Flexibility assessment and management in supply chain : a new framework and applications

Yueru Zhong

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Yueru Zhong

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FREIN Yannick	Professeur à l'Institut national polytechnique de Grenoble	**Président du jury**
ALLAOUI Hamid	Professeur à l'Université d'Artois	**Rapporteur**
GRABOT Bernard	Professeur à l'École nationale d'ingénieurs de Tarbes	**Rapporteur**
LECŒUCHE Loïc	Manager de Louis Vuitton	**Examinateur**
CHU Chengbin	Professeur à l'École Centrale Paris	**Directeur de thèse**
JEMAI Zied	Maître de conférences - HDR à l'Ecole Nationale d'Ingénieurs de Tunis	**Co-encadrant de thèse**

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To my dear parents... who have always been so close to me whenever I needed. It is their unconditional love, support and encouragement to motivate me to set higher targets.

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Abstract

This thesis focuses on flexibility issues in supply chain. These issues are becoming more and more important for firms because of the increasingly changing business environment and customer behaviors. Although some of these issues have been tackled in academic research in recent years, but studies have mainly concentrated in conceptual levels and there is little consensus even on the definition of flexibility. This thesis aims at defining a new framework for the supply chain flexibility, proposing quantitative measures of the flexibility and optimizing the use of flexibility, especially in an integrated production and transportation planning context.

The new framework of supply chain flexibility is based on classification of different flexibility aspects in a supply chain into three main categories - *manufacturing flexibility*, *logistic chain flexibility* and *system flexibility*. These flexibility types are further distinguished into *major flexibility dimension* and *other flexibility dimension*.

In order to measure supply chain flexibility from a quantitative point of view, Mechanical Analogy method is particularly discussed. A procedure is established to enlarge and carry out this method in supply chain, provided with a case study to evaluate the flexibility of Louis Vuitton stores.

One of the most important issues is to optimally make use of the available flexibility. We investigate an Integrated Production and Transportation Planning problem with given flexibility tolerances, where the production and transportation activities are intimately linked to each other and must be scheduled in a synchronized way. Particularly, heterogeneous vehicles are taken into account. Two mixed integer linear programming models are constructed. Three algorithms are developed and compared with linear relaxation bounds for large sized real life instances and with optimal solutions for small sized instances. These comparisons show the effectiveness of our heuristics in solving real life problems.

Keywords: Supply chain flexibility, manufacturing flexibility, flexibility assessment, mechanical analogy, integrated production and transportation planning, heuristic, mixed integer program, heterogeneous vehicles

Résumé

Cette thèse étudie la problématique de la flexibilité dans les chaînes logistiques. La recherche académique a commencé à s'intéresser à cette problématique depuis quelques années, mais les études existantes restent pour la plupart au niveau conceptuel et il y a peu de consensus sur la définition même de la flexibilité. Cette thèse a pour ambition de définir un nouveau cadre pour la flexibilité dans les chaînes logistiques, proposer des mesures quantitatives pour la flexibilité et enfin optimiser l'utilisation de la flexibilité, en particulier dans un contexte de planification intégrée de la production et du transport.

Ce travail de thèse vise tout d'abord à établir un nouveau cadre pour la flexibilité de la chaîne logistique, où les différents aspects de la flexibilité sont classifiés en trois catégories principales: flexibilité de la production, flexibilité de la chaîne logistique et flexibilité du système. Dans chacune de ces catégories, on peut trouver des dimensions primordiales et des dimensions moins importantes.

Afin d'évaluer la flexibilité de manière quantitative, nous faisons appel à la méthode Analogie Mécanique. Cette méthode propose une analogie entre un système mécanique vibratoire et une chaîne logistique. Dans ce contexte, nous avons développé une étude de cas pour Louis Vuitton afin d'évaluer la flexibilité de leurs magasins, et nous avons établi une procédure pour implémenter cette méthode.

Une autre problématique importante est l'utilisation optimale de la flexibilité existante. Nous nous sommes particulièrement intéressés à la planification intégrée de la production et du transport avec des flexibilités sur la capacité de transport, où la production et le transport sont intimement liés du fait du manque de capacité de stockage et doivent être planifiées conjointement. Particulièrement, les véhicules hétérogènes sont pris en compte. Nous avons construit deux modèles de programmation linéaire en nombres mixtes et développé trois algorithmes qui ont été comparées par rapport à la relaxation linéaire pour les instances de grande taille et aux solutions optimales pour des instances de petite taille. Ces comparaisons montrent que les heuristiques proposées sont efficaces pour résoudre des problèmes réels, aussi bien en termes de qualité de solution qu'en termes de temps de calcul.

Mots clefs: Flexibilité de la chaîne logistique, flexibilité de la production, évaluation de la flexibilité, analogie mécanique, planification intégrée de la production et du transport

intégrée, heuristiques, véhicules hétérogènes

1 General introduction

Context and motivations

A supply chain of a company can be viewed as a wide cooperative network involving a set of partners for the procurement of materials, transformation of these materials into products, transportation and distribution of products to customers. On the one hand, the supply chain is becoming more and more complex, involving more specialized firms or organizations looking for lower cost. On the other hand, business environment and customer behaviors have changed drastically in the last decades. Because of the globalization which has increased the competition with new information and communication technologies, customer demand has become more and more personalized, and the expected lead time has been shortening steadily. In this context, firms are in need of a flexible supply chain to cope with the increasingly uncertain demand in a responsive and cost-effective way. This thesis aims precisely at addressing the flexibility issue, and particularly flexibility in supply chains, which is critical to all the firms.

Despite the importance of this issue, academical research is relatively limited. There is even no consensus on the definition of flexibility and existing research mainly focuses on concepts. Quantitative studies have been relatively few even though there seems to be steadily increasing interests from researchers. To contribute to bridging the gap between the academical research and real world needs, we study three fundamental aspects:

1. proposition of a new framework for flexibility with a clear definition of the flexibility and by answering the following questions: Which kind of flexibility is important or frequently mentioned and studied in academic study and in industries? How to classify them and what are the flexibility levers to concretize the conceptual flexibility issues into implementation?

2. evaluation or measurement of the flexibility, especially from a quantitative point of view. A case study is provided to assess the flexibility by using the mechanical analogy method, and extend this method to whole supply chain.

3. exploitation of the flexibility in an optimal way. A case study is carried out for an integrated production and transportation planning.

The Chair Supply Chain at Ecole Centrale Paris with leading industrial partners such as

Carrefour, Danone, Louis Vuitton, PSA Peugeot-Citroën and Vallourec have facilitated very much this research and made the obtained results relevant.

Principal contributions

The objective of our work is doubled. The first objective is the development of theoretical knowledge in the academic environment. The second objective is the development of applicable methods in the industrial world, which can be implemented to tackle their real life problems.

