Design of Robust Supply Chains: an Integrated Hierarchical Approach

Ontwerp van robuuste supply chains: een geïntegreerde hiërarchische aanpak

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Nederlandse samenvatting –Summary in Dutch–

In de huidige concurrentiële bedrijfseconomische context vormen talloze bedrijven allianties om een concurrentieel voordeel uit te bouwen. Zodoende stellen zij zich nochtans bloot aan risico's en onzekerheden veroorzaakt door de andere partners in de alliantie. Klantvraag en productiecapaciteit zijn de meest courante vormen van onzekerheid in een supply chain. Een dergelijke supply chain vereist een goede opbouw, ontwerp en planning om deze vormen van onzekerheid het hoofd te bieden. We stellen een geïntegreerd supply chain model voor waarin alle planningsbeslissingen robuust zijn met betrekking tot deze onzekerheden.

In de meeste supply chains is het planningsproces hiërarchisch gestructureerd, wat betekent dat één planning op het hoogste niveau steeds verder wordt vertaald en uitgewerkt naar de lagere niveaus toe. Typisch zijn er drie planningsniveaus: strategisch, tactisch en operationeel. Hoewel de meeste supply chains hiërarchisch georganiseerd zijn, heeft de studie van de hiërarchische planning in supply chains weinig aandacht gekregen in de literatuur. Wij geloven dat er onderliggende verbanden bestaan tussen verschillende planningsniveaus (d.w.z. tussen strategisch niveau en tactisch niveau, en tussen tactisch niveau en operationeel niveau). We stellen een model voor dat die planning in de supply chain hiërarchische behandelt. Dit proefschrift tracht om nieuwe planningsbenaderingen te onderzoeken die oplossingen kunnen bieden voor complexiteiten inherent aan supply chains.

Op het strategisch niveau wordt een plaatsingsmodel voor veiligheidsvoorraad voorgesteld dat omgaat met de vraagonzekerheid in een supply chain met capaciteitsbeperkingen. Eerst simuleren wij het effect van capaciteit in een single-stage (één stadium) supply chain en veralgemenen vervolgens de resultaten naar een seriéle supply chain modellering. De capaciteitsbeperkingen langsheen de supply chain verhogen de minimale hoeveelheid veiligheidsvoorraad, nodig om een bepaald service level te kunnen garanderen. De verhoging van veiligheidsvoorraad hangt samen met de ratio van overcapaciteit en de standaardafwijking van de vraag gedurende de netto aanvullingstijd. Zelfs wanneer de netto aanvullingstijd nul of negatief is, moet een stadium met capaciteitsbeperkingen veiligheidsvoorraad plaatsen om het voorgeschreven service level te behouden. Voor een special geval van supply chain (namelijk een seriéle supply chain) wordt de shortest path (kortste pad) benadering voorgesteld.

Op het tactisch niveau moet elk stadium van de supply chain zijn eigen geagreggeerde planning genereren om vraag en aanbod in evenwicht te brengen. In overeenstemming met scenario-gebaseerde benaderingen wordt de onzekerheid vertegenwoordigd door een eindig aantal scenario's. Het nadeel van die benaderingen is de behoefte aan een gigantische rekentijd. Wij stellen een robuust deterministisch model voor dat gebruik maakt van de beschikbare informatie over de onzekerheid. Op het tactisch niveau gebruiken wij het extra capaciteit of capaciteitskussen om de vraagonzekerheid te behandelen. De gemiddelden en de standaardafwijkingen van de vraag worden gebruikt voor het berekenen van de cumulatieve vraag, waaruit vervolgens de grootte van het capaciteitskussen (en dus de veiligheidsvoorraad) voor elke twee opeenvolgende periodes in de planningshorizon volgt. De resulterende informatie is in feite deterministisch, maar incorporeert de variatie en onzekerheid in de vraag. Het robuust deterministische model resulteert in een robuust plan, die aan gerealiseerde vraag voor de daaropvolgende periode voldoet bij een bepaalde service level. De benodigde rekentijd en geheugenruimte bij dit deterministisch model zijn veel kleiner dan bij de scenario-gebaseerde modellen alhoewel het voorgestelde model even goed presteert als de scenario-gebaseerde modellen.

Op het operationeel niveau wordt het tactisch plan naar afzonderlijke eindproducten opgesplitst, waarbij de machines progressief slijten, hetgeen zich uit in een vermindering van de capaciteitsniveaus. Het is daarom noodzakelijk om zowel productie- als onderhoudsplanning op een geïntegreerde manier uit te voeren. Wij stellen voorop dat de preventieve onderhoudsacties best op het tactisch niveau worden geïntegreerd aangezien de onzekerheid van de machinepannes op het operationeel niveau ageert. Omdat de machinepannes een Poisson distributie volgen, wordt een scenario-gebaseerd model voorgesteld met meerdere doelfuncties. De eerste doelfunctie minimaliseert de gemiddelde absolute runout-afwijking tussen de families en hun individuele eindproducten, dit komt neer op het synchroniseren van de productie langsheen de lijn. De tweede doelfunctie minimaliseert de onderproductie (in vergelijking met de geplande hoeveelheid).

