_{mr}))} - e^{(k_r \times \tau_{rm})}\}$ measures the savings or additional cost from investing an amount of $c_r Q_r$ for a period of length) $\tau_{rm}(\tau_{rm} > t_{mr})$. The term $c_r \times Q_t \times \{e^{(k_m \times (\tau_{rm} - t_{mr}))} - e^{(k_r \times \tau_{rm})}\}$ can be elaborated as follows. If the retailer extends his/her delay in payments to a period τ_{rm} beyond the interest-free period t_{mr}, the manufacturer is then entitled to charge interest on the outstanding balance $c_r Q_r$ at a rate of k_m, for the period $\tau_{rm} - t_{mr}$, and the retailer has to pay the amount including interest to the manufacturer by the time τ_{rm} equal to $c_r \times Q_r \times e^{(k_m \times (\tau_{rm} - t_{mr}))}$. Also, there is a gain on the side of the retailer who may invest the outstanding balance $c_r Q_r$ at a rate of k_r for a period τ_{rm}, equal to $c_r \times Q_r \times e^{(k_r - \tau_{rm})}$.

Profit of the retailer = Sales revenue − Net cost

Net cost per unit cycle $= \psi_r\left(Q_r, d_r, t_{mr}, \tau_{rm}, d_m\right)$
= order cost + procurement cost + storage cost + holding cost
+Interest paid to manufacturer + discount to customer
–(discount frommanufacturer + savings from investment)

Total quantityordered by the retailer $= Q_r$

Discount offered by theretailer to the customer $= dr$

Total discount $= d_r \times Q_r$

Order cost $= A_r$

Procurement cost $= c_r \times Q_r$

Storage cost $= \frac{s_r \times (Q_r)^2}{2D}$

Holding cost $= H_r\left(Q_r, t_{mr}, \tau_{rm}\right)$

$= \frac{h_r\left(Q_r - D \times t_{mr}\right)^2}{2D}$ (case 1) or $\frac{h_r\left(Q_r - (D \times \tau_{rm})\right)^2}{2D}$ (case 2) or 'Zero' (case 3)

Inventory cycle time for retailer $= T_r = \frac{Q_r}{D}$

Discount by manufacturer = $d_m \times Q_r$

Interest paid to manufacturer = $c_r \times Q_r \times e^{(k_m \times (\tau_{rm} - t_{mr}))}$

Savings from the investments = $c_r \times Q_r \times e^{(k_r \times \tau_{rm})}$

Net cost of retailer = $\psi_r \left(Q_r, d_r, t_{mr}, \tau_{rm}, d_m\right)$

$$\psi_r \left(Q_r, d_r, t_{mr}, \tau_{rm}, d_m\right) = A_r + \left(c_r \times Q_r\right) + \left(\frac{s_r \times Q_r^2}{2D}\right) + H_r \left(Q_r, t_{mr}, \tau_{rm}\right)$$
$$+\left(d_r \times Q_r\right) - \left(d_m \times Q_r\right) + c_r \times Q_r \times \left\{e^{(k_m \times (\tau_{rm} - t_{mr}))} e^{(k_r \times \tau_{rm})}\right\}$$

Net cost of retailer per unit time = $\dfrac{\psi_r \left(Q_r, d_r, t_{mr}, \tau_{rm}, d_m\right)}{T_r}$

$$= \frac{A_r \times D}{Q_r} + \left(c_r \times D\right) + \frac{s_r \times Q_r^2}{2} + \frac{D \times H_r \left(Q_r, t_{mr}, \tau_{rm}\right)}{Q_r}$$
$$+ d_r \times D - d_m \times D + c_r \times D \times \left\{e^{(k_m \times (\tau_{rm} - t_{mr}))} - e^{(k_r \times \tau_{rm})}\right\}$$

Sales revenue per cycle = $Q_r \times p_r$

Sales revenue per unit time = $\dfrac{Q_r \times p_r}{T_r} = \dfrac{Q_r \times p_r \times D}{Q_r} = p_r \times D$

Net Profit for the retailer per unit time = Sales revenue per unit time
−Net cost per unit time

$$Po_r \left(Q_r, d_r, \tau_{rm}, t_{mr}, d_m\right) = \left(p_r \times D\right) - \left[\frac{A_r \times D}{Q_r} + \left(c_r \times D\right) + \frac{s_r \times Q_r}{2}\right.$$
$$\left. + \frac{D \times H_r \left(Q_{r,\, t_{mr}}, \tau_{rm}\right)}{Q_r} + d_r \times D - d_m \times D + c_r \times D \times \left\{e^{k_m \times (\tau_{rm} - t_{mr})} - e^{(k_r \times \tau_{rm})}\right\}\right]$$

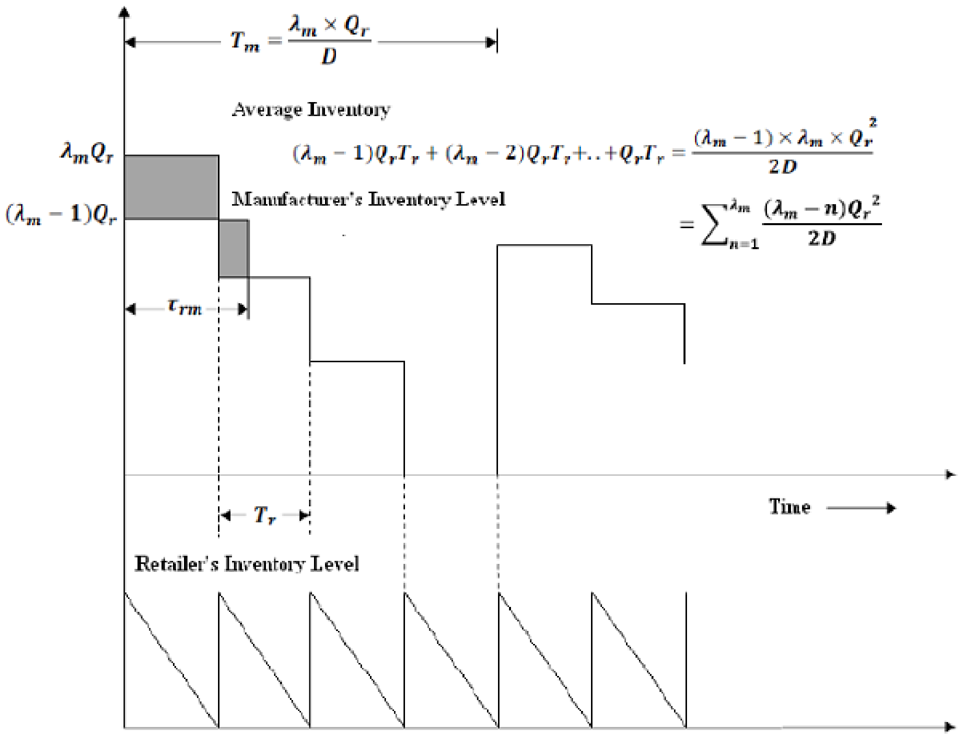
3.2 Profit function for manufacturer

The manufacturer delivers to the retailer shipments of Q_r units every cycle. Unlike the lot-for-lot policy, the manufacturer replenishes his/her inventory instantaneously with $\lambda_m Q_r$ units every $T_m = \dfrac{\lambda_m Q_r}{D}$ units of time, where λ_m = 1, 2, … at a cost of c_m per unit, such that $c_m < c_r$, with an order cost of A_m. Once it does that, the manufacturer instantaneously delivers the first shipment to the retailer and thereafter his/her every inventory cycle time $T_r = \dfrac{Q_r}{D}$. For every unit in inventory, the manufacturer incurs two costs viz. holding cost (h_m) and storage cost (s_m). Therefore, the manufacturer's storage cost is computed to $\dfrac{s_m \times (\lambda_m - 1) \times \lambda_m \times Q_r^2}{2D}$. The manufacturer offers the retailer an incentive to make payment by t_{mr} units of time, $t_{mr} > 0$, after delivering the shipment. By doing so, the manufacturer will also lose the opportunity to invest his/her profit per order over the permissible delay period, $(c_r - c_m) \times \lambda_m \times Q_r \times e^{(k_m \times t_{mr})}$, where it is assumed that the manufacturer pays his total cost, $c_m \times \lambda_m \times Q_r$, at the beginning of each manufacturer's cycle. If the retailer makes payment to the manufacturer by the time $\tau_{rm} > t_{mr}$, then the manufacturer will charge the retailer interest, k_m, for a period $(\tau_{rm} - t_{mr})$.

Since the retailer pays for the purchase by time τ_{rm}, where $\tau_{rm} > t_{mr}$, the holding cost of each shipment of size Q_r delivered to the retailer has to be incurred by the manufacturer since the manufacturer will not recover the revenue from such shipment until time τ_{rm}. The manufacturer replenishes his/her inventory in lots of sizes $\lambda_m Q_r$ every T_m units of time that are delivered to the retailer in lots of size Q_r every T_r units of time.