If we classify the flexibility related issues as four study fields: i) define the flexibility; ii) evaluate the flexibility; iii) size the flexibility; iv) exploit and manage the flexibility. Our work mainly concentrates on the i) define the flexibility; ii) evaluate the flexibility; and iv) exploit and manage the flexibility.

Our first contribution is to provide a global view of supply chain flexibility, and raise up a new framework of supply chain flexibility with literature support in recent years. It is noticed that no universal consensus has been achieved to date, even on definition and taxonomies of supply chain flexibility. In this context, we clearly define all the *flexibility dimensions* and study their relations with environmental uncertainties and between dimensions themselves. Based on an 8-dimension core of machine, labor, routing, product-mix, volume, supplier, delivery and transshipment flexibilities, we construct a new framework with major flexibilities and other less important ones, covering the majority of issues in this field. At the end of this flexibility framework, we briefly present the flexibility levers, which are specified as detailed actions to operate and implement flexibility dimensions.

Secondly, our next contribution is to concretize the study of supply chain flexibility into quantitative flexibility evaluations. We investigate the existing measures and methods to evaluate supply chain flexibility, and concentrates on the mechanical analogy method.

With the *mechanical analogy method*, a supply chain system can be treated as a mechanical system, whose input is the excitation force, and the output is responsive displacement. This method is still vague and has never been used in supply chain level, but is of great advantages in the fact that with known input and output data of the system, the interior configuration of the studied system becomes unimportant. This property is particularly interested and appreciated by partner companies, because the interior configuration data in detail of a supply chain is generally complex and difficult to acquire at a time, while the input and output data of the supply chain or of a part of supply chain are generally well within reach. Thus, we study its features, raise the hidden problem of *period-differentiation*, and apply it to a case analysis in Louis Vuitton to measure the flexibility of stores in Japan. Good understandable and reasonable results are obtained. From the traditional mechanical analogy method once in manufacturing use, we extend the methodology to whole supply chain, and establish a general procedure to carry out this method in supply chain.

Thirdly, to optimally make use of the available flexibility, we investigate an Integrated Production and Transportation Planning problem, particularly with incorporated given flexibilities. For an integrated production and transportation problem, the transportation decisions may extremely interfere decisions of the production plan, which is a common case for many companies with such situations as no storage space on sit, or no time delay allowance for fresh food sectors, etc. In this case, few or no finished items are left in inventory in their supply chains, so that production and transportation activities are intimately linked to each other, and must be scheduled and optimized in a synchronized way. In our problem, the flexibility tolerances serve as buffers to integrated production and transportation plans, differ from heterogeneous modes of transportation (train and truck), and is closely linked to production quantities. That means in our studied problem, two principal modes of transportation - train and truck - are available at the same time to deliver goods to destinations, which lead to the third mode of transportation: train with truck.

To solve the studied problem, we propose methods in solving two appropriate mixed integer program models according to different assumptions. Three types of methods: heuristics, CPLEX program and heuristic-CPLEX combined algorithm, are developed and compared with each other for each model. The heuristics we proposed proved to be effective in yielding, within a reasonable amount of computation time, good near-optimal solutions, whose gaps from optimal solutions are insignificant (<0.05%). These results are applied to solve an integrated production and transportation planning problem in Evian of Danone Group.

Organization of the work

This report is structured around the three elements mentioned above.

The chapter 2 starts by outlining a new framework of supply chain flexibility. To explain this framework, we begin by introducing the definition of supply chain flexibility with our partner companies in Chair Supply Chain. The conceptual aspects on supply chain flexibility are then presented regarding the causative environmental uncertainties, the flexibility terms often mentioned in the literature and the relation between different flexibility dimensions. After that, the framework of 8-dimension based supply chain flexibility is clearly and completely defined, with a long table exhibiting the literature support on each of the flexibility dimensions. Afterwards, the action levers to implement the flexibility dimension with detailed operations are presented.

In the next chapter, we take a glance at the state of art of the evaluation methodologies on supply chain flexibility. Two categories of methods are introduced, the development of measures and the evaluation of detailed dimensions pertaining to the supply chain activities, and the methodologies that investigate a rough or total flexibility performance without subdivision in precise dimension of flexibility. To finish this chapter, we establish a general evaluation procedure to carry out the mechanical analogy method in supply chain, and present an industrial application in Louis Vuitton.

In the chapter 4, we focus on an methodology that does not investigate a precise dimension of flexibility but treat flexibility as some given fluctuate intervals. We first review the literature on the integrated production and transportation problems. Following this, we outline our integrated production and transportation approach with given flexibility considerations. The applied Evian problem is described in details, and solved in a model with average transportation cost, and in another with fixed and variable transportation cost.

The last part of report is devoted to a general conclusion on all the work, and to some future prospects on areas of research that seem important to us.

2 A new framework of supply chain flexibility

In this chapter, we first define the supply chain flexibility from our point of view, analyze the relation and the difference with existing definitions in the literature. We then review different flexibility dimensions, analyze them to identify their overlapping and minor ones. Based on these analysis, we establish a new framework of supply chain flexibility and provide a clear and complete definition with literature support in recent decades. And for industrial focus, flexibility levers are introduced and presented in various aspects such as its effects, time of implementation, responsiveness and effect durations.

2.1 Introduction and definition of supply chain flexibility

In the 1990's, firms started to extend from the borders of their own firms to their suppliers, suppliers' suppliers and customers to improve the overall profit. This remarkable change is due to various key factors, such as intense and fierce competition in both local and global market, the uncertain economic environment if there is an economic crisis undergoing, the increasing customer expectations in terms of "faster, better, cheaper" on products and services, or even the rarity of some resources including certain raw materials. Besides, suppliers and customers may come from different cultures and different geographical origins. The globalization contributes in every different aspects on information, products, labor, money, available technologies, utilization of Internet, etc. As a result, firm's focus is gradually modified from internal management of themselves to supply chain management across enterprises.

In this context, Supply Chain Council [Cou02] defines the concept of supply chain as: "The supply chain – a term now commonly used internationally – encompasses every effort involved in producing and delivering a final product or service, from the supplier's supplier to the customer's customer. Supply Chain Management includes managing supply and demand, sourcing raw materials and parts, manufacturing and assembly, warehousing and inventory tracking, order entry and order management, distribution across all channels, and delivery to the customer." Supply chain management has then emerged as the term defining the integration of all these activities into a connective process as a whole, more specifically, it integrates all the physical and information flows in creating and transferring products from raw materials to the final customers [CL88, CR05]. The complexity of such a supply chain network, varies from industry to industry and firm to firm in both their sourcing, manufacturing and service sectors.