Wij stellen twee integratiestappen voor in de hiërarchische planningsbenadering: [1] de integratie van de planning tussen strategich en tactisch niveau en [2] de integratie van de planning tussen tactisch en operationeel niveau. Op het strategisch niveau levert het plaatsingmodel voor veiligheidsvoorraad de servicetijden -en dus de netto aanvullingstijden- voor alle stadia in een supply chain. De gegarandeerde servicetijden worden dan gebruikt om de gerealiseerde vraag aan individuele eindproducten voor opeenvolgende periodes in de planningshorizon te berekenen. Aangezien de tactische planning vraag en aanbod in evenwicht moet brengen, is het ook noodzakelijk om de machinecapaciteit, die van het onderhoudsbeleid afhangt, in rekening te brengen. Op het tactisch niveau wordt de gezamenlijke productieplanning geformuleerd rekening houdend met twee soorten onzekerheid: de vraag- en capaciteitsonzekerheid. Het capaciteitskussen wordt gebruikt om de vraagonzekerheid aan te pakken en preventief onderhoudsplanning om capaciteitsonzekerheid het hoofd te bieden. Wij stellen een algemene planning voor preventief onderhoud voor waarbij de tijd tussen verschillende onderhoudsperiodes niet noodzakelijk even lang is. Met betrekking tot capaciteitsonzekerheid wordt de distributie van machinepannes gebruikt om de onderhoudsduur in een periode te berekenen, gezien de informatie over het laatste preventieve onderhoud beschikbaar is. Op het operationeel niveau wordt het productieplan van familieniveau naar eindproducten opgesplitst waarbij machinepannes gemodelleerd worden.

Samengevat, proberen wij één van de belangrijkste problemen in supply chain planning op te lossen, namelijk het voldoen aan een onzekere vraag met een onzekere productiecapaciteit. De complexiteit van een supply chain wordt gedeeltelijk beheersbaar gemaakt door het gebruik van veiligheidsvoorraad op het strategich niveau, de formulering van de beperkingen van de inventarisbeweging op het tactisch niveau en de formulering van de runout afwijkingen op het operationeel niveau. Het gebruik van veiligheidsvoorraad op het strategisch niveau laat elk stadium in de supply chain toe om onafhankelijk zijn eigen tactische planning te genereren. De beperkingen van de inventarisbeweging op het tactisch niveau koppelen de machines van de productielijn los zodat elke machine de eigen operationele planning kan opmaken. Voorts kan de formulering van de runout-afwijkingen op het operationeel niveau de productie van eindproducten over de gehele lijn synchroniseren, alhoewel elke machine onafhankelijk werkt.

English summary

In today's competitive business world, many companies form alliances in order to boost competitive advantage. However, in doing so, they expose themselves to uncertainties brought by other partners in the alliance. Customer demand and production capacity are the two most common sources of uncertainty in a supply chain. A supply chain requires good design and planning to deal with these types of uncertainty. We present an integrated model for a supply chain design that allows all planning in the supply chain to be robust against these uncertainties.

In most supply chains, the planning process is executed hierarchically, which means that an upper level plan has to be translated into one at the lower level. Typically, there are three levels of planning: strategic, tactical, and operational. Although most supply chains operate hierarchically, the study of hierarchical planning in supply chains has garnered little interest. We believe that underlying relationships exist among different planning levels (i.e. between strategic level and tactical level, and between tactical level and operational level). We therefore propose an integrated study, which addresses this hierarchical planning process in a supply chain. This PhD work attempts to explore new approaches in integrating plans in a supply chain in order to resolve the complex issues inherent in the supply chain.

At the strategic level, we propose a safety stock placement model to deal with demand uncertainty in a supply chain subject to capacity limitations. We first simulate the effect of capacity in a single-stage supply chain and then generalize the results for a serial supply chain modeling. The effect of capacity limitation leads to an increase in the quantity of safety stock required to guarantee a certain service level. The increase of safety stock depends on the ratio of excess capacity and standard deviation of demand during the net replenishment time. Even when the net replenishment time is zero or negative, a capacitated stage in the supply chain must place safety stocks in order to maintain the prescribed service level. For a special case of supply chains (i.e. serial chain), the shortest path based approach is proposed to solve the problem.

At the tactical level, each stage in the supply chain must generate its own aggregate plan in order to balance supply and demand. According to scenario-based approaches, uncertainty is represented by a finite number of scenarios. The drawback of such an approach is the need for a huge computational time, which is less practical for the planning process. We propose a robust deterministic model, which makes use of readily available information regarding uncertainty. At the tactical level, we use extra capacity or capacity cushion levels to deal with demand uncertainty. The averages and standard deviations of demand are used to calculate cumulative demand which lead to capacity cushion level (hence the safety stock) for any set of consecutive periods in the planning horizon. The resulting information is in fact deterministic, but also able to capture uncertain information regarding demand. The robust deterministic model results in a robust plan, one that satisfies all realized demand for a consecutive period at a certain service level. The computational time and space required by the robust deterministic model is far less important if compared with the scenario-based models even though the proposed model performs as well as the scenario-based ones.

At the operational level, we solve the problem of disaggregating a family production plan into finished products where machines progressively deteriorate leading to a reduction in capacity levels. It is therefore necessary to perform both production and maintenance planning in an integrated way. We conjecture that the preventive maintenance actions should be integrated into the tactical level planning as the uncertainty due to machine breakdowns is confronted at the operational level. Since machine failures follow a Poisson distribution, a scenario-based optimization model with a multi-objective function is proposed. The first objective function is to minimize the mean absolute deviation of runout time of families and their corresponding finished products. It attempts to synchronize the production of finished products across the production line. The second objective function is to minimize the expected unmet production in attempt to produce finished products as close as possible to the planned production.