The manufacturer orders Q_m units from a supplier at a unit procurement cost of c_m and ordering cost of A_m. The supplier offers the manufacturer an incentive to pay by t_{sm} units of time, $t_{sm} \geq 0$, after the shipment is received by the manufacturer and price discount of d_s on the ordered quantity is also given. The manufacturer in turn provides a discount, d_m to the retailer as mentioned earlier. The decision on ordered quantity Q_r and customer-discount d_r is taken by the retailer, while the decision on integer multiplier λ_m and retailer-discount d_m is taken by the manufacturer. The total sales revenue earned by the manufacturer and the net cost for the manufacturer provides the profit function for the manufacturer in the SC.

Figure 3 Illustrates the behaviour of inventory levels for the manufacturer and the retailer



As far as delay in payments is concerned, three cases can happen between manufacturer and supplier as in the case of retailer and manufacturer (discusses in Section 3.1 above).

The manufacturer must settle his/her purchase cost, $c_m\lambda_mQ_r$ with the supplier either by the time t_{sm} or by time τ_{ms}, Thus, manufacturer's holding cost per cycle is reduced from $\frac{h_m(\lambda_m \times Q_r)^2}{2D}$ to either $\frac{h_m(\lambda_m \times Q_r - D \times t_{ms})^2}{2D}$ (case 1) or $\frac{h_m(\lambda_m \times Q_r - D \times \tau_{ms})^2}{2D}$ (case 2) or 'Zero' (case3). The holding cost is zero for the case 3 as the payment is done by the manufacturer to supplier only after the manufacturer's inventory cycle time. The manufacturer incurs storage cost per cycle as $\frac{s_m \times (\lambda_m - 1) \times \lambda_m \times Q_r^2}{2D}$.

Figure 3 depicts the behaviour of inventory level of retailer and manufacturer for a typical SC system for $\lambda_m = 4$.

With permissible delay in payment, the manufacturer has the opportunity to invest the unpaid balancer $c_m\lambda_mQ_r$, for a period t_{sm} at a return rate of k_m. When the return rate for the manufacturer exceeds that for the supplier, $k_m > k_s$, it might be advantageous for the manufacturer to settle his/her account by the time (τ_{ms}, $\lambda_{ms} - t_{sm}$). Assuming a continuous compounding rate of return, the term $c_m \times \lambda_m \times Q_r \times \{e^{(k_s \times (\tau_{ms} - t_{sm}))} - e^{k_m \times \tau_{ms}}\}$ measures the savings or additional cost form investing an amount of $c_m\lambda_mQ_r$ for a period of length) $\tau_{ms}(\tau_{ms} > t_{sm})$. The term $c_m \times \lambda_m \times Q_r \times \{e^{(k_s \times (\tau_{ms} - t_{sm}))} - e^{k_m \times \tau_{ms}}\}$ can be elaborated as follows. If the manufacturer extends his/her delay in payments to a period τ_{ms} beyond the interest-free period t_{sm}, the supplier is then entitled to charge interest on the outstanding balance $c_m\lambda_mQ_r$ at a rate of k_s, for the period $\tau_{ms} - t_{sm}$, and the amount including interest the manufacturer has to pay to the supplier by the time τ_{ms} is $c_m \times \lambda_m \times Q_r \times e^{(k_s \times (\tau_{ms} - t_{sm}))}$. On the other hand, there is a gain on the side of the manufacturer who may invest the outstanding balance $c_m\lambda_mQ_r$ at a rate of k_m for a period τ_{ms}, with the term $c_m \times \lambda_m \times Q_r \times e^{(k_m \times \tau_{ms})}$. Even though the shipment is physically at the retailer's end, the manufacturer carries his/her financial burden till the retailer settles his/her balance with the supplier. That is, the manufacturer incurs an additional holding cost for each shipment of size Q_r delivered to the retailers, who in turn settles his/her balance by time τ_{rm}, ($\tau_{rm} \geq t_{mr}$). The additional cost is computed by multiplying $Q_r\tau_{rm}$ by the manufacturer's cost of capital h_m. Since this cost is incurred λ_m times in a manufacturer's cycle, then the total additional cost incurred by the supplier in each cycle is $h_mQ_r\lambda_m\tau_{rm}$. This holding cost term is different than the storage cost calculated earlier.

$$\text{Profit of manufacturer} = \text{Sales revenue} - \text{Net cost}$$

$$\begin{aligned}
\text{Net cost per unit cycle} &= \psi_m\left(Q_r, d_r, d_m, d_s, \tau_{ms}, t_{sm}, \lambda_m\right) \\
&= \text{Order cost} + \text{Procurement cost} + \text{Storage cost} + \text{Holding cost} \\
&\quad + \text{Interest paid to supplier} + \text{Cost due to loss of opportunity to invest the profit} \\
&\quad + \text{Discount to retailer} - (\text{savings from investment} \\
&\quad + \text{Interest paid by retailer} + \text{Discount by supplier}.
\end{aligned}$$

$$\text{Discount rate by manufacturer to retailer} = d_m$$

$$\text{Quantity ordered by the manufacturer} = Q_m = \lambda_m \times Q_r$$

$$\text{Discount by supplier} = d_m \times Q_m = d_m \times \lambda_m \times Q_r$$

Order cost = A_m

Storage cost = $s_m \dfrac{\sum_{n=1}^{\lambda_m} (\lambda_m - n) Q_r^2}{2D} = \dfrac{s_m \times (\lambda_m - 1) \times \lambda_m \times Q_r^2}{2D}$

Holding cost = $H_m(Q_m, t_{sm}, \tau_{ms})$

$= \dfrac{h_m(\lambda_m \times Q_r - D \times t_{ms})^2}{2D}$ (case 1), $\dfrac{h_m \times ((\lambda_m \times Q_r) - (D \times \tau_{ms}))^2}{2D}$ (case 2),
'Zero' (case 3)

Additional holding cost = $h_m Q_r \lambda_m \tau_{rm}$

Inventory cycle time for manufacturer = $T_m = \dfrac{\lambda_m \times Q_r}{D}$

Procurement cost = $c_m \times \lambda_m \times Q_r$

Interest paid to supplier = $c_m \times \lambda_m \times Q_r \times e^{(k_s \times (\tau_{ms} - t_{sm}))}$

Saving from investment = $c_m \times \lambda_m \times Q_r \times e^{(k_m \times \tau_{ms})}$

Interest paid by retailer = $c_r \times Q_r \times e^{(k_m \times (\tau_{rm} - t_{mr}))}$

Cost due to loss of opportunity to invest the profit = $(c_r - c_m) \times \lambda_m \times Q_r \times e^{(k_m \times t_{mr})}$

Cost function per unit cycle = $\psi_m(Q_r, d_r, d_m, d_s, \tau_{ms}, \tau_{rm}, t_{sm}, t_{mr}, \lambda_m)$

$$
\begin{aligned}
&= A_m + (c_m \times \lambda_m \times Q_r) + \frac{s_m \times (\lambda_m - 1) \times \lambda_m \times Q_r^2}{2D} \\
&+ H_m(Q_r, \lambda_m, t_{sm}, \tau_{ms}) + c_m \times \lambda_m \times Q_r \times e^{(k_s \times (\tau_{ms} - t_{sm}))} \\
&+ c_m \times \lambda_m \times Q_r \times e^{(k_m \times \tau_{ms})} - c_r \times Q_r \times e^{(k_m \times (\tau_{rm} - t_{mr}))} \\
&+ (c_r - c_m) \times \lambda_m \times Q_r \times e^{(k_m \times t_{mr})} + h_m Q_r \lambda_m \tau_m \\
&- d_s \times \lambda_m \times Q_r + d_m \times \lambda_m \times Q_r
\end{aligned}
$$

Cost function per unit time = $\dfrac{\psi_m}{T_m} = \dfrac{A_m \times D}{\lambda_m \times Q_r} + c_m \times D + \dfrac{s_m \times (\lambda_m - 1) \times Q_r}{2}$

$$
\begin{aligned}
&+ \frac{D \times H_m(Q_r, \lambda_m, t_{sm}, \tau_{ms})}{\lambda_m \times Q_r} + c_m \times D \times e^{(k_s \times (\tau_{ms} - t_{sm}))} \\
&- c_m \times D \times e^{(k_m \times \tau_{ms})} - d_s \times D + d_m \times D + h_m \times \tau_{rm} \times D \\
&- \frac{c_r \times D \times e^{(k_m \times (\tau_{rm} - t_{mr}))}}{\lambda_m} + (c_r - c_m) \times D \times e^{(k_m \times t_{mr})}
\end{aligned}
$$