All these led to enormous concerns on how to adapt existing supply chain against various current changes. Firms then discovered that they would need much longer time to tackle complex changes in the environment, while customer demands became more unpredictable and complex with requirements of higher quality, more technological extensions and higher personalization demands. This results in a phenomenon, illustrated in Fig. 2.1 and called as "Time Scissors" by Bleicher [Ble04]. More product differentiation, new product development or innovation, and delivering the products at lower cost in shorter time or higher speed had shown their industry-wide awareness [Sta90]. Thus, traditional methods may be no longer suitable for today's turbulent environment.

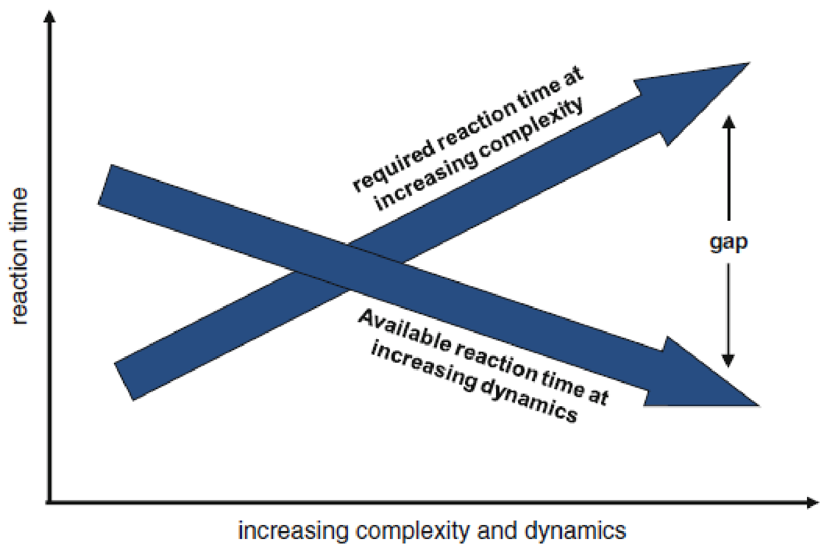

Figure 2.1: Phenomenon of Time Scissors [Ble04]

The concept of flexibility is raised up in this context. Conceptual works started in the 1980s on the flexibility of manufacturing systems. A broad range of rationales have been done. Slack [Sla83] states the motivation of seeking flexibility lies in the instability and unpredictability of the environment, in order to meet various goals of operational production systems. Frazelle [Fra86] cites some issues such as a rapidly decreasing product half-life, the introduction of new products, materials and processes, etc. Slack [Sla87] interviews a group of managers about their perception of manufacturing flexibility in 10 different manufacturing organizations, to sum up a hierarchical framework of flexibility dimensions and aspects. Production strategies have evolved from Computer Integrated Manufacturing [Har74, RNS93] and Total Quality Management [HW95] to Generalized Kanban Conrol [FDMD95], Business Re-engineering, Lean Management [AM05], with the first ones enhanced over years [KRS06].

However, with more than two decades of researches in the domain, manufacturing flexibility is still in various definitions [BMP+00]. In much of literature from the 1980s, the flexibility was often mentioned while referring to some fully automated manufacturing systems, like flexible manufacturing system (FMS). Early definition of manufacturing flexibility provided by Gupta and Goyal [GG89], claims it as: “the ability of a manufacturing system to cope with changing circumstances or instability caused by the environment”. Uption [Upt94] provides a general and abstract definition, characterizes flexibility as ‘‘the ability to change or react with little penalty in time, effort, cost or performance’’. And, some others consider it to be the overall capability of the manufacturing system to be flexible [Adl88, JC06].

Furthermore, compared with the large literature concerning manufacturing flexibility, the research addressing flexibility issues on supply chain level is still limited to date. To clarify the flexibility terms, Lee [Lee04] expresses the supply chain flexibility of a firm in three distinctive components: adaptability (adapt to structural shifts in environment), alignment (keep along with the partners to achieve better overall performance), agility (respond and handle disruptions smoothly). Thus, flexibility is also considered to be connected to *Agility*. The concept of agility was defined as “the ability of an organization to thrive in a continuously changing, unpredictable business environment”, as a result, flexibility is sometimes viewed as a subset of agility according to Lummus [LDV03]. However, Winkler [Win08] proposes another definition of system flexibility as “the ability of a system to perform proactive and reactive adaptations of its configuration in order to cope with internal and external uncertainties” and starts to pronounce on the importance of proactive role. Afterwards, the authors of [MYN12] interpret it as “the capability of an organization to respond to internal and external changes in order to gain or maintain a competitive advantage.”

According to discussions with the industrial partners of our Chair Supply Chain, we have finally achieved an agreement to define the word as: “La flexibilité est la capacité d’une organization à pro-agir et réagir face aux facteurs externes et internes, et à répondre à la variabilité de la demande avec la maîtrise du coût, sur un horizon donné.” That means, the supply chain flexibility refers to the ability of an organization to pro-act and respond to internal and external environment factors, and respond to variability in customer demand over a given time horizon with cost control. This definition emphasizes on the pro-action as well as on the following response, and puts high accent on cost control in the time horizon, which is more practical and realistic to address industrial concerns.

The cost control is of high importance, also because if we implement flexibility strategy directly into industrial world, some negative consequences may arise here and there. The increased flexibility may be good for firms, but at the downside, firms adopting directly or indirectly a flexible strategy may at the same time have largely increased the demand uncertainty in the product level, and discover themselves under high pressure to look for adequate flexibilities to cope with their suppliers. The flexibility increase requires heavy investment. This implies, though the supply chain flexibility is important for firms to survive in the fierce competitions, some implementations often yield no improvement [MR95]. As a result, Gerwin [Ger93] states that ‘‘an unintentional bias exists in favor of recommending more flexibility than is economically appropriate.’’ Even in recent literature, some researchers still suggest trying partial flexibility rather than full flexibility-driven [MSZ06, CCTZ10]. The increased flexibility does not always bring an evident income, especially in the case where the industrial production scale is large [GG89, Len92].

Nevertheless, the complexity of a supply chain itself can manifest an obstacle to achieve better performance. This may be due to different internal and external conditions, as marked by [Ser12], such as a big number of product references, a lot of suppliers, a complicated network, etc. Firms should avoid any action that may increase the process complexity if it is not necessary. Long and complex global supply chains are consequently more vulnerable to face more risks and business disruptions. Tang and Tomlin [TT08] propose 6 major categories of supply chain risks that occur regularly: supply risks, process risks, demand risks, intellectual property risks, behavioral risks and political/social risks, within which the supply, process and demand risks are inherent to all supply chains. Consequently, a more comprehensive view of flexibility integrating different major echelons in a supply chain is widely studied [Cox89, LDV03, LVD05, Saw06], while manufacturing flexibility and other logistic flexibility types interact each other.