We propose two steps of integration in the hierarchical planning approach: [1] the integration of strategic and tactical level planning and [2] the integration of tactical and operational level planning. At the strategic level, the safety stock placement model yields guaranteed service times -hence the net replenishment times- for all stages

in a supply chain. The guaranteed service times are then used to calculate demand realizations of finished products for any consecutive periods in the planning horizon. Since tactical level planning is concerned with balancing supply and demand, it is also necessary to take into account machine capacity, which depends on maintenance policy. At the tactical level, the aggregate production planning is formulated addressing two types of uncertainty: demand and capacity uncertainty. Some capacity cushion levels are used to deal with demand uncertainty and preventive maintenance planning to deal with capacity uncertainty. We propose a general preventive maintenance planning where maintenance periods do not necessarily fall at equally distant epoch. In term of capacity uncertainty, the failure rate distribution are used to calculate the expected maintenance duration in any period given that the last preventive maintenance is known. At the operational level, a family production plan is then disaggregated into finished products taking into account machine breakdowns.

In summary, we aim to solve one of the most important problems in supply chain planning, namely how to meet uncertain demand using an uncertain capacity. The complexity of a supply chain is partly reduced by the use of safety stock at the strategic level, the formulation of inventory movement constraints at the tactical level and the formulation of runout deviations at the operational level. The use of safety stock at the strategic level permits each stage in the supply chain to act independently generating its own tactical planning. The inventory movement constraints at the tactical level also decouple machines from the production line so that each machine can produce its own operational planning. Furthermore, the formulation of runout deviations at the operational level is capable of synchronizing the production of finished products across the whole production line, even though each machine operates independently.

1

Introduction

1.1 Introduction

Supply chain uncertainty is defined by a lack of precise information on critical parameters to manage all involved activities in the supply chain. Galbraith (1973) defined uncertainty as the difference between the amount of information required to perform a task and the amount of information already possessed.

Supply chain uncertainty can be classified into four general types: process uncertainty, supply uncertainty, demand uncertainty, and control uncertainty (Geary et al., 2002). According to Geary et al. (2002), process uncertainty affects on organization's internal ability to meet a production delivery target. Supply uncertainty results from poorly performing suppliers' not meeting an organization's requirements. Demand uncertainty can be seen as the difference between the actual end-market-place demand and orders placed with an organization by its customers. Control uncertainty is associated with information flow and the way an organization transforms customer orders into production target and supply of raw material. There are also various sources of uncertainty in supply chains as described by several authors, such as exchange rates, supplier lead time, supply quality, stochastic demands, available capacity, political environment and many more (Vidal and Goetschalckx, 2000; Van Landeghem and Vanmaele, 2002).

Managing uncertainty in supply chains has been a challenging subject for many years. Incorrect responses to uncertainty in supply chains often lead to an increase in costs and a deterioration in service levels. Uncertain demand, for example, leads to an increase in unnecessary stocks along supply chains as a consequence of managers' natural reactive responses. As a matter of fact, decisions related to inventory locations and their corresponding levels throughout a supply chain has a fundamental impact on the service levels, delivery lead time and the total costs of the supply chain. These interactions, present at every link of the chain, render the analysis at the supply chain level much more difficult and complex. Therefore, it is important to understand the relationship between supply chain performance and uncertainty.

For production planning problems, Mula et al. (2006) carried out a literature survey regarding production models under uncertainty. Although the study is extensive, it points out the need to further investigate new approaches, especially in the context of supply chains. Because the conditions effecting supply chains are typically complex, new approaches are required to manage supply chains effectively and efficiently. We have conducted a literature review on articles which are published in international journals during period 1988 - 2009. However, a vast majority of literature on uncertainty in supply chains was only published after the year 1995. Table 1.1 shows some literature addressing the sources of uncertainty in supply chains and their corresponding planning levels, solution approaches and performance measures. Most of this literature, however, discusses the issues of uncertainty at a specific level.

At the strategic level, the following problems are discussed: supplier selection (Vidal and Goetschalckx, 2000; Wu and Olson, 2008), capacity planning (Aghezzaf, 2005), safety stock placement (Graves and Willems, 2000; Lesnaia et al., 2004; Sitompul et al., 2008), and network design (You and Grosmann, 2008; Francas and Minner, 2009). A vast majority of the literature emphasizes problems at the tactical level, such as lot sizing (Cohen and Lee, 1988; Van Landeghem and Vanmaele, 2002; Lodree et al., 2004; Sounderpandian et al., 2008), aggregate planning (Leung and Wu, 2004; Aghezzaf et al., 2010), and multi location inventory (Cheung and Powell, 1996; Gupta and Maranas, 2003; Aghezzaf, 2005). Van Landeghem and Vanmaele (2002) argued that at this level, sufficient time is available to decide upon appropriate measures to protect the operational level from the disruptive impact of uncertain factors. An extensive survey of supply chain planning under uncertainties was carried out by Dolgui and Prodhon (2007). They surveyed some techniques in an MRP environment such as lot sizing rules, safety stocks and safety lead times when demand and lead times are uncertain. At the operational level,