Sales revenue per unit cycle = $Q_r \times \lambda_m \times p_m$

$$\text{Sales revenue per unit time} = \frac{Q_r \times \lambda_m \times p_m}{T_m} = p_m \times D$$

$$\text{Profit of manufacturer per unit time} = Po_m\left(Q_r, d_m, d_s, \lambda_m, \tau_{ms}, t_{sm}\right)$$

$$= \text{Sales revenue per unit time} - \text{Net cost per unit time}$$

$$= p_m \times D - \left[\frac{A_m \times D}{\lambda_m \times Q_r} + c_m \times D + \frac{s_m \times (\lambda_m - 1) \times Q_r}{2}\right.$$

$$+ \frac{D \times H_m\left(Q_r, \lambda_m, t_{sm}, \tau_{ms}\right)}{\lambda_m \times Q_r} + c_m \times D \times e^{(k_s \times (\tau_{ms} - t_{sm}))}$$

$$-c_m \times D \times e^{(k_m \times \tau_{ms})} - d_s \times D + d_m \times D + h_m \times \tau_{rm} \times D$$

$$\left. - \frac{c_r \times D \times e^{(k_m \times (\tau_{rm} - t_{mr}))}}{\lambda_m} + \left(c_r - c_m\right) \times D \times e^{(k_m \times t_{mr})}\right]$$

3.3 Profit function for supplier

The supplier delivers to the manufacturer shipments of size $Q_m = \lambda_m Q_r$ units every cycle. Unlike the lot-for-lot policy, the supplier replenishes his/her inventory instantaneously with $\lambda_m \lambda_s Q_r$ units in every $T_s = \frac{\lambda_m \lambda_s Q_r}{D}$ units of time, where λ_m, λ_s = 1, 2, …, at a cost of c_s per unit, such that $c_s < c_m$, with an order cost of A_s. Once it does that, the supplier instantaneously delivers the first shipment to the manufacturer and thereafter its every inventory cycle time $T_m = \frac{\lambda_m Q_r}{D}$. For every unit in inventory, the supplier incurs two costs viz. holding cost (h_s) and storage cost (s_s). Therefore, the sum of supplier's holding cost and storage cost is computed to $\frac{(s_s + h_s) \times (\lambda_m \times Q_r)^2 \times \lambda_s \times (\lambda_s - 1)}{2D}$. The supplier will offer the manufacturer an incentive to settle his/her account by t_{sm} units of time, $t_{sm} > 0$, after delivering the shipment. By doing so, the supplier will also lose the opportunity to invest his/her profit per order over the permissible delay period, $(c_m - c_s) \times \lambda_m \times \lambda_s \times Q_r \times e^{(k_s \times t_{sm})}$, where it is assumed that the supplier pay his/her procurement total cost, $c_s \times \lambda_m \times \lambda_s \times Q_r$, at the beginning of each supplier's cycle. If the manufacturer pays the amount with the supplier by the times $\tau_{ms} > t_{sm}$, then the supplier will charge the manufacturer interest, k_s, for a period ($\tau_{ms} - t_{sm}$). The suppler also provides a unit discount of d_s to the manufacturer as mentioned earlier.

Since the manufacturer settles his/her balance by time τ_{ms}, where $\tau_{ms} \geq t_{sm}$, then the cost of capital for each shipment of size $\lambda_m Q_r$ delivered to the manufacturer has to be incurred by the supplier since the supplier will not recover the revenue from such shipment until time τ_{ms}. The supplier replenishes his/her inventory in lots of sizes $\lambda_m \lambda_s Q_r$ in every T_s units of time that are delivered to the manufacturer in lots of size in every T_m units of time. Even though the shipment is physically at the manufacturer's end, the supplier carries his/her financial burden till the manufacturer settles his/her balance with the supplier. That is, the supplier incurs an additional holding cost for each shipment of size $\lambda_m Q_r$ delivered to the manufacturer, who in turn settles his/her balance time τ_{ms}, ($\tau_{ms} \geq t_{sm}$). The additional cost is computed by multiplying $Q_r \lambda_m$ by the supplier's cost of capital

h_s. Since this cost is incurred λ_s times in a supplier's cycle, then the total additional cost incurred by the supplier in each cycle is $h_s Q_r \lambda_m \lambda_s \tau_{ms}$. This holding cost term is different than the holding cost calculated earlier.

Profit of supplier = Sales revenue − Net cost

Net cost of supplier per unit cycle = Order cost + Procurement cost
+Storage cost + Holding cost + Cost due to loss of opportunity to invest the profit
+Discount to manufacturer − Interest paid by manufacturer

Cost function per unit cycle = $\psi_s\left(Q_r, d_r, d_m, d_s, t_{sm}, \tau_{ms}, \lambda_m, \lambda_s\right)$

Discount rate by the supplier to the manufacturer = d_s

Quantity ordered by the supplier = $\lambda_m \times \lambda_s \times Q_r$

Order cost = A_s

Discount to manufacturer = $d_s \times Q_s = d_s \times \lambda_m \times \lambda_s \times Q_r$

Procurement cost = $c_s \times \lambda_m \times \lambda_s \times Q_r$

$$\text{Storage cost and holding cost} = \frac{\left(s_s + h_s\right)\sum_{n=1}^{\lambda_s}\left(\lambda_s - n\right)Q_r^2\lambda_m^2}{D}$$

$$= \frac{\left(s_s + h_s\right)\times\left(\lambda_m \times Q_r\right)^2 \times \lambda_s \times \left(\lambda_s - 1\right)}{2D}$$

Additional holding cost = $h_s \times \lambda_m \times \lambda_s \times Q_r \times \tau_{ms}$

Inventory time of cycle for the supplier = $T_s = \dfrac{\lambda_m \times \lambda_s \times Q_r}{D}$

Interest paid by manufacturer = $c_s \times \lambda_m \times Q_r \times e^{\left(k_s \times \left(\tau_{ms} - t_{sm}\right)\right)}$

Investment due to delay in payments = $\left(c_m - c_s\right)\times \lambda_m \times \lambda_s \times Q_r \times e^{\left(k_s \times t_{sm}\right)}$

Net cost per unit cycle = $\psi_s\left(Q_r, d_r, d_m, d_s, t_{sm}, \tau_{ms}, \lambda_m, \lambda_s\right)$

$$= A_s + \left(c_s \times \lambda_m \times \lambda_s \times Q_r\right) + \frac{s_s \times \left(\lambda_m \times Q_r\right)^2 \times \lambda_s \times \left(\lambda_s - 1\right)}{2D}$$
$$+ \frac{h_s \times \left(\lambda_m \times Q_r\right)^2 \times \lambda_s \times \left(\lambda_s - 1\right)}{2D} + h_s \times \lambda_m \times \lambda_s \times Q_r \times \tau_{ms}$$
$$= d_s \times \lambda_m \times \lambda_s \times Q_r - c_m \times \lambda_m \times Q_r \times e^{\left(k_s \times \left(\tau_{ms} - t_{sm}\right)\right)}$$
$$+ \left(c_m - c_s\right)\times \lambda_m \times \lambda_s \times Q_r \times e^{\left(k_s \times t_{sm}\right)}$$

$$\text{Net cost per unit time} = \frac{\psi_s}{T_s} = \frac{A_s \times D}{\lambda_m \times Q_r \times \lambda_s} + (c_s \times D) + \frac{s_s \times Q_r \times \lambda_m \times (\lambda_s - 1)}{2}$$
$$+ \frac{h_s \times Q_r \times \lambda_m \times (\lambda_s - 1)}{2} + h_s \times \tau_{ms} \times D$$
$$- \frac{c_m \times D \times e^{(k_s \times (\tau_{ms} - t_{sm}))}}{\lambda_s} + d_s \times D + (c_m - c_s) \times D \times e^{(k_s \times t_{sm})}$$

$$\text{Sales revenue per unit cycle} = \lambda_m \times \lambda_s \times Q_r \times p_s$$

$$\text{Sales revenue per unit time} = \frac{\lambda_m \times \lambda_s \times Q_r \times p_s}{T_m} = p_s \times D$$

$$\text{Profit of supplier per unit time} = Po_s\left(Q_r, d_r, d_m, d_s, \tau_{ms}, t_{sm}, \lambda_m, \lambda_s\right)$$
$$= \text{Sales revenue per unit time} - \text{Net cost per unit time}$$
$$= p_s \times D - \left[\frac{A_s \times D}{\lambda_m \times Q_r \times \lambda_s} + (c_s \times D) + \frac{s_s \times Q_r \times \lambda_m \times (\lambda_s - 1)}{2} \right.$$
$$+ \frac{h_s \times Q_r \times \lambda_m \times (\lambda_s - 1)}{2} + h_s \times \tau_{ms} \times D - \frac{c_m \times D \times e^{(k_s \times (\tau_{ms} - t_{sm}))}}{\lambda_s} + d_s \times D$$
$$\left. + (c_m - c_s) \times D \times e^{(k_s \times t_{sm})} \right]$$

3.4 Total SC profit function

The total SC profit in this case has been taken as the sum of the retailer, manufacturer and supplier profits. On coordinating the SC with two mechanisms (price discounts and delay in payments) simultaneously, the SC profit function P is obtained by the sum of the players' profit functions. The mathematical programming problem could then be written as follows:

$$\text{Maximise supply chain profit} = P = Po_r + Po_m + Po_s$$

Subject to the constraints:

Integer multipliers $\lambda_m, \lambda_s \geq 1$,

Order quantity

$$Q_r \geq 1$$

Maximum discount permitted:

$$d_s \leq p_s - c_s,\ d_m \leq p_m - (p_s - d_s),\ d_r \leq p_r - (p_m - d_m),\ \tau_{ij} \geq 0,\ t_{ij} \geq 0$$