Therefore, finding answers to the core questions regarding the supply chain flexibility is crucial and of great value for companies. Articles [SS90, BMP$^+$00, DVL03] have provided comprehensive reviews on manufacturing flexibility. How to recognize and define the different dimensions of industrial flexibility? How to qualify and characterize the relations between them? These questions have drawn attention and been vastly discussed during the last two decades, and will be presented in sec. 2.2. To end these perplexed terms and discussions, a new framework of supply chain flexibility is presented in sec. 2.3 with all terms explicitly redefined, together with a table listing the literature support of supply chain dimensions in supply, manufacturing plant, intermediate locations and customer fields.

At the same time, we wonder how to concretise the flexibility dimensions to final changes. That means, what are the levers of supply chain flexibility and what are the attributes concerning their costs, the action times and the consequences? Levers of flexibility to activate the flexibility changes and influence the whole supply chain in different echelons, will be discussed and resumed in sectionsec.2.4. All these are principal concerns in this chapiter - defining the flexibility.

2.2 Conceptual aspects on supply chain flexibility

2.2.1 Flexibility and uncertainties

Flexibility always deals with uncertainties. Flexibility needs arise first in front of different external uncertainties in the market, and partially, due to the inherent internal problems or complex process within a supply chain itself. Gerwin [Ger87] believes that each type of flexibility must cope with a particular type of uncertainty to accommodate the corresponding environmental condition. Hence, the first association between types of uncertainty and types of flexibility is proposed by [Ger87] and shown in Tab.2.1. Gerwin also cites five “levels” at which flexibility can be considered: individual machines, manufacturing function zone (e.g. forming, assembly), production line, factory and the company’s factory system. Consequently, different uncertainties lead to different flexibility requirement in levels.

Flexibility type	Nature of uncertainty
Mix	*Uncertainty of demand for the kinds of products offered*
Changeover	*Uncertainty as to the length of product life cycles*
Modification	*Uncertainty as to which particular attributes customers want*
Rerouting	*Uncertainty with respect to machine downtime*
Volume	*Uncertainty with regard to the amount of aggregated customer demand of products*
Material	*Uncertainty as to whether the material inputs to a manufacturing process meet standards*
Sequence	*Uncertainty with timing of arrival of input*

Table 2.1: Association of flexibility types and uncertainty [Ger87]

Since two decades, a number of elements on a traditional supply chain or on a traditional manufacturing site have changed, for example, the workforce have become more multi-skilled in some operations or more specialized in some other sectors, and machine capabilities have advanced over years, whereas, the nature and characteristics of them have hardly changed. In this context, not only in manufacturing activities, but also in a supply chain, Schmenner and Tatikonda [ST05] claim that an effective supply chain reduces the uncertainty of material operations, and suggest a flexibility network reproduced in Fig.2.2.

In Fig. 2.2, different flexibility mechanisms [C] have different capabilities to manipulate particular flexibility types [B]. Flexibility mechanisms comprise useful tools, multi-skilled workers, systems that can be effective, and management practices, e.g. FMS, ERP. A flexibility measurement [D] is necessary to characterize and evaluate the uncertainty types [A] and flexibility types, and also evaluate the flexibility mechanisms. These elements differ remarkably by operational levels [E], varying from individual machine to the entire supply chain. In this framework, arrows *a* and *b* are bilateral rather than one-way facing, which is more realistic because the uncertainties do not always lead to a negative consequence, they may sometimes bring opportunities and competitive differentiators for firms [ST05].

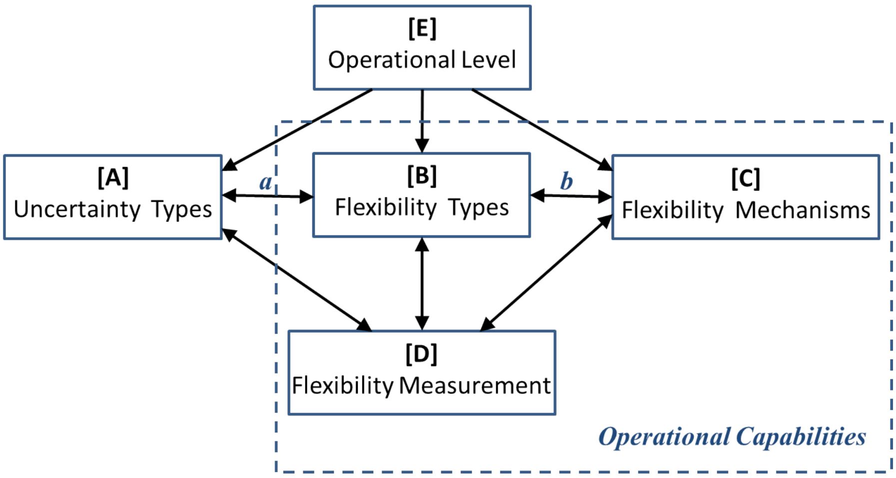

Figure 2.2: The flexibility framework [ST05]

To cope with those uncertainties in real world, Gerwin [Ger93] distinguishes four strategies, such as reduction of uncertainty by investing, banking by the use of safety stock, defensive adaptation to unknown event such as strike, and proactive use of redefinition function.

In summary, flexibility and uncertainty linked to each other, but how to react in the best way, such as against shortening product life cycles or proactively gain competitive advantage is not clear so far. And, the firm's particular characteristics and properties count a lot in flexibility reaction behaviors.

2.2.2 Dimensions of supply chain flexibility

To clarify the flexibility notion, researchers' taxonomy of different flexibilities has never stagnated.

Gupta and Goyal [GG89] reproduce an early matrix analysis in which columns represent the dimensions of manufacturing flexibility defined by Browne et al. [BDR$^+$84], and rows represent the paper that adopts it, with many types added in exploring manufacturing activities in different industrial sectors, shown in Tab. 2.2. Sethi and Sethi [SS90] state the existence of at least 50 different terms for the various types of flexibility mentioned in the literature, which "are not always precise and are, at times even for identical terms, not in agreement with one another". They add several types of flexibility as material, program and market and form eleven main manufacturing flexibility dimensions: machine, material handling, operation, process, product, routing, volume, expansion, program, production and market flexibility. This classification places manufacturing flexibility in a wider context of the organization environment. Machine, material and operation of the eleven, are considered as basic system components.