Table 1.1: Literature review

Author(s)	Source of uncertainty	Problem	Planning level	Solution approach	Performance
Cohen and Lee (1988)	Demand	Lot sizing	Tactical	Heuristics	Service level
Huchzermeier and Cohen (1996)	Exchange rate	Manufacturing & financial analysis	Operational	Analytic	Profit
Cheung and Powell (1996)	Demand	Multilocation inventory	Tactical	Stochastic programming	Costs
Vidal and Goetschalckx (2000)	Supplier reliability	Supplier selection	Strategic	MIP	Costs
Graves and Willems (2000)	Demand	Safety stock placement	Strategic	Dynamic programming	Costs
Van Landeghem and Vanmaele (2002)	Demand	Lot sizing	Tactical	Monte carlo	Service level
Gupta and Maranas (2003)	Demand	Production-Transportation	Tactical	Stochastic programming	Costs
Lodree et al. (2004)	Demand	Lot sizing	Tactical	Analytics	Response time
Cheng et al. (2004)	Demand	Capacity planning- Lot sizing (joint)	Strategic Tactical	Simulation	Multi objective
Aghezzaf (2005)	Demand	Capacity planning- Warehouse location	Strategic	Decomposition Method	Costs
Dolgui et al. (2005)	Machine breakdown	Lot sizing- Sequencing (joint)	Tactical Operational	Decomposition Method	Service level
Lim et al. (2006)	Vehicle breakdown	Distribution scheduling	Operational	Genetic algorithms	Completion time
Leung et al. (2007)	Demand	Aggregate planning	Tactical	Robust optimization	Costs
Sounderpandian et al. (2008)	Material supplies	Lot sizing	Tactical	Genetic algorithm	Profit
Aghezzaf (2008)	Demand	Distribution planning	Tactical	Column generation	Costs
Wu and Olson (2008)	Costs	Vendor selection	Strategic	Simulation	Costs
You and Grosmann (2008)	Demand	Network design- Lot sizing (joint)	Strategic- Tactical	MINLP	Costs
Francas and Minner (2009)	Demand	Network design	Strategic	Stochastic programming	Profit
Aghezzaf et al. (2010)	Demand	Aggregate planning	Tactical	Deterministic approximation	Costs

Huchzermeier and Cohen (1996) discussed a manufacturing and financial analysis when exchange rates fluctuate and Dolgui et al. (2005) discussed the sequencing problem which occurs with the possibility of machines breaking down. Even though there exists a general rule in a supply chain, the term strategic, tactical and operational level should be loosely defined (Shapiro, 2001). Their usage may require modification for a specific supply chain.

Following the existing literature, we also believe that underlying relationships exist among different planning levels (i.e. between strategic level and tactical level, and between tactical level and operational level) and that it is necessary to address the issue of uncertainty in supply chains hierarchically as a result. A few authors, such as Gupta and Maranas (2003); Cheng et al. (2004); Dolgui et al. (2005); You and Grosmann (2008), have formulated a joint optimization of different problems. In some cases, such a formulation brings about more complexity in term of computational time. To resolve this computational complexity, it will be beneficial to decompose a complex problem into simpler and manageable problems while maintaining the targeted performance measure. In this research, we use a hierarchical approach to decompose a complex problem into simpler problems at the strategic, tactical and operational level. Furthermore, the fact that most supply chains operate hierarchically requires a proper approach to translate a strategic plan into a tactical plan and from a tactical plan into an operational plan. Therefore, we explicitly take into account this hierarchical planning during the formulation process.

1.2 Definition and terminology

We propose that the following definitions and body of terms used throughout this dissertation.

- *Supply chain*: a series of manufacturers, distributors, and retailers employed to meet the customers' demand.
- *Hierarchical planning*: a concept of planning that acknowledges the existence of a hierarchy in decision making.
- *Performance measure*: a measure of effectiveness and efficiency of a system.
- *Robustness* : a property of a system which is characterized by its ability to strongly protect itself against changes or uncertainties.

We discuss and elaborate the terminology in the following details.

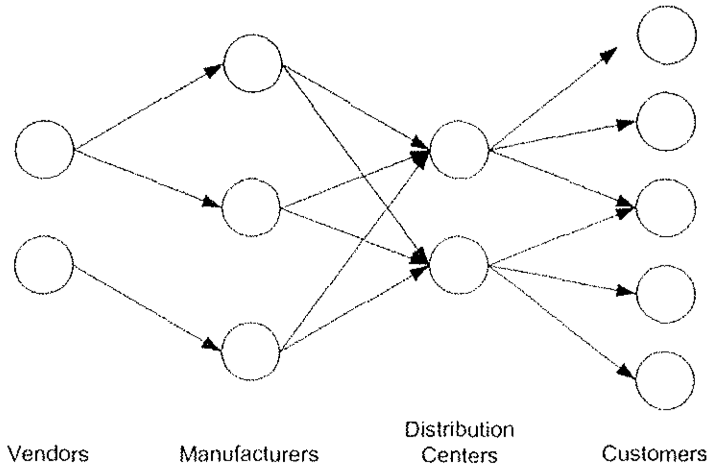

Figure 1.1: A typical supply chain network

1.2.1 Supply chain

There exists an extensive literature devoted to supply chains. For an introduction to modeling in supply chains, we refer readers to a textbook by Shapiro (2001) (Modeling the supply chain). A supply chain consists of a number of facilities where raw materials, semi-finished products or finished products are acquired, transformed, stored or sold and transportation links that connect those facilities. A facility can be a manufacturer which physically transforms raw materials into semi-finished products or semi-finished products into finished products. A distribution center is a facility where products are received, sorted, put away in inventory, picked from inventory, and dispatched but not physically transformed. A supply chain is often represented as a network where nodes which represent facilities are connected by arcs that represent flow of goods, information and money. A typical supply chain as depicted in Figure 1.1 may consist of vendors, manufacturers, distribution centers and customers, and arcs which represent flow of goods.