Table 1 Conditions used in different cases of delay in payments

Case 1	*Case 2*	*Case 3*
$Q_{r/D} - t_{mr} \geq 0$	$Q_{r/D} - \tau_{rm} \geq 0$	$\tau_{rm} - Q_{r/D} \geq 0$
$\lambda_m Q_{r/D} - t_{sm} \geq 0$	$Q_{r/D} - t_{mr} \geq 0$	$t_{mr} - Q_{r/D} \leq 0$
	$\lambda_m Q_{r/D} - \tau_{ms} \geq 0$	$\tau_{ms} - \lambda_m Q_{r/D} \geq 0$
	$\lambda_m Q_{r/D} - t_{sm} \geq 0$	$t_{sm} - \lambda_m Q_{r/D} \leq 0$
	$\tau_{rm} \geq t_{mr}, \tau_{ms} \geq t_{sm}$	$\tau_{rm} \geq t_{mr}, \tau_{ms} \geq t_{sm}$

As mentioned in the beginning, the price discounts and delay in payments are implemented in transactions between supplier and manufacturer and manufacturer and retailer. Retailer permits only price discount to the customer but no delay in payments. Under these circumstances, three cases are possible for delay in payments as explained below. Each case is considered separately for solving the above mathematical model and the results are compared and analysed.

Case 1 The seller permits interest free permissible delay in payments to the buyer up to a maximum period of buyer's inventory cycle time and no extension of delay in payment is allowed after the permitted period.

Case 2 The buyer can extend the delay in payment period even over the permitted interest free delay in payment period but maximum up to his/her inventory cycle time. That means, interest free delay in payment period will be less than or equal to delay in payment period with interest and both can be maximum up to buyer's inventory cycle time.

Case 3 Delay in payments period can be extended even over the buyer's inventory cycle time. But, the maximum interest free delay in payment period is up to the buyer's inventory cycle time only as in above two cases.

4 Numerical results

The non-linear mathematical model developed for the three-level SC coordination with case 1, case 2 and case 3 are solved using 'Excel solver'. This study shows that the profit is more for the case 3 and the same is used for the comparison with results obtained when using price discounts only as mechanism used by Jaber and Osman. (2006).

Table 2 consists of data adopted from Munson and Rosenblatt (2001) is used for analysis. It is assumed that a fixed annual demand of 150,000 units and it increases with increase in discount offered by the retailer and the elasticity of demand. This means that the chain is driven by the retailer's annual sales volume. Thus, the actual demand (D) is equal to $D_0 + D_1 \times dr$ where D_1 = 1,000 … 5,000 … 10,000 … 15,000, etc. The ROI is taken as 15% per annum (normal state of the business) in all cases except in the sensitivity analysis of this SC system under different market conditions/ROI of each player. Unit time in this study is taken as a year.

Table 2 Munson and Rosenblatt's (2001) dataset used for this study

Player	*Setup cost (Rs)*	*Purchase cost (Rs)*	*Holding cost (Rs)*	*Storage COST* (Rs)*	*Profit margins (%)*	*Selling price (Rs)*	*Return on investment* (%)*
Supplier	400	200	10	2	25	250.00	15
Manufacturer	200	250	12	3	25	312.50	15
Retailer	30	312.50	16	4	25	390.63	15

Note: *added in this study.

Table 3 SC performance for the three cases of delay in payments along with price discounts (D_1 = 1,000, k_r = 15%, k_m = 15%, k_s = 15%)

Case	λ_m	λ_s	t_{mr}	τ_{rm}	t_{sm}	τ_{ms}
1	3	1	0.009	-	0.028	-
2	3	1	0.009	0.009	0	0.028
3	3	1	0.009	0.009	0	0.050

	d_r	d_m	d_s	*Supply chain profit (Rs.)*	*Increase in profit (%) in case 2&3 (with base as case 1)*
1	21.28	10.0	3.69	29,107,526	0
2	21.28	10.0	3.69	29,143,672	0.12
3	20.61	10.0	3.99	29,250,439	0.51

Table 3 shows the SC performance for the three cases of delay in payments along with price discounts. This analysis shows that case 2 provides slightly more profit than case1 and case 3 provides significantly higher profit than cases 1 and 2. This is due to the increase in net savings from investing the purchase cost amount for the delay in payment period permitted over the buyer's inventory cycle time in case 3. So, it is suggested to follow case 3 for the delay in payments along with price discounts for comparatively better SC profit.

Table 4 Profit comparison when using price discounts alone and along with 'delay in payments' vs. 'no coordination' (D_1 = 1,000, λ_m = 3, λ_s = 1, k_r = 15%, k_m = 15%, k_s = 15%)

Benefit when using price discounts alone and 'no coordination' (Jaber et al., 2006)			*Profit under combination of mechanisms (price discounts with delay in payments) (case 3) (c)*	*Increase in profit (%) under combination of mechanisms (case 3) compared to 'no coordination' ((c–a)/a) × 100*
SC profit under no coordination (a)	*SC profit under discount alone (b)*	*Increase in profit (%) under discount alone compared to no coordination ((b–a)/a) × 100*		
28,538,426	28,950,375	1.44	29,250,439	2.49

Table 4 shows the profit comparison when using price discounts alone and along with delay in payments versus no coordination. The analysis shows the use of price discounts along with delay in payments (case 3) enhances the SC profit significantly and this hike in profit from price discount alone is approximately equal to the hike in profit between no coordination and price discount alone. So, this study suggest to incorporate price discounts along with delay in payments as strategic coordination mechanisms to improve the SC performance than the case of price discount alone.

5 Sensitivity analysis

The effect of change in various parameters on SC performance are also analysed to understand the sensitivity of this SC system and it will enable the decision maker to take proper decisions accordingly. The parameters considered for the sensitivity analysis are elasticity of demand, ROI and order cost/setup cost.

In any business, boom and recession is a common phenomenon depending on various external and internal factors. That means, the players (supplier, manufacturer or retailer) can be either in recession, normal or boom state of market. So, the ROI can vary in the case of any of these players in a SC system based on the existing market conditions. The following table shows such an analysis how difference in ROI or the market conditions affects the profit of individual players and over all SC profit.

Table 5 Analysis of SC profit (case 3 – maximum profit case) for the different market conditions/values of ROI of various players (D_1 = 1,000, λ_m = 3, λ_s = 1, A_r = 30, A_m = 200, A_r = 400)

Case	*Return on investment*	λ_m	λ_s	*Retailer profit (Rs)*	*Manufacturer profit (Rs)*	*Supplier profit (Rs)*	*Supply chain profit (Rs.)*
I	k_r = 10, k_m = 15, k_s = 20	3	1	11,562,235	8,811,524	8,858,144	29,231,904
II	k_r = 10, k_m = 20, k_s = 15	3	1	11,562,235	9,043,522	8,798,461	29,404,219
III	k_r = 20, k_m = 15, k_s = 10	3	1	11,632,264	9,020,682	8,643,984	29,296,930
IV	k_r = 20, k_m = 10, k_s = 15	3	1	11,708,837	8,820,650	8,704,013	29,233,500
V	k_r = 15, k_m = 10, k_s = 20	3	1	11,601,901	8,745,856	8,789,760	29,137,517
VI	k_r = 15, k_m = 20, k_s = 10	3	1	11,586,459	9,172,128	8,669,856	29,428,443
VII	k_r = 10, k_m = 10, k_s = 10	3	1	11,562,236	8,922,942	8,618,435	29,103,613
VIII	k_r = 15, k_m = 15, k_s = 15	3	1	11,587,056	8,912,452	8,750,931	29,250,439
IX	k_r = 20, k_m = 20, k_s = 20	3	1	11,610,695	8,914,532	8,927,451	29,452,678

Notes: 10% ROI – recession state, 15% ROI – normal state, 20% ROI – boom state.

Table 5 shows the performance of players under different market conditions/values of ROI. The above analysis reveals that the state of the manufacturing sector (cases II and VI – boom and cases III and V – recession) affects more on the total SC profit. At the same time, the state of the retailer in which it operates affects very little on the total SC profit. The rate of increase in the SC profit as the whole market condition improves (cases VII, VIII and IX) is almost constant.

The order cost/setup cost is normally highest for Manufacturer or supplier and lowest for other players in a SC system. Table 7 shows the analysis of how the variation in order cost/setup cost of various players affects the SC profit. The other parameters such as elasticity of demand, ROI, and lot size multiplier remains same.