Author(s)	Machine	Process	Product	Routing	Volume	Expansion	Sequence	Production
[Man78]		Action						State
[Buz82]	Machine	Job						
[SP87]	Process		Equipment		Demand			Product
[Zel82]		Adaptation						Application
[Ger82]		Design	Parts	Routing	Volume			Mix
[Fra86]		Design	Parts	Routing	Volume			Mix
[Car86]	Machine	Mix	Mix change	Routing		Expansion		Production
[AB87]		Process	Product	Routing				Production
[BS88]	Machine setup	Process		Routing			Operations	
[CCMM84]		Part specific	Part Mix	Routing				
[Gus84]			Product		Demand	Machine		
[Sla83]		Quality	New product		Volume			Product mix

Table 2.2: Classification of flexibility literature [GG89]

Afterwards, Upton [Upt94] raises a flexibility framework in Fig. 2.3 and proposes that flexibility of the system be characterized on three aspects:

- The dimensions of flexibility: what needs to exactly change, modified or be adapted?
- Time horizon: what is the general period or frequency over which changes must occur? Hourly, daily, weekly, monthly or yearly? Strategic, tactical or operational?
- Elements: which element are we trying to manage or improve: *Range* of the flexibility dimension, *Uniformity* across its range, or *Mobility*?

For the third aspect, *Range*, *Uniformity* and *Mobility* are different properties for systems that can be flexible. According to Upton, *Range* can increase with the size of the set of options or alternatives, for example, the range of components' sizes that can be processed, and the range of output volume in which a plant is still profitable. *Mobility* is evaluated by penalties of transfers moving within the range, and the lower the transition penalties are, the higher the mobility is. These penalties can be interpreted by time or costs of change. For instance, the mobility property for a production line can be measured by the set-up times and set-up costs needed to switch between different productions. *Uniformity* refers to the extent to which general performance measures such as product quality and inventory costs are indifferent to at what particular point within the range of the system operation. Under this definition, consider a company with a production line that produces each of the products within the range at the same costs per unit, and with another production line that produces the same product range at the same average costs, but on this latter line, some products are produced at lower cost than average and others are produced at a higher cost than average. In this case, the former line is viewed as being more flexible than the latter one.

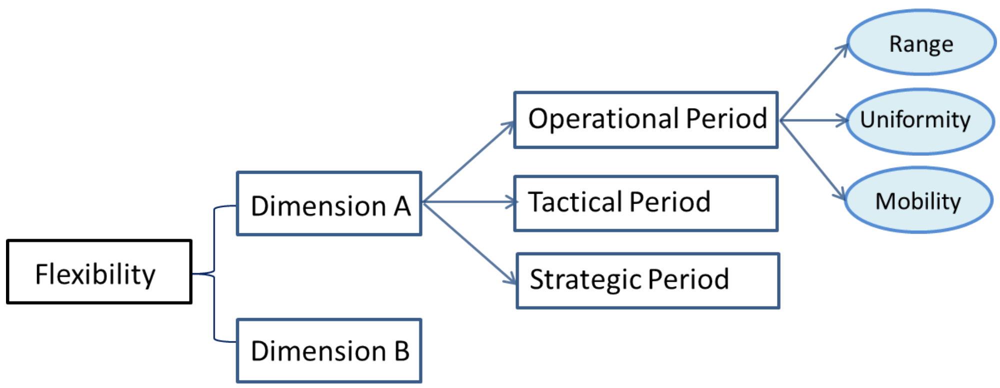

Figure 2.3: Flexibility framework, reproduced from [Upt94]

In this point of view, each of the six main dimensions of flexibility of Gerwain in Tab.2.1 has the *Time horizon*, *Range*, *Uniformity* and *Mobility* properties, expressed in [GS92]. The main dimensions are: mix flexibility, changeover flexibility, product modification flexibility, volume flexibility, process routing flexibility (rerouting), material and sequence flexibility.

Furthermore, Rogers et al. [ROW11] provide a summary of the manufacturing flexibility dimensions proposed in previous studies by adding the *author support level* to each dimension. They conclude ten manufacturing flexibility dimensions that have a slight consensus: new product, modified product, machine/equipment, material handling, routing, process/mix, volume, labor, infrastructure, and supplier/supply management flexibilities. They also suggest eliminating some of them due to overlapping, therefore leave only product-mix, routing, equipment, volume, labor flexibility and the supply management as the sixth flexibility. Still, the interrelationship which exists between the various flexibility types and the trade-offs with the enterprises needs to be refined and more quantified.

In France, the new legislative context increases the difficulty to find acceptable answers to these questions. The French law that sets the weekly working time at 35 h at the end of the year 2000 emphasizes the interest of the managers for annualized hours, which can help to increase the manpower flexibility. The signing of agreements between companies and unions is actually in progress in the various industrial branches. In all the already signed agreements, the following principles are present [27].

However, these are still regular flexibility in manufacturing sectors. In addition to manufacturing flexibilities, researchers also put eyes on external environmental factors, e.g. suppliers, customers [VOK00, NJHA05]. Uzzi [Uzz97] studies buyer-supplier networks within the New York fashion industry by an ethnographic fieldwork conducted at 23 entrepreneurial firms. He claims most organizations have relation to two types of suppliers, those with embedded ties and those kept not so close. Authors of [SCW00, DTT01] support the idea that managing the buyer–supplier relationship can result in critical influences on an organization's performance, and can be integrated into manufacturing flexibility [Saw06, SGM06]. Therefore, supplier flexibility, sometimes referred to as supply management flexibility, is considered to be an additional aspect to regular industrial flexibility. A variant of supplier flexibility is called sourcing flexibility, which indicates particularly the company's ability to find another supplier for its specific component or raw materials. Tachizawa and Thomsen [TT07] consider that flexible sourcing should involve the adoption of a larger supplier base and constantly redesigning and reconfiguring the supply chain.

Apart from the supplier selection and management, focus in distribution part of supply chain can neither be neglected. Regular logistic distribution keys are time, quantity, packaging and load carriers. Kress [Kre00] talks about several types of changes that the military logistics flexibility has to cope with: the quantities of the needed resources, their mix, timing and location. Herer and Tzur [HT01] study the transshipment approach involving movement of stock between locations at the same echelon level where physical distances between the demand locations and the supply locations are small. This can be viewed as a typical transport routing flexibility. Barad and Even Sapir [BE03] propose a so called "trans-routing flexibility" as a logistic flexibility which combines principles of transshipment flexibility, routing flexibility and decision-making rules. This trans-routing flexibility can be measured in each of the two directions: response and range. For the response direction they measure it as the transfer time between two locations at the same echelon level; for the range direction they measure it through which indicates the number of transshipment links per end user at the echelon level.

Naim et al. [NPMB06] suggest a full definition of transport flexibility dimension for transport service companies, listed in Tab. 2.3. The transportation routes (transshipment) are important in both of the replenishment and distribution parts. In a summary, transport flexibility (transport network routing, transport vehicle, transport mode, transport service product, ...) , delivery flexibility (lead time/postpone) are the main logistics flexibilities referred to in the literature, where the concept of "logistics" here does not step into the manufacturing activities.