1.2.2 Hierarchical planning

Liberatore and Miller (1985) used Anthony's framework on hierarchical decision processes for an integration of production planning, scheduling and inventory control. The hierarchy may range from strategic planning through tactical planning to operational planning. In supply chains, Tayur et al. (1999) proposed a framework of hierarchy which comprises of six optimization modeling systems and

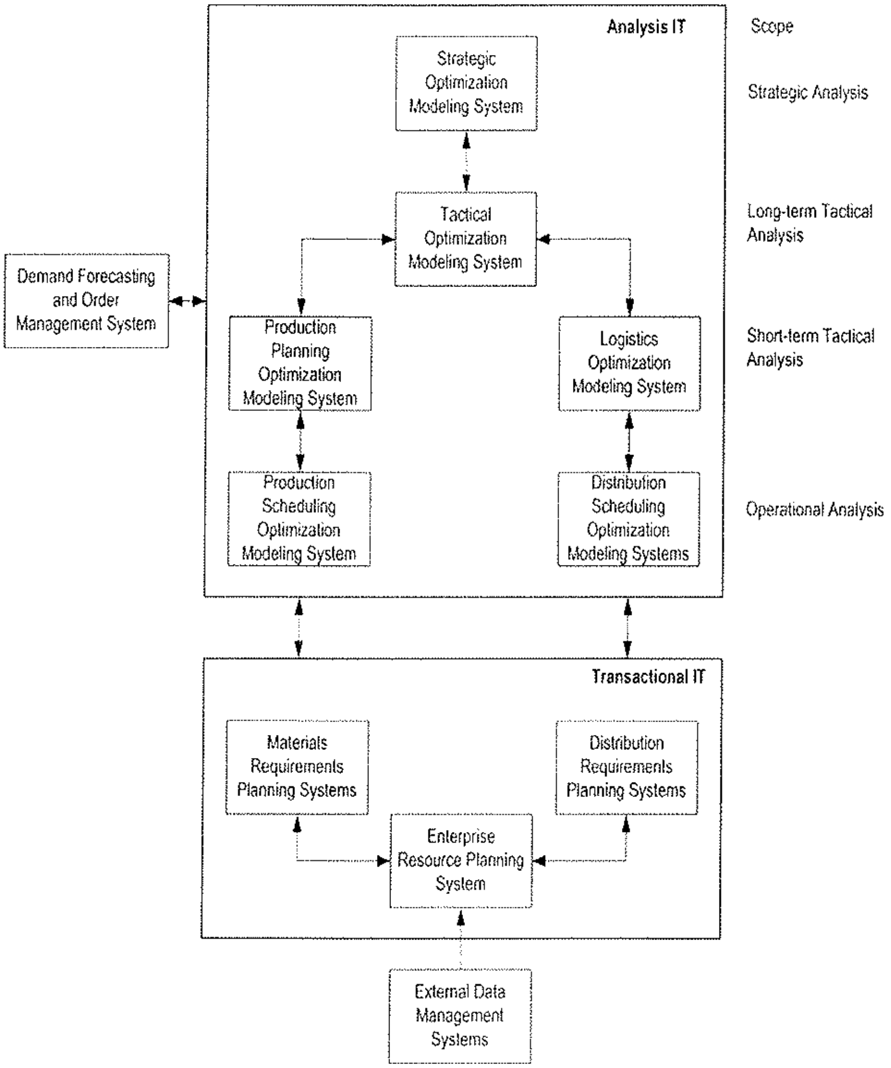

Figure 1.2: Supply chain system hierarchy (Tayur et al. (1999) in Shapiro (2001))

four transactional systems as seen in Figure 1.2. The framework is naturally hypothetical and its usage may require modification for a specific application. Shapiro (2001) stated that there is a lack of interest by companies that have successfully used optimization modeling systems for strategic planning in extending them to tactical modeling applications. Without loss of generality, we limit this research to hierarchical relations in production and logistic optimization modeling system. Strategic modeling is used for resource acquisition decisions, construction of new manufacturing facilities or the design of a new product. Most contractual decisions are usually strategic, such as supplier selection and guarantee for service levels (Graves and Willems, 2000). The strategic planning horizon is normally 1 - 5 years. Tactical modeling determines an integrated supply/manufacturing/distribution/inventory plan for the whole supply chain. Raw materials, intermediate products and finished products are aggregated into product families. The tactical planning horizon is normally 12 months. Production planning modeling determines a master production plan for the next quarter for each stage of manufacturing, along with resource levels and resource allocation. Logistic planning modeling determines a logistic master plan for the entire supply chain that analyzes how demand for all finished products will be met. The horizon for both production and logistic planning is normally a quarter (13 weeks).

1.2.3 Performance measures

Roughly classified, there are two types of performance measures of supply chains: financial related measures and service level. Financial measures, such as costs and profits, are performance measures that drive businesses in the first place (Huchzermeier and Cohen, 1996; Vidal and Goetschalckx, 2000; Aghezzaf, 2005; Francas and Minner, 2009). The goal of a supply chain is, naturally, to satisfy a customer's demand in the right amount of time. Therefore, the service level is also a very important measure in supply chains (Cohen and Lee, 1988; Van Landeghem and Vanmaele, 2002; Dolgui et al., 2005).

There are extensive studies devoted to measuring of service levels, such as Dullaert et al. (2007). The definition of a service level is used to determine the amount of safety stock to protect supply chains against uncertainty. They noted that over the years, the study of service levels has shifted from service measures specifying a probability of no stockout per replenishment cycle (S1) to service measures specifying a fraction of demand to be satisfied with stock on hand (S2). In practice, however, it turns out that the S1 measures are still the most frequently used.