Table 6 Performance of the players and SC profit for different order/setup cost

Case	*Order/ setup cost* A_r A_m A_m	*Delay in payment* t_{sm} t_{mr} τ_{ms} τ_{rm}	*Discount given by each player* *dr* *dm* *ds*	*Retailer profit (Rs)*	*Manufacturer profit (Rs)*	*Supplier profit (Rs)*	*Supply chain profit (Rs.)*	*Increase in SC profit (with base as case I)*
I	30	0.000	20.61	11,587,056	8,912,452	8,750,931	29,250,439	0
	200	0.009	10.00					
	400	0.050	0.00					
		0.009						
II	30	0.000	20.61	11,587,056	8,905,342	8,758,041	29,250,439	
	400	0.009	10.00					
	200	0.050	0.00					
		0.009						
III	200	0.000	21.11	11,639,946	8,882,569	9,171,962	29,694,477	1.52
	400	0.024	10.00					
	30	0.129	0.00					
		0.024						
IV	200	0.000	21.11	11,639,946	8,887,671	9,166,860	29,694,477	
	30	0.024	10.00					
	400	0.129	0.00					
		0.024						
V	400	0.000	21.45	11,676,371	8,864,368	9,454,440	29,995,179	2.54
	200	0.034	10.00					
	30	0.184	0.00					
		0.034						
VI	400	0.000	21.45	11,676,371	8,866,027	9,452,781	29,995,179	
	30	0.034	10.00					
	200	0.184	0.00					
		0.034						
VII	30	0.000	20.61	11,499,830	8,962,616	8,806,642	29,269,088	0.06
	30	0.009	10.00					
	30	0.050	0.00					
		0.009						
VIII	200	0.000	21.11	11,605,083	8,902,844	9,186,979	29,694,906	1.52
	200	0.024	10.00					
	200	0.129	0.00					
IX	400	0.000	21.45	11,677,210	8,861,996	9,450,402	29,989,608	2.52
	400	0.034	10.00					
	400	0.184	0.00					
		0.034						

The analysis of SC performance for different values of order cost in Table 6 shows that as retailer order cost increases, the overall SC profit also increases. This study also reveals that mutual change in the order cost between supplier and manufacturer does not affect the over SC performance provided the retailers order cost is same. This phenomenon can be seen in the cases of I and II, III and IV and V and VI. The order/setup costs given for players in each case of VII, VIII and IX are equal but they are in an increasing order from VIIIth to IXth case. The SC profit is also found to be increasing in the same order. All these findings show that the order cost of the retailer plays a major role in the performance of the SC. This is due to the fact that when retailer order cost is high, the retailer order quantity increases and there by the retailers cycle time increases. As a result, the optimal delay in payments changes in such a way that the net savings from investment increases in the case of retailer and supplier. But, it does not have much effect on manufacturer performance.

As a part of sensitivity analysis, the SC profit when using price discounts along with delay in payments for different price elasticity of demand is also found out and compared with the SC profit under price discounts alone.

Table 7 Analysis of SC profit under no coordination with price discounts alone and price discounts in conjunction with delay in payments

Sl. no.	*Elasticity of demand*	*Supply chain profit under price discounts alone as mechanism Jaber et al. (2006) (a)*	*Supply chain profit under price discounts along with delay in payments as mechanisms (b)*	*Percentage of increase in profit (%) ((b-a)/a) × 100*
1	1,000	28,950,375	29,250,439	1.036
2	5,000	60,743,508	61,293,115	0.905
3	10,000	105,566,572	106,317,166	0.711
4	15,000	150,698,412	151,659,658	0.638
5	20,000	195,992,817	197,120,813	0.576
6	25,000	241,328,917	242,570,598	0.515
7	30,000	286,686,783	288,012,060	0.462
8	35,000	332,057,668	333,536,940	0.445
9	40,000	377,437,082	379,013,058	0.418
10	45,000	422,822,466	424,484,781	0.393
11	50,000	468,212,240	469,953,006	0.372

Table 7 shows that as elasticity increases, the increase in profit also increases but the rate decreases. This indicates that if the price elasticity of demand is very high, there will not be much benefit by implementing these coordination mechanisms to enhance the profit.

6 Summary and scope for further research

From this study, it can be concluded that the implementation of the two coordination mechanisms: ‘price discount’ along with ‘delay in payment’ improves SC profit significantly (about 1.5% in the case studied). It is also found that the SC profit becomes maximum in case 3 where the delay in payment period taken from the seller exceeds the buyer's inventory cycle time. Sensitivity analysis reveals the effect of variation of order cost of different players on their performance. The overall SC profit is seen to increase with the increase in the order cost of the retailer. This indicates that the retailer has a major role in this SC system. Sensitivity analysis on ROI shows that the SC profit is most sensitive to the manufacturer's ROI. Coordination mechanisms studied become less effective when price elasticity of demand becomes very high.

The managerial implication of the findings is that coordination mechanisms should be used when very high price elasticity of demand does not exist. SC managers must understand that using both price discounts and delay in payment produces nearly the same increase in SC profit, over use of only price discount, as that between no coordination and use of price discounts. The Sc profit is more sensitive to retailer order cost and manufacturer ROI.

Some areas for further studies include investigating the effect of simultaneous use of these mechanisms in stochastic SC system. The effect of the combination of other mechanisms can also be explored and a comparative study done with a more detailed sensitivity analysis. This study has used dataset from a study reported in literature; the same can be done with different datasets. Simulation and game-based studies also can be conducted to analyse the behaviour of the SC system in a dynamic and competitive environment.

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Analysis of interactions among the drivers of green supply chain management

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Abstract: The aim of the present research was to identify and analyse the interactions among drivers of implementing green supply chain management (GSCM) in automobile industries located in National Capital Region (NCR) of India. To meet out the above objective, 11 drivers were identified and analysed for the purpose of developing an ISM-based model; which provide a visible representation of driver's position, based on their driving and dependence nature. The analysis reveals that the driver 'legislative and regulatory compliances' occupy the base position due to its high driving nature. The other drivers namely: improve quality and ISO-14000 certification exists at the top positions and can be seen as an output of ISM model. The findings of this research may enable managers to make appropriate policy decisions and to formulate the strategies towards various enablers/drivers, depending upon the corresponding importance, for the effective implementation of green aspects in the supply chain.

Keywords: green supply chain management; GSCM; green drivers; ISM approach.

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1 Introduction

The issue of implementing the green aspect in the traditional supply chains, because of increased awareness and consciousness among the industries and organisations in the last few years, is gaining importance. Also, there is an increased awareness among the consumers for conservations of environment resources. The government legislations together with consumers are making it imperative for the industries to plan for action for going green. As a result and aiming to contribute towards global problem of environment, the researchers are getting motivated to provide solutions or strategies to handle various issues related with the green supply chain of the companies.

There is an increased pressure from the various stakeholder of the organisation to go for greening of their traditional supply chain. The various stakeholders are consumers, government regulatory bodies, competitors, non-profit or non-government organisations, investors, employees, shareholders, etc.

Green supply chain is defined as an executive attitude that pursues to minimise the services ecological and societal influences (Rettab and Ben Brik, 2008). It seems as a way of implementing ecological concern into legislative buying judgments and also provides an extensive relationship with suppliers (Gilbert, 2001). Green supply chain management (GSCM) activities can provide the effective long term performance to organisations by improving the management of environmental risks and through the development of capabilities for continuous environmental improvement.

For converting the resources into usable products and to make the product competitive in the market, environmental thinking need to be integrated with the decision making process. GSCM has emerged an effective management tool and philosophy for proactive and leading manufacturing organisations. GSCM issues are implemented for all junctures ranging from point of origin to point of usage by the final customer including reverse logistics (if any) (Zhu et al., 2008a, 2008b, 2008c).

Most of the organisations globally are constantly demanding to improve original and advanced conducts to enhance their effectiveness. Green supply chain directly affects the competitiveness and economic performance of the organisations (Rao and Holt, 2005). To make the green supply chain, it is required to think environmentally ranging from raw material purchasing stage to the final delivery of finished products to the customers and also during handling the products after its valuable life stages (Srivastava, 2007).

The drivers such as governmental legislations and consumer awareness play a precise and imperative role in the implementation of green practices and product recovery programs (Irland, 2007). In the present scenario, due to community pressure and environmental conscious consumers has to follow these eco-friendly regulations; which also force manufacturers to assimilate eco-friendly criteria into their management activities (Rao and Holt, 2005; Paulraj, 2009).

Collaboration among the supply chain members provides a successful implementation of environmental management databases. According to Vachon and Klassen (2006) most of the organisations are developing supportive plans to handle environmental happenings within the supply chain. These events or happenings prepare an emergent path for collaborative interaction between organisation and supply chain associates to decrease environmental influence and provide a solution for environmental related problems.

In view of the above and to sustain the competitiveness and promote collaboration in the global environment, it is essential for an organisation to adopt green practices in their traditional supply chains. In adoption of greening concept, an industry may face many hindrances during its implementation stages.

The present research work aims to identify the drivers/enablers of GSCM and to analyse their subsequent interaction. The analysis of interaction among the drivers of GSCM may help the companies to plan their strategies appropriately for the effective implementation of greening in their traditional supply chains.