Transport flexibility types		Definition
External	Product	The range and ability to accommodate the provision of new transport services
	Mix	The range and ability to change the transport services currently being provided
	Volume	The range and ability to accommodate changes in transport demand
	Delivery	The range and ability to change delivery date
	Access	The ability to provide extensive distribution coverage
Internal	Mode	Ability to provide different modes of transport
	Fleet	Ability to provide different vehicle types to carry different goods
	Vehicle	Ability to configure vehicles to carry products of different types or to cater for different loading facilities
	Node	Ability to plan, approve and implement new nodes in the network
	Link	Ability to establish new links between nodes
	Temporal	Ability to sequence infrastructure investment and the degree to which the use of such infrastructure requires coordination between users
	Capacity	Ability of a transport system to accommodate variations or changes in traffic demand
	Routing	Ability to accommodate different routes
	Communication	Ability to manage a range of different information types

Table 2.3: Association of flexibility types and uncertainty [NPMB06]

Moreover, frequent and extensive communications are quite needed in order to build the relationship between the supply chain participants. The information technology plays an important role to link the participants with each other, but it does not always provide a positive impact on system performance. One specific area where information technology may provide flexibility is through information system architecture, facilitating rapid response to changing market environment. Some studies argue that IT is often a cause of rigidity and inflexibility [AB91, APK^{+}95], because the adoption of IT does not automatically lead to increased flexibility. This observation is shown by Upton [Upt95] who discovers that in some paper mills the range of manufacturable products often fell by 20–30% after the mill made a major investment in computer integrated manufacturing. Rai et al. [RPS06] states that IT integration comprises three elements: information flow integration, physical flow integration and financial flow integration. Prager [Pra96] shows that newly developed object-oriented technology provides effective methods to help the enterprise handle market uncertainties. Some other viewpoints of how the information technology affects the manufacturing system in total enterprise flexibility are discussed and suggested in [SM84, Ric96, GP00] by decreasing time taken in departments such as working time and communication time in and between departments, or to external environment. Hence, a right implementation of information integration will certainly increase the competency of the enterprise, and enhance the total system flexibility.

2.2.3 Relation between different flexibilities

To extract a core basis of supply chain flexibility dimensions, we first take a glance at relations between flexibilities. For enormous terms and various taxonomies of flexibility dimensions presented above, some further inter-relations and even lots of overlapping exist among them.

Some of the dimensions manifest a very low consensus across the literature: operations/process, delivery, expansion, production, program, market and automation. The primary cause could be the conceptual overlap among definitions resulting in redundancies [ROW11]. The operation/process flexibility connect intrinsically to routing and product-mix flexibility, because they all require the alternative manufacturing pathways in a plant. Production flexibility is globally an aggregated flexibility that encompasses all of the other manufacturing flexibilities to be a functional level concept [BDR^{+}84, KM99]. Expansion flexibility seems to be a mid-range or long-range increase in capacity referring to the volume flexibility in each echelon of the supply chain. Market flexibility is also a functional level ability in a strategic view.

Furthermore, delivery flexibility in manufacturing is often a result of all the system's ability in product-mix, routing, flexible labor and machine flexibility. The literature supporting the dimension of automation flexibility is quite limited, because it often overlaps with machine flexibility [SS90, Upt94, VOK00] and there may be no clear pattern regarding the impact of automation technology [KMS04]. We finally decide not to consider automation as a flexibility dimension in the further work. Or, if we need to consider it as one flexibility dimension, it can only be a kind of system flexibility - overall flexibility across the system. In the next section we will not talk on the automation flexibility.

On the other hand, operation and routing flexibilities provide conditions around machine, labor and material handling flexibilities, but are also influenced by product and process design [KM99]. Volume flexibility and mix flexibility are two dimensions of output flexibility. Labor contracts, machine abilities, management and organizational techniques are important factors for achieving volume and mix flexibility as output. New product and modified product flexibility overlaps with product-mix flexibility as the three dimensions of flexibility treating the diversity of products. Material handling flexibility relates to both routing flexibility and machine flexibility, and can be achieved by machine flexibility if there exists flexible material handling equipment. Labor flexibility is often talked about as manpower scheduling plans [GL00, Arv05, Lam08, FLM11] to facilitate and interact with the machine flexibility and operation flexibility. However, it remains a dependent flexibility dimension which most of time cannot be substituted by other dimensions.

Removing all the obvious interconnections and overlappings from the terms listed above, we could conclude that the basis of the manufacturing flexibility system is formed by machine flexibility, labor flexibility, routing flexibility, product-mix flexibility and volume flexibility. This coincides with the viewpoints of Rogers [ROW11], who adds supply management flexibility in addition to the previous 5-dimension base, to form a 6-dimension basis of manufacturing flexibility. In our point of view, supply management flexibility is not a pure manufacturing dimension flexibility, but a part of logistics dimension flexibility. Here the word “logistics” does not step into internal manufacturing activities in a supply chain but refers to “logistics chain flexibility” in the next sub-section.

The transport flexibility can occur in each echelon of supply chain. In the sub-section above, we have obtained a comprehensive knowledge of transport flexibility types in table Tab. 2.3. However, in our points of view, it is suggested to briefly define transport flexibility in two categories, instead of stepping into tiny details in each of the transportation field:

- Transportation tool flexibility: all the terms as transport mode, transport fleet, transport vehicle... are considered aggregately as the flexibility of transportation tools.
- Transshipment/transport routing flexibility: all the terms as transshipment, transrouting, transport access, spatial and temporal linkage ability between locations lead to a final term transshipment flexibility, or we say transport routing. It is a flexibility to fit the transportation network.

This simple classification of transport flexibility can quickly eliminate immense tiny information given in transport literature and clarify different roles of transport flexibility dimensions. The transportation tool flexibility is quite less attractive to both firms and researchers, whilst the transshipment or transport routing flexibility problem receives extensive attention. Thus, the latter is considered as a major dimension of supply chain flexibility.

On the other hand, delivery flexibility of supply and distribution (often characterized by time delay) echelon may belong to the category of transport flexibility, but if is more often studied than the other dimensions across the distribution literature, and have drawn immense attention for both firms and researchers. That’s the reason why we are inclined to extract it out of the transport flexibility and let it alone, as a major dimension of logistics flexibility.

Hence, consider an entire supply chain with upstream and downstream activities: we add supplier flexibility (also referred to as supply management), delivery flexibility (mostly referred to distribution lead time) and transshipment flexibility (transport network) to form a basis of supply chain flexibility dimensions. Therefore, in the supply chain level, we obtain an 8-dimension basis of machine, labor, routing, product-mix, volume, supplier, delivery and transshipment flexibility as a core of supply chain flexibility. It must be noticed that the former five flexibility dimensions can also occur at the interior of a supplier, who manufactures semi-finished products, or works on preparation tasks for certain raw materials.