Bhagwat and Sharma (2007) and Gunasekaran and Kobu (2007) in parallel carried out extensive surveys on performance measures in supply chain management. Their surveys include performance measures at the strategic, tactical, and operational levels, in both financial (e.g. rate of return on investment, inventory costs, etc) and non-financial (e.g. delivery lead time, responsiveness, quality of delivered goods, etc).

1.2.4 Robustness

The term robustness defines the ability of a system to strongly protect itself against changes or uncertainty. The robustness concepts of a study can be easily identified by the way it is measured. There are a number of different ways of measuring robustness:

- The number of times that its solution lies within a pre-specified percentage of the optimal solution, for different set of scenarios. See e.g. Rosenblatt and Lee (1987).
- A low variability of key performance measures. See e.g. Mulvey et al. (1995); Van Landeghem and Vanmaele (2002).
- The existence of a feasible solution for the detailed problem for each possible realization of demand. See e.g. Lasserre and Mercé (1990); Gfrerer and Zäpfel (1995); Zäpfel (1998).
- The solution remains optimal while maintaining a targeted service level. See e.g. Sitompul and Aghezzaf (2008); Aghezzaf et al. (2010).

We will first discuss the framework from Mulvey et al. (1995) which has been applied to a number of different kind of problems, such as capacity expansion problems (Laguna, 1998), telecommunication and financial planning problems (Bai et al., 1997), lot sizing problems (Yu, 1997), logistic problems, (Yu and Li, 2000), fleet planning problem (List et al., 2003), and aggregate production planning problems (Leung and Wu, 2004; Aghezzaf et al., 2010).

Mulvey et al. (1995) defined a solution to an optimization model as *solution robust* if it remains 'close' to optimal for all scenarios of the input data, and *model robust* if it remains 'feasible' for all data scenarios. Let $x \in R^{n_1}$, denote the vector of decision variables (design variables) whose optimal value is not conditioned on the realization of the uncertain paramaters and $y \in R^{n_1}$ denote the vector of control variables that are subjected to adjustment once the uncertain parameters are observed. Its optimal value depends on both the realization of uncertain parameters and on the optimal value of the design variables. The linear program is formulated as follows:

Minimize

$$c^T x + d^T y,$$

subject to

$$Ax = b,$$

$$Bx + Cy = e,$$

$$x, y \geq 0.$$

Consider a set of scenario $\Omega = 1, 2, .., S$ and for each corresponding scenario $s \in \Omega$, the set d_s, B_s, C_s, e_s of realizations for the coefficients of the control constraints and the probability of the scenario p^s. The scenario is robust with respect to optimality if it remains 'close' to optimal for any realization of scenario $s \in \Omega$ (*solution robust*). The solution is also robust with respect to feasibility if it remains 'almost' feasible for any realization of s (*model robust*). If a set $y_1, y_2, ..., y_s$ of control variables for each scenario $s \in \Omega$ is introduced, and then a set $z_1, z_2, ..., z_s$ of error variables that will measure the infeasibility in the control contraints under scenario s is also introduced, the robust optimization model according to Mulvey et al. (1995) is then formulated as follows:

Minimize

$$\sigma\left(x, y_1, ..., y_s\right) + \omega\rho\left(z_1, z_2, ..., z_s\right),$$

subject to

$$Ax = b,$$

$$B_s x + C_s y_s + z_s = e_s, \forall s \in \Omega,$$

$$x \geq 0, y_s \geq 0, \forall s \in \Omega.$$

With multiple scenarios, the objective function $\xi = c^T x + d^T y$ becomes a random variable taking the value $\xi_s = c^T x + d_s^T y_s$ with probability p^s. We can use the mean value $\sigma(.) = \sum_{s \in \Omega} p^s \xi_s$, which is the function used in stochastic linear programming formulations. In the worst-case analysis, the model minimizes the maximum value and the objective function is defined by $\sigma(.) = max_{s \in \Omega} p^s \xi_s$. Robust planning also handles risk or higher moments of the objective function distribution, e.g. its variance. Hence, the objective function becomes $\sigma(.) = \sum_{s \in \Omega} p^s \xi_s + \lambda \sum_{s \in \Omega} p^s \left(\xi_s - \sum_{s' \in \Omega} p^{s'} \xi_{s'}\right)^2$, meaning the mean value plus a constant (λ) times variance. The second term in the objective function is a feasibility penalty function which is used to penalize violations of the control constraints