2 Literature review

GSCM is an effective theme to support the environmental based activities. It focuses on how firms utilise their supplier's processes, technology and capability, and integrating environmental concerns to enhance its competitiveness (Vachon and Klassen, 2008). According to Geffen and Rothenberg (2000) cooperative relations with suppliers provides a base for the acceptance and improvement of innovative environmental technologies. In furtherance, proper partnership agreements, interaction between customer and supplier, and joint research programmes lead to improvements in environmental performance. Successful implementation of GSCM initiatives depends on proactivity and synchronisation among supply chain stages to certify the environmental impact minimisation of the manufacturing and to deliver the better facilities (Hervani et al., 2005; Zhu and Sarkis, 2006; Linton et al., 2007; Vachon and Klassen, 2008).

In a competitive environment, it has been noticed that the automobile industries (Honda, General Motor, Ford, Toyota, Suzuki, Hyundai, and Fiat) are expanding their production capabilities into Asian region (Kumar and Bali Subrahmanya, 2010). That is why, assessment and measurement of these industries performance is crucial with environmental issues considerations (Olugu et al., 2010). Since, there have been limited studies in the context of GSCM performance evaluation, hence, it is required to apply green concepts into automobile manufacturing to condense the environmental impacts, boost market competition, and certify regulation passivity (Gan, 2003).

Sarkis (2003) applied analytical network process to analyse and select the importance level of alternatives of green supply chain. Hervani et al. (2005) identified various dimensions to evaluate the green performance of an organisation. Various internal and external drivers discussed by Trowbridge (2001) for the execution of GSCM at a chip manufacturer. The readiness to increase risk management due to different disruptions in the supply chain and the relationship with suppliers to catch substitute of constituents and tools that reduce green impacts, comes under the slope of interval drivers. Non-governmental organisations, customers, and investors are considered as external drivers.

Holt et al. (2001) identified and discussed the various classes of GSCM to enhance the environmental performance of organisations. Duber-Smith (2005) identifies the ten important reasons to implement the green supply chain system. Testa and Iraldo (2010) say that implementation of GSCM with the considerations of other advanced management practices improves the environmental performance very rapidly and this statement is also supported by Lin and Ho (2010). Shang et al. (2010) discussed the taxonomy of GSCM capability with six GSCM dimensions as green manufacturing and packaging, green marketing, green stock and green design, green suppliers, and environmental participation. Azevedo et al. (2011) analyse the importance of a set of green practices for the automotive supply chain. Liang et al. (2006) say that it is significant to assess the performance of GSCM in the entire supply chain as a whole, instead of individual stage supply chain. The green companies are trying to manage and keep the trail of regulatory compliance, waste and emissions and customer and community satisfaction using various performance dimensions (Florida and Davison, 2001).

To evaluate different product design alternatives based on environmental consideration an efficient green fuzzy design analysis (GFDA) method was used by Kuo et al. (2006). Further, Ravi and Shankar (2005) applied ISM approach to discuss the analysis of barriers of reverse logistics activities. Kannan et al. (2008) applied ISM and analytic hierarchy process as a hybrid approach to analyse the developed model and to select the suppliers based on their green performance. Qureshi et al. (2008) developed a model to categorise and analyse the important measures with their role in the assessment of 3PLs services providers. A combination of ISM and fuzzy TOPSIS approach was used by Kannan et al. (2009) to analyse and select the 3-P reverse logistics providers. Diabat and Kannan (2011) have proposed ISM methodology to analyse the drivers affecting the implementation of green supply chain management. Luthra et al. (2011) identified 11 barriers to implement GSCM in the automobile industry and developed a contextual relationship among them. Mathiyazhagan and Haq (2013) identify and analysis influential pressures of motivations for GSCM adoption using ISM approach. Mathiyazhagan et al. (2013) applied ISM approach to analyse the barriers in implementing the GSCM. Kannan et al. (2013) identify and analyse the GSCM practices in the Brazil's industry (electrical and electronics) using ISM approach.

Many research studies have been reported regarding GSCM in sectors like electrical, electronics, automobile etc. Some important of them, as discussed above, are related with identifications and analysis of barriers/drivers and some of the studies are related with the assessment of green practices in the industries at global and national levels.

In the present work, various drivers have been identified primarily on the basis of literature review. After discussion with field experts and academicians, a set of 11 drivers, suitable for automobile industries, were finalised as given in Table 1. Data have been collected exclusively from automobile industries located in National Capital Region (NCR) of India.

3 Proposed methodology

ISM is a technique to analyse the complex socio economic system to analyse the complex socio economic systems (Warfield, 1973, 1974). It is a computer-assisted learning process that generally used to resolve the complex situations by providing a feasible course of action (Kannan et al., 2009).

This approach addresses visibility of a model by transforming uncertain and roughly expressed models of systems into the precise and observable models (Sage, 1977). It is used only as an approach to give directions about the difficulty in relationship among the drivers but will not provide any weight vector for existing drivers (Kannan et al., 2009).

The steps, involved in the ISM methodology, are given below (Kannan and Haq, 2007):

1 Identify and enlist the existing drivers of green supply chain management.

2 Establish a contextual relationship for each pair of drivers recognised in step 1.

3 Develop a structural self-interaction matrix (SSIM) for drivers which indicate pairwise relationships among drivers of the system under consideration.

4 Development of reachability matrix from the SSIM and checking of reachability matrix for transitivity. The transitivity rule for the contextual relationship follows the Zeroth law of thermodynamics.

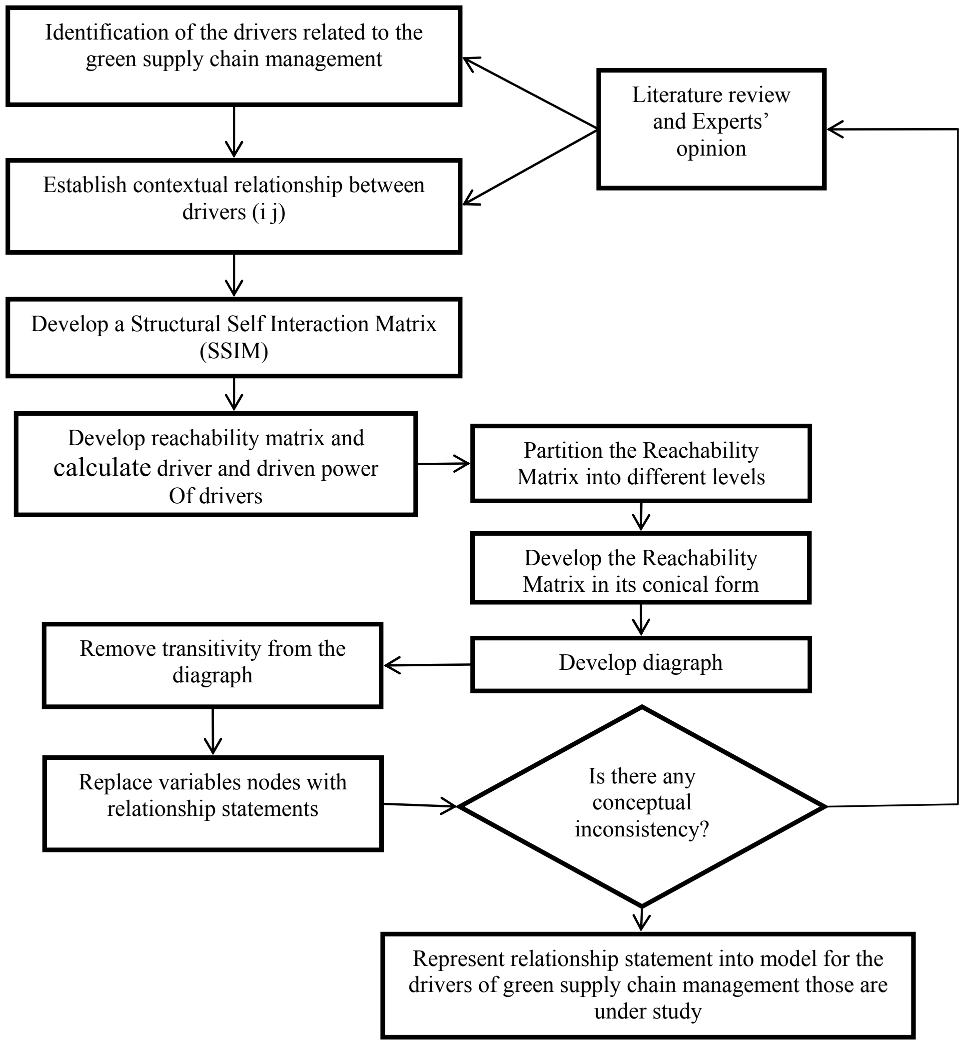
5 On the basis of the established relationships in the reachability matrix, a flow graph may be drawn without indicating transitive links.

6 Convert the resultant digraph into an ISM by replacing driver nodes with statements.

7 Check for conceptual inconsistency and necessary modifications made.

The flow chart of the methodology adopted for the present work is shown in Figure 1.

Figure 1 Flow chart for ISM approach



3.1 Drivers identification

The various important GSCM drivers are identified from the critical review of literature as well as out of discussion with the field experts and are given in Table 1.

3.2 Data collection

During the study, stakeholders of Indian automobile industries, located near New Delhi region (NCR), were contacted for the discussion and identification of GSCM drivers. A questionnaire was structured and posted on the Google doc, and opinions of field experts were gathered. From the collected data, a Cronbach's alpha coefficient was computed using SPSS-16 software and contextual relationship among the drivers were developed.