With the 8-dimension based supply chain flexibility established, we are prepared to raise a new supply chain flexibility network.

2.3 A new framework of supply chain flexibility

2.3.1 Definition of a new framework of supply chain flexibility

In a general supply chain's view, there exist a few different frameworks to classify the supply chain flexibility.

Gosling et al. [GPN10] propose a classification by vendor flexibility and sourcing flexibility, in which the manufacturing flexibility, the warehousing and logistics part flexibility all belong to vendor flexibility. They explain sourcing flexibility as: (i) the ability to reconfigure the supply chain; (ii) ability to adapt to market requirements; (iii) increased supplier's responsiveness; (iv) integration of the supply chain. Whereas from our point of view, the (i)-(iii) are considered to be the result of integrating multiple dimensions on manufacturing flexibility, supply flexibility and distribution flexibility. In our point of view, the (iv) is rather a kind of method than a kind of flexibility in order to improve the overall system performance.

Kopecka [KPS09] describes the supply chain flexibility into three aspects: (i) buyer-supplier relationship; (ii) demand driven and the role of marketing; (iii) production/manufacturing. However, this kind of categorization seems to be a little illegible and limited to clarify the nature of flexibility dimensions, for example, the (ii) "demand driven and the role of marketing" is too ambiguous to be understood. We then start off to establish a new classification framework with all terms explicitly defined.

With extensive literature reviewed and flexibility relationships discussed in previous sections, we have been provided with comprehensive knowledge on supply chain flexibility. Based on these understanding and discussions, we suggest the boundaries of flexibilities distinguished in four levels in supply chain :

- Machine level
- Workshop/factory level
- Firm level
- Supply chain level

According to different classes of uncertainties and the exposed structure of the supply chain, we propose to classify the supply chain flexibility into a frame of three main categories:

- MANUFACTURING FLEXIBILITY: all the types of flexibility requiring an explicit resource in manufacturing system, called "internal flexibility" as well, such as machine, labor, routing, product-mix, operations, volume, material handling, etc. These flexibilities usually lie in machine level and workshop/factory level. Some flexibilities like new product and product modification flexibility (also called launch flexibility) are at firm level.

- LOGISTICS CHAIN FLEXIBILITY: all the types of flexibility requiring explicit logistics resources other than manufacturing ones, such as transshipment routing, transportation mode, vehicles, supplier and delivery flexibility. The last one is extracted out of the transport flexibility and is particularly addressed in the literature. These flexibilities mostly lie in machine and workshop/factory level, except for supplier and delivery flexibility in firm or supply chain level. Here the word "logistics chain" implies it does not step into production operations in a manufacturing site, thus, the logistics chain flexibility does not overlap the manufacturing flexibility.
- SYSTEM FLEXIBILITY: all the aggregated, non-inherent or long-term flexibility types, called "external flexibility" as well, such as market, expansion, information technology, access and organizational flexibility. Those flexibilities commonly lie in firm level and supply chain level.

It must be noticed that, in this definition, the word "logistics chain flexibility" is different from an overall supply chain flexibility which comprises all manufacturing flexibility dimensions, transportation dimensions and the others in a supply chain. The term "logistics chain flexibility" does not overlap the manufacturing flexibility and serves to provide another class of flexibility in our taxonomy.

In the previous sub-section sec. 2.2.3, we have arrived at a basis of 8-dimensions for supply chain flexibility: machine, labor, routing, product-mix, volume, supplier, delivery and transshipment flexibilities. These flexibility dimensions must be clearly defined and imported into our three-category frame.

On the basis of integrating existing concepts in literature and particularly our own points of view, we provide a complete and clear definition of all supply chain dimensions as follows:

MAJOR MANUFACTURING FLEXIBILITY:

Machine Machine flexibility is the ability of a machine to perform different operations/tasks required by a given set of components, and including quick machine set-up and changeover, also referred to as equipment flexibility. It can be improved by introducing a sophisticated specific tool-changing and part-loading device for workpieces, or using a general-purpose equipment capable of multiple operations and programs. Machine flexibility may allow smaller batch sizes to be possible, resulting in shorter manufacturing lead times and higher rate of machine utilization.

Labor Labor flexibility is the ability of a worker or a work team to perform more than one task in number or in the variety of tasks within the organizational system, and includes the labor working time. It can be improved by training experienced worker, recruiting new high quality worker and increase the working time in night shifts or other time windows. For researches imposing extra hours to the manufacturing system, we consider it to support the labor flexibility in Tab. 2.4.

Routing Routing flexibility is the ability of processing a given set of components using alternative routes through the system. Alternatives are created by using different machines, operations and sequences of operations as substitutions. Routing flexibility can be improved by adding redundant multipurpose machines, or a versatile material handling system. It allows efficient scheduling to handle possible contingencies and emergencies such as machine breakdown and rush orders.

Product-Mix Product-mix flexibility is the ability to offer customers with a broad variety of products or services with the given system architecture economically and effectively. It enables a firm to enhance customer satisfaction by providing mix kinds of products. High product-mix flexibility allows the organization to introduce new and modified products more frequently. It is often measured by the cost and time of switching production between two products in a current system, without any major facility modifications.

Volume Volume flexibility is the ability to respond to big changes in demand while remaining profitable. This implies that the manufacturing system can increase or decrease volume without impacting the current system capacity, and operate at various batch sizes and/or at different output levels effectively and economically. It represents the firm's competitive potential to vary production volume in order to meet rising demand and to keep inventory low if the demand falls.

For reasons of inter-relationship and overlappings between various dimensions of manufacturing flexibility, we arrive at a conclusion to consider the following manufacturing flexibility dimensions as less important:

OTHER MANUFACTURING FLEXIBILITY:

Operation Operation flexibility is "the ability to interchange the ordering of several operations for each part" [SS90]. It occurs when an operation has more than one predecessor or successor. It allows easier manufacturing scheduling and can increase equipment availability and rate of equipment utilization.

Material Material handling flexibility is the ability of a manufacturing system to effectively hold and deliver materials or components to the appropriate stage of the manufacturing process, and position the material or the part throughout the manufacturing facility in a manner so as to permit value adding operations [DW00]. It covers the storage flexibility talked in [ST11], which is related to the inventory level to balance variations in supply and demand.

Program Program flexibility is the ability of system to run virtually unattended or automatically for a long enough period [SS90].

Process Process flexibility is the ability of the system to adjust to and accommodate changes between the production of different products with minimal delay [SMR08].

New-prod New product flexibility is the ability to introduce new product and product varieties with or without new package or new technologies. The speed of promotion and the quality are key elements of new product flexibility.