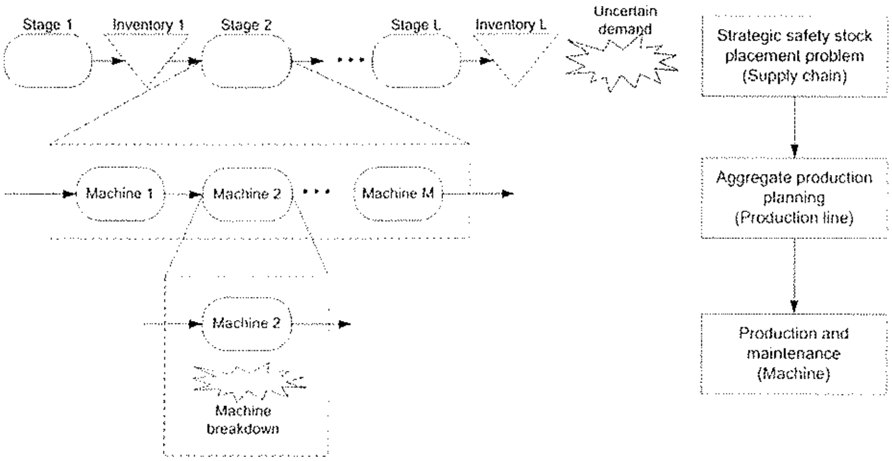

Figure 1.3: Body of the PhD research

under some of scenarios. The introduction of penalty function distinguishes the robust optimization model from existing approaches dealing with uncertainty. There are two alternative penalty functions: $\rho(z_1, z_2, ..., zs) = \sum_{s\in\Omega} p^s z_s^T z_s$ as a quadratic penalty function in which both positive and negative violations are equally undesirable and an exact penalty function in which only positive violations are of interest $\rho(z_1, z_2, ..., zs) = \sum_{s\in\Omega} max\{0, z_s\}$. Thus, Mulvey's framework can be seen as a weighted objective function whose objectives are: (1) the mean value, (2) the variability of the objective, and (3) the penalty of violating control constraints where λ and ω are the trade-off parameters for the objective function, which is to say for the variability and penalty trade-off respectively.

1.3 PhD contribution

We have studied three levels of planning in supply chains, namely strategic, tactical and operational levels as seen in Figure 1.3. At the strategic level, the safety stock placement deals with the positioning and sizing of safety stocks in a supply chain with stochastic demand. The system analyzed at this level is a serial supply chain having L stages. The tactical planning deals with the allocation of resources for production. At this level, the aggregate production planning for each stage is constrained by decisions made at the strategic level. The system analyzed at this tactical level is a multi-stage production system having M machines. The operational planning deals with the disaggregation of product families into finished products. The system analyzed at this level is a machine with the possibility of breaking down. The hierarchical planning suggests that an upper level plan must be disaggregated into a lower level plan. Two types of uncertainty are investigated in this study: demand uncertainty and process uncertainty (in this case, machine uncertainty). Given that demand is uncertain and machines may break down, a proper strategy is needed to keep all plans robust, which is to say remaining optimal while maintaining a targeted service level.

At the strategic level, the safety stock placement problem deals with the positioning and sizing of safety stocks in a supply chain in such a way that the targeted service level is maintained. The safety stock placement problem in uncapacitated supply chains was studied by Graves and Willems (2000) and Lesnaia et al. (2004). Both addressed the general structure of supply chains and formulated the problem into a network optimization problem. Graves and Willems (2000) developed a dynamic programming algorithm to find the optimal solution while Lesnaia et al. (2004) solved the problem using branch and bound algorithms. We extend the problem into a capacitated one where some clients (partners) in the supply chain have a limited production capacity. We first simulate the effect of capacity in a single-stage capacitated supply chain and then generalize the results for serial supply chain modeling. It is shown that the size of safety stock needs to be corrected by a certain factor which depends on the average value of the demand, its standard deviation and the capacity; even when the net replenishment time is zero. Concerning a special case of supply chains (i.e. a serial chain), the shortest path based algorithm has been proposed to solve the problem (see Sitompul et al., 2008).

At the tactical level, aggregate production planning deals with the allocation of resources (machine and labours) for production to satisfy demands. Leung and Wu (2004) formulated the aggregate production planning which occurs when demand is uncertain and made use the framework postulated by Mulvey et al. (1995) to solve this problem. According to Mulvey et al. (1995), uncertainty is represented by a finite number of scenarios. The drawback of such an approach is the need for a huge computational time, which leads to less practical time for large problems. Guan et al. (2006) formulated the problem using multi-stage stochastic integer programming and solved it using branch and bound algorithms. We propose an alternative model which allows for a robust resulted plan, one which satisfies all realized demand for a consecutive period at a certain service level. The proposed model is basically a deterministic model which makes use some of readily available parameters that require averages and standard deviations of demand to produce robust plans within a reasonable computational time (see Aghezzaf et al., 2010).

At the operational level, the production planning deals with the disaggregation of product families into finished products subject to machine breakdowns. It is therefore necessary to perform both production planning and maintenance planning in an integrated way. Most research on the integration of production planning and maintenance planning is dedicated to a specific level, in particular to the operational level (e.g. Li and Cao, 1995; Li and Glazebrook, 1998; Albers and Schmidt, 2001; Alcaide et al., 2002). Only few have confronted the problem at the tactical level (Aghezzaf et al., 2007; Aghezzaf and Najid, 2008; Aghezzaf et al., 2008). To our knowledge, only Weinstein and Chung (1999) have addressed the integration of production and maintenance hierarchically. At the tactical level, they used a pre-defined preventive maintenance policy to produce an aggregate production plan. In the second phase, a master schedule was generated using a multiple goal linear programming model. In the third phase, they simulated the master schedule and the maintenance plan to evaluate the pre-defined policy's performance using some experimental parameters. We also believe that the issue of integrating production and maintenance should be dealt with hierarchically. Unlike Weinstein and Chung (1999), we propose a two-level integration model where the preventive maintenance is integrated into the aggregate production planning as the uncertainty due to machine breakdowns is confronted at the operational level. At the tactical level, we formulate the problem using integer linear programming where the preventive maintenance periods do not necessarily fall at equally distant epochs (i.e. no fixed cycle size). Concerning operational planning, the family production is disaggregated into finished products where machine failures are stochastically following Poisson distributions. Table 1.2 shows the summary of this dissertation for each planning level, problems, related literatures, contributions, solution approaches and the robustness tools employed.