Table 1 GSCM drivers

S. no.	*Drivers*	*Sources*
1	Pressure by customers to green supply chain	Lamming and Hampson (1996), Walton et al. (1998), Green et al. (1996), Handfield et al. (1997), Hall (2001)
2	Legislative and regulatory compliance	Walton et al. (1998), Min and Galle (2001), Beamon (1999)
3	Collaboration with suppliers	Klassen and Vachon (2003)
4	Improve quality	Pil and Rothenberg (2003)
5	ISO 14000 certification	Montabon et al. (2000)
6	E-logistics and environment	Sarkis (2003)
7	Pressure by environmental advocacy groups	Hall (2001)
8	Supply integration	Vachon and Klassen (2006)
9	Collaboration with customers	Vachon (2007), Paulraj (2009), Holt and Ghobadian (2009)
10	Public pressure	Beamon (1999)
11	Employee involvement	Hanna et al. (2000)

3.3 Structural self-interaction matrix

An SSIM was developed on the basis of contextual relationship among the existing drivers, as given in Table 2. This matrix gives the pairwise relationships among these drivers. The symbols used for the relationship between the drivers (i and j) are given as:

V – driver i will aid to ameliorate driver j

A – driver j will aid to ameliorate driver i

X – drivers i and j will aid to ameliorate each other

O – drivers i and j are isolated.

Using the above symbols and their corresponding description, drivers in SSIM matrix are illustrated as follows:

- The driver 'collaboration with suppliers' will help to ameliorate 'improve quality'. Thus the relationship between these drivers is denoted by 'V' in the SSIM.
- The driver 'improve quality' will be ameliorated by the driver 'employee involvement'. Hence the relationship between these drivers is denoted by 'A' in the SSIM.
- The driver's public pressure and employee involvement are unrelated to each other, means the relationship between these drivers will be denoted by 'O'.

Table 2 SSIM for the drivers

	Drivers	*11*	*10*	*9*	*8*	*7*	*6*	*5*	*4*	*3*	*2*
1	Pressure by customers to green supply chain	V	V	V	X	V	X	X	V	O	V
2	Legislative and regulatory compliance	V	V	V	V	V	V	V	V	O	
3	Collaboration with suppliers	O	A	O	X	A	O	O	V	-	
4	Improve quality	A	O	A	A	A	O	X	-		
5	ISO 14000 certification	O	A	O	O	A	X	-			
6	E-logistics and environment	O	A	O	X	A	-				
7	Pressure by environmental advocacy groups	O	X	V	V	-					
8	Supply integration	O	A	O	-						
9	Collaboration with customers	X	A	-							
10	Public pressure	O	-								
11	Employee involvement	-									

3.4 Reachability matrix

An initial reachability matrix, using SSIM and the following rules, was developed:

- If the (i, j) record in the SSIM is V, then set the (i, j) record in the reachability matrix to 1 and the (j, i) record to 0.
- If the (i, j) record in the SSIM is A, then set the (i, j) record in the reachability matrix to 0 and the (j, i) record to 1.
- If the (i, j) record in the SSIM is X, then set the (i, j) record in the reachability matrix to 1 and the (j, i) record to 1.
- If the (i, j) record in the SSIM is O, then set the (i, j) record in the reachability matrix to 0 and the (j, i) record to 0.

The final reachability matrix as shown in Table 3 was built with the help of initial reachability matrix by using the transitivity rule, which states that if the driver 'X' is associated to 'Y' and 'Y' is associated to 'Z', then it is necessary that X will be associated with Z.

Table 3 Final reachability matrix

	Drivers	*1*	*2*	*3*	*4*	*5*	*6*	*7*	*8*	*9*	*10*	*11*	*Driver power*
1	Pressure by customers to green supply chain	1	1	1	1	1	1	1	1	1	1	1	11
2	Legislative and regulatory compliance	1	1	1	1	1	1	1	1	1	1	1	11
3	Collaborate with suppliers	1	0	1	1	1	1	0	1	0	0	0	6
4	Improve quality	1	0	0	1	1	1	0	0	0	0	0	4

Table 3 Final reachability matrix (continued)

Drivers		*1*	*2*	*3*	*4*	*5*	*6*	*7*	*8*	*9*	*10*	*11*	*Driver power*
5	ISO 14000 certification	1	1	0	1	1	1	1	1	1	1	1	10
6	E-logistics and environment	1	1	1	1	1	1	1	1	1	1	1	11
7	Pressure by environmental advocacy groups	1	0	1	1	1	1	1	1	1	1	1	10
8	Supply integration	1	1	1	1	1	1	1	1	1	1	1	11
9	Collaboration with customers	0	0	0	1	1	0	0	0	1	0	1	4
10	Public pressure	1	0	1	1	1	1	1	1	1	1	1	10
11	Employee involvement	0	0	0	1	1	0	0	0	1	0	1	4
	Dependence power	9	5	7	11	11	9	7	8	9	7	9	

3.5 Level partitions

The final reachability matrix was partitioned into different levels to find the reachability set, and antecedent set for each driver. The reachability set of a specific driver, involves of itself and the other drivers, which it may aid to accomplish. The antecedent set includes of the drivers themselves and the other drivers, which may provide assistance in achieving it, and then derived the intersection of these sets for all considered drivers. The reachability and antecedent set for each driver were found from the final reachability matrix as given in Tables 4 and 5. The driver which has same reachability set and intersection exists at level 'I' and occupies peak place in ISM model (Kannan and Haq, 2007).

The drivers founding at level 'I' are discarded in next iteration. The next iteration was performed with the remaining drivers and by repeating the above process and performs these iterations continuously until the levels of each driver have been obtained.

Table 4 Level partition (Iteration – I)

Drivers	*Reachability set*	*Antecedent set*	*Intersection*	*Level*
1	1,2,3,4,5,6,7,8,9,10,11	1,2,3,4,5,6,7,8,10	1,2,3,4,5,6,7,8,10	
2	1,2,3,4,5,6,7,8,9,10,11	1,2,5,6,8	1,2,5,6,8	
3	1,3,4,5,6,8,	1,2,3,6,7,8,10	1,3,6,8	
4	1,4,5,6,	1,2,3,4,5,6,7,8,9,10,11	1,4,5,6	I
5	1,2,4,5,6,7,8,9,10,11	1,2,3,4,5,6,7,8,9,10,11	1,2,4,5,6,7,8,9,10,11	I
6	1,2,3,4,5,6,7,8,9,10,11	1,2,3,4,5,6,7,8,10	1,2,3,4,5,6,7,8,10	
7	1,3,4,5,6,7,8,9,10,11	1,2,5,6,7,8,10	1,5,6,7,8,10	
8	1,2,3,4,5,6,7,8,9,10,11	1,2,3,5,6,7,8,10	1,2,3,5,6,7,8,10	
9	4,5,9,11	1,2,5,6,7,8,9,10,11	5,9,11	
10	1,3,4,5,6,7,8,9,10,11	1,2,5,6,7,8,10	1,5,6,7,8,10	
11	4,5,9,11	1,2,5,6,7,8,9,10,11	5,9,11	

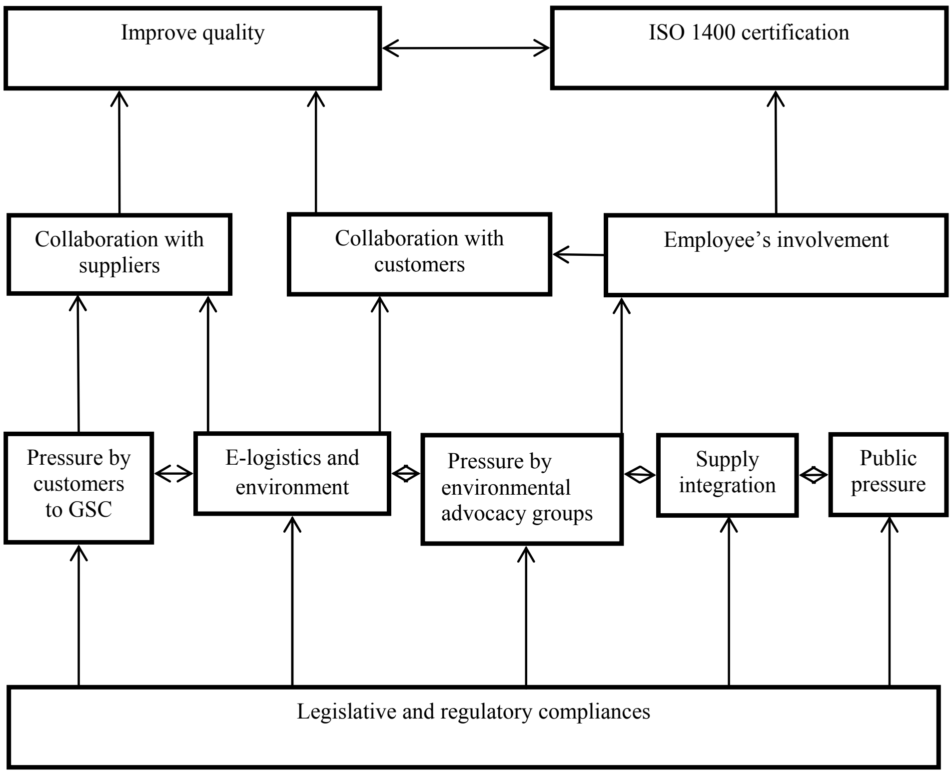
Table 5 Level partition (Iteration II–IV)