We believe that problems described in Figure 1.3 are very important to discuss in this research because their significance are still relevant in today's practices. In a real situation, the problem of hierarchical planning in a supply chain is a lot more complex than that described in the figure. This figure, however, serves as a basic structure to gain more insight into the mechanism behind robust planning in a supply chain when the issue of uncertainty is tackled hierarchically. Furthermore, we can always elaborate and adapt upon the framework and add a new model to obtain a more realistic framework.

Table 1.2: PhD work

Level	Problem	Related literatures	PhD Contribution	Solution approach
Strategic	Safety stock placement	Simpson (1958) Mapes (1992) Graves and Willems (2000) Lesnaia et al. (2004)	Extension with capacity limitations	Simulate the effect of capacity for a single stage supply chain Use a shortest path algorithm to a serial supply chain problem
Tactical	Aggregate production planning	Mulvey et al. (1995) Leung and Wu (2004) Guan et al. (2006) Sitompul and Aghezzaf (2008)	A model solved within a reasonable computational time	A deterministic model makes use available parameters, such as average and standard deviation of the demand
Tactical-Operational	Integrated production and maintenance planning	Weinstein and Chung (1999) Aghezzaf et al. (2007) Aghezzaf and Najid (2008) Aghezzaf et al. (2008)	A hierarchical planning A general preventive maintenance policy	A deterministic model at the tactical level A scenario-based model at the operational level

Level	Robustness tools
Strategic	Guaranteed service time: provides 100 % service level for demand smaller or equal the maximum reasonable demand' for a certain fixed percentage of the time intervals.
Tactical	Capacity cushion levels: cover all realized demands from period u to v, $u \leq v$ with a certain level of confidence.
Tactical-Operational	Preventive maintenance actions at the the tactical level: ensure the feasibility of disaggregation at the operational level for one period We formulate inventory movement constraints at the tactical level and deviations of runout family and its finished products as objective function at the operational level

We have contributed to a number of international publication in journals and refereed conferences, such as:

1. Aghezzaf, E. -H., Sitompul, C., Najid, N., 2010. Models for robust tactical planning in multi stage production systems with uncertain demands. Computers and Operations Research 37 (5), pp. 880-889.
2. Sitompul, C., Aghezzaf, E. -H., 2009. A multi-item lot sizing model for a practical capacitated two-stage production system. In: IFAC Symposium on Information Control Problems in Manufacturing, Moscow, Russia, pp. 1-6.
3. Sitompul, C., Aghezzaf, E. -H., Van Landeghem, H., Dullaert, W., 2008. Safety stock placement problems in capacitated suply chains. International Journal of Production Research 46, pp. 4709-4727.
4. Sitompul, C., Aghezzaf, E. -H., 2008. Robust production planning: an alternative to scenario based optimization model. In: Le Thi, H. A., Bouvry, P., Pham, D. (Eds.), Modelling, Computation and Optimization in Information Systems and Management Sciences. Vol. 14 of Communications in Computer and Information Science. Springer, Metz, France, pp. 328-337.
5. Sitompul, C., Aghezzaf, E. -H., 2008. A practical solution for two-stage production systems with stochastic demands. In: 2nd International Conference of Logistics Systems, Madison, USA, pp. 416-427.
6. Aghezzaf, E. -H., Sitompul, C., Najid, N., 2008. Integrated production and preventive maintenance in production systems subject to random failures. In: 7ème Conférence de Modélisation, Optimisation et Simulation. Paris, France, pp. 1-8.
7. Sitompul, C., Aghezzaf, E. -H., 2007. Alternative robust solution for the capacitated lot sizing problem with stochastic demands. In: 7e Congrès International de Génie Industriel, Quebec, Canada, pp. 1-6.
8. Sitompul, C., Aghezzaf, E. -H., 2006. Designing of robust supply networks: the safety stock placement problem in capacitated supply chains. In: International Conference IEEE Service Systems and Service Management, Troyes, France, pp. 203-209.
9. Sitompul, C., Aghezzaf, E. -H., 2006. A preliminary study on safety stock placement in capacitated supply chains. In: IFAC

Symposium on Information Control Problems in Manufacturing, St Etienne, France, pp. 623-628.

1.4 Contents

The following outline describes the content of this dissertation. Chapter 1 gives an introduction to the PhD research, definitions and terminology in addition to the body of the research. Chapter 2 discusses the strategic safety stock placement problem in supply chains. The model used by Graves and Willems (2000) is extended for capacitated supply chains. In this chapter, a simulation is carried out to evaluate the effect of capacity in a single-stage supply chain. It is shown that the size of safety stocks requires some adjustment depending on capacity, average demand and variation of demand. The results are then generalized for a serial supply chain problem, which is solved using a shortest path algorithm. In Chapter 3, the aggregate production planning problem is discussed with the objective to compare two types of robust approaches. A deterministic equivalence model is proposed and evaluated against the well known scenario-based optimization approach. Chapter 4 discusses the integration of production and maintenance planning in a hierarchical way. In this chapter, the idea of translating a higher level plan to a lower level plan is discussed thoroughly. Chapter 5 provides a robust integrated hierarchical planning approach. This chapter deals with two phases of integration: [1] integration between strategic level planning and the tactical level planning and [2] between tactical level planning and operational level planning. A discussion of the PhD work, which includes the scope of the work, its limitations and some unresolved issues, is also presented in this chapter. Chapter 6 wraps up this dissertation with conclusions and suggestions for future research.