Drivers	*Reachability set*	*Antecedent set*	*Intersection*	*Level*
1	1,2,3,6,7,8,9,10,11	1,2,3,6,7,8,10	1,2,3,6,7,8,10	III
2	1,2,3,6,7,8,9,10,11	1,2,6,8	1,2,6,8	IV
3	1,3,6,8,	1,2,3,6,7,8,10	1,3,6,8	II
6	1,2,3,6,7,8,9,10,11	1,2,3,6,7,8,10	1,2,3,6,7,8,10	III
7	1,3,6,7,8,9,10,11	1,2,6,7,8,10	1,6,7,8,10	III
8	1,2,3,6,7,8,9,10,11	1,2,3,6,7,8,10	1,2,3,6,7,8,10	III
9	9,11	1,2,6,7,8,9,10,11	9,11	II
10	1,3,6,7,8,9,10,11	1,2,6,7,8,10	1,6,7,8,10	III
11	9,11	1,2,6,7,8,9,10,11	9,11	II

3.6 ISM-based model

An ISM model has been formulated on the basis of level partition (Tables 4 and 5) for the existing drivers of green supply chain management. The model shows relationship between these drivers. With the help of final reachability matrix, a structured model is created and diagraph is drawn. The conversion of diagraph into the ISM model is shown in Figure 2. This figure shows the relationship among the existing drivers.

Figure 2 ISM based model for drivers of green supply chain management



From Figure 2, it is clear that legislative and regulatory compliance (driver 2) is a very significant driver of green supply chain and build the base of ISM hierarchy. This hierarchy is like a network, which explains the mutual relationship of existing drivers. The improvement in quality (driver 4) and ISO-14000 certification (driver 5) are the desired outputs, which help in the implementation of greening concept. Both these drivers have a position at the top of ISM hierarchy. The driver legislative and regulatory compliances leads to the five drivers, appeared at level-III in the ISM hierarchy. These leading drivers are: pressure by customers to green supply chain (driver 1), e- logistics and environment (driver 6), pressure by environmental advocacy groups (driver 7), supply integration (driver 8) and the public pressure (driver 10).

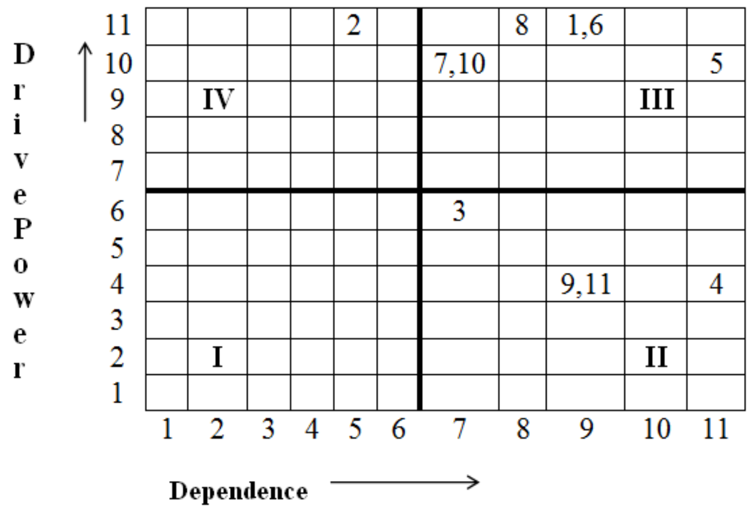
Pressure by customers to green supply chain (driver 1) and pressure by environmental advocacy groups (driver 7) enforces to the company to build an e-logistics and environmental (driver 6) friendly system and also helps in achieving the collaboration with suppliers (driver 3) and collaboration with the customers (driver 9). From the drivers of level III, it is observed that all five drivers are helping each other and also provides strength to the company to make green policies effectively and efficiently.

E-logistics and environment (driver 6) leads to the collaboration with suppliers (driver 3) and collaboration with customers (driver 9) simultaneously. Hence, e-logistics and environment works as a key driver for green supply chain management. Pressure by environmental advocacy groups (driver 7) leads to the employee involvement (driver 11) to make green process easy and efficient. The involvement of employee helps in achieving the collaboration with customers (driver 9). The drivers of level II, collaboration with suppliers (driver 3), collaboration with customers (driver 9) and employee involvement (driver 11) together helps to improve quality (driver 4) of a product with ISO-14000 certification.

3.7 MICMAC analysis

In MICMAC analysis, the drivers, based on the analysis of dependence power and driver power of the variables, were classified into four sectors and are shown in Figure 3. The driving power and dependence of each driver has been calculated on the basis of final reachability matrix. The four sectors of MICMAC analysis are: Sector I: autonomous elements; Sector II: dependent elements; Sector III: linkage elements; and Sector IV: driver/independent elements. The drivers having weak driver and weak dependence power exists in the Sector I. Such type of drivers has few links with the other sectors drivers and also disconnected from the system. Those drivers having weak driving and strong dependence power will drop in Sector II. The drivers with strong driving as well as dependence power will fall in Sector III and in last drivers that have strong driving and weak dependence power exists in Sector IV (Kannan and Haq, 2007).

Figure 3 Driving power and dependence power diagram



Because, drivers of Sector IV have high driving power thus they strongly affect the drivers of other sectors. Hence, it is required to pay more attention to the drivers that occupy the top position in ISM hierarchy to achieve better results.

From Figure 3, it is noted that no driver falls in the Sector I. The four drivers namely collaboration with suppliers, collaboration with customers, improve quality and employees involvement falls in a Sector II. It means these drivers have weak driving power and strong dependence. Six drivers' falls in Sector III, are: pressure by customers to green supply chain, ISO 14000 certification, e-logistics and environment, pressure by environmental advocacy groups, supply integration and public pressure. The driver 'legislative and regulatory compliance' exists in Sector IV, which has high driving power and lowest dependence power as compare to the other drivers. Therefore it has been considered as a base driver for ISM hierarchy as shown in Figure 2.

4 Results and discussion

The driver and dependence power diagram (Figure 3) drawn from MICMAC analysis indicates the relative importance and interdependencies of existing drivers. Some of the observations drawn from the analysis are discussed as following:

- Noticed that among the considered drivers, no driver falls in the autonomous category i.e., in the Sector I. Such type of situation provides a positive base for the study, because autonomous drivers have weak driving and weak dependence power. Hence, in the study, all drivers are interrelated and play an equally important role in improving the performance of green supply chain.

- Found that drivers viz. improve quality, collaboration with customer and employee's involvements are dependent drivers, with strong dependence and weak driving power (driving power 4) exist in the Sector II. Such type of dependence nature shows that these drivers can be achieved only through the drivers those have high driving nature/power.
- The 'ISO 1400 certification' has strong driving and dependence power and exists in the Sector III, and also occupies top position in the ISM hierarchy due to its high dependence. Other variables of Sector III are: pressure by customers to green supply chain, e-logistics and environment, pressure by environmental advocacy groups, supply integration and public pressure, as shown in Figure 3. From Figure 2, it is observed that improve quality (driver 4) and ISO certification (driver 5) occupied top position in ISM hierarchy and represents the desired objectives and outcome of the analysis.
- The legislative and regulatory compliance comes out as an independent driver and falls in the Sector IV, and have a strong driving power with weak dependence power. Hence, to achieve the desired result this driver need to be addressed more and stringently.

5 Conclusions

The objective of this research was to identify and analyse the interaction among drivers of implementing GSCM in automobile industries located in NCR of India. To meet out the above objective, eleven drivers were identified and analysed for the purpose of developing an ISM-based model (Figure 2); which provides a visible representation of driver's position, based on their driving and dependence nature. The driver 'legislative and regulatory compliances' occupy the base position due to its high driving nature and works as an engine in ISM hierarchy, that's why; more efforts are needed in proper understanding and strict compliance. The drivers namely: improve quality and ISO-14000 certification exists at the top positions and can be seen as an output of ISM model. Hence, it concludes that initially company should focus towards the legislative and regulatory compliances, improvement in quality and ISO certification.

The present study provides a systematic analysis of various GSCM drivers and highlights their importance. The findings of this research may enable managers to make appropriate policy decisions and to formulate the strategies towards various enablers/drivers, depending upon the corresponding importance, for the effective implementation of green aspects in the supply chain.

6 Limitations and future scope

The basic limitation of the present work is that it cannot be generalised for automobile industries as the data, used in the study, represents only a specific region of India. The automobile industries have their existence at various locations in India. A comprehensive analysis by taking into account all major automobile industries situated in almost in the entire region of India may be taken as future scope of the present work.

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