Modified-prod Modified product flexibility is the ability to modify existing product in response to client demand or market trends. The speed of promotion and the quality are key elements of modified product flexibility.

Launch Launch flexibility is the ability to rapidly introduce many new products and product varieties. It requires the integration of numerous value-adding activities across the entire supply chain and overlaps the new product and modified product flexibility. In the following table (Tab. 2.4), we use launch flexibility instead of new product and modified product flexibility. That means, for all literature supporting new product and modified product flexibility, we consider it to support the launch flexibility.

Product Product flexibility is the ability to change over to produce a new (set of) product(s) [BDR+84], in this sense, partially overlapped with flexibility of process. In some articles [Gri07], it is defined as the ability to handle difficult, non-standard orders to meet special customer demand and to manufacture products in different features. For instance, the product flexibility defined in [GN11] is exactly the same to product-mix flexibility, so we consider that the author supports the product-mix flexibility. Due to its great ambiguity, we remove it from the left column of literature table Tab. 2.4 and make use of the distinct terms like the flexibility of product-mix and process.

Production Production flexibility is the universe of part types that the manufacturing system is able to make [SS90]. As an aggregated term to some degree, the particular literature supporting production flexibility is not sufficient and often overlaps with product, product-mix and volume flexibility, therefore it is not listed in the literature table to be an independent dimension.

The same happens to logistic chain flexibility, consisting of dimensions requiring explicit logistics resources other than manufacturing ones, distinguished by major and not major sub-classes.

MAJOR LOGISTICS CHAIN FLEXIBILITY:

Supplier Supplier flexibility is the ability of suppliers to reconfigure the supply chain to respond to changes requested by the customer and of the customers to manage the buyer-supplier relationship in a better controlled way. The supplier flexibility indicates the responsiveness to client demand of the supplier. It is also called as supply management flexibility, reflecting the internal influence the organization has over this external environment. Firms can reduce some environmental uncertainties through their supplier selection and solicit short-term bids enter into long-term contracts for a strategic partnership.

Delivery Delivery flexibility in logistic sense here is the ability to adapt lead times to customer requirements. Just-in-time (JIT) represents the high flexible delivery level that suppliers must deliver their products to the customer at the immediate right quantity, time and place.

Transshipment Transshipment flexibility can also be interpreted as transport routing flexibility. It is the ability that the firms move the products and hold the inventory between locations at the same echelon level where physical distances between the demand locations and the supply location are small [HT01, HTY06]. It is a bit enlarged in our definition to be a transport network flexibility.

For reasons of inter-relationship, overlapping and low support level of literature in logistics chain flexibility, we consider the following dimensions of logistics chain flexibility as less important and classify them as “other logistics chain flexibility”:

OTHER LOGISTICS CHAIN FLEXIBILITY:

Sourcing Sourcing flexibility is the availability of qualified materials and services and the ability to effectively purchase them in response to changing requirements [DVL03, LDV03]. Other definition refers to the ability of making better choices in a larger supplier base and constantly redesign and reconfigure the supply chain [TT07]. We adopt the former one but each of the two definitions overlaps with the normal supplier flexibility to some degree. Hence, for all literature supporting the sourcing flexibility, we consider it to support as well the supplier flexibility. But the reverse sense does not work .

Partner Partner flexibility is the ease of changing supply chain partners (supplier, transporter, retailer, ...) in response to business environment changes in the role of long-term relationships of supply chain [GMES05]. Due to the partial overlapping between supplier flexibility and partner flexibility, for all literature supporting partner flexibility, we consider it to support the supplier flexibility in Tab. 2.4. But the reverse sense does not work.

Postponement Postponement flexibility is the ability of keeping product in their generic form as long as possible, in order to incorporate the customer's product requirement in later stages [EK00]. It overlaps with the delivery flexibility. For all literature supporting the postponement flexibility, we consider it to support the delivery flexibility. But the reverse sense not.

Logistics Logistics flexibility is one type of *logistics chain flexibility* often appeared in the literature, refers to different logistics strategies which can be adopted either to procure and receive a piece of product from a supplier or to release a product to a customer.

Trans-prod Transport product flexibility is the ability and the range to accommodate the provision of new transport service.

Transport-tool Transportation tool flexibility is the ability and the range to accommodate the transport mode, transport fleet, different vehicle and other transport services without any major facility modifications. It contains different branches, for instance, the transport product flexibility is the ability and the range to accommodate the provision of new transport service, and the transport mode flexibility is the ability to provide different mode of transportation. For other detailed transport flexibility terms, see Tab. 2.3 for a comprehensive knowledge. For any literature supporting the transport mode, fleet, vehicle or other transport services, we consider it supporting the transportation tool flexibility.

All the aggregated, non-inherent, transversal and cross-management or long-term flexibility types, are referred to as overall system flexibility and frequently lie in firm level and supply chain level.

SYSTEM FLEXIBILITY:

Expansion Expansion flexibility is concerned with the easiness of modifying the capacity of an existing manufacturing system adding more or new resources (machines, labor, materials handling systems) in order to be able to expand the overall output of the system [Ber03]. It is in long-term strategic level. The expansion flexibility enables the firm to adapt progressively to perceived future changes of demand, rather than purchasing all equipments which may place a heavy burden on the firm.

Access Access flexibility is the ability to provide widespread or extensive coverage and reflects the capability of a supply chain to provide the required geographical coverage for different customers [NPMB06]. This access coverage flexibility is samely applicable to supplier, manufacturer and distributor sectors. It can be improved by the close coordination of upstream or downstream activities in the supply chain to the firm.

Information Information technology flexibility is the ability to align information system architecture and systems with the changing information needs of the organization as it responds to changing customer demand. It is also called as information integration [SGM08]. It can be effective in every echelon of the supply chain.

Market Market flexibility is the ability to mass customize and build close relationships with customers, including designing new product and modifying new and existing ones [Gri07]. It is associated with external decisions and intended to quickly respond to the challenges imposed by the competitive market conditions. Market flexibility is a need of flexibility in both manufacturing and logistic firms, and is partially overlapped with launch flexibility, new and modified product flexibility. It is closely related to customer flexibility.

Customer Customer flexibility is considered to be both the range of customer's indifference to various attributes of customer requirements (such as delivery schedule, order quantity, product specification, etc.), and the customer's willingness to make trade-offs on these attributes. It is a newly raised dimension by [ZT09]. The support of this flexibility dimension is weak and thus, we neglect its presence in the literature review table Tab. 2.4. The interrelationship and complement among customer flexibility, manufacturing flexibility and market flexibility is inherent in the mapping relations across customer requirements, product design, manufacturing process and marketing strategies.

Organizational Organizational flexibility is the ability to align the organization departments, especially labor force skills to the needs of the supply chain to meet customer requirements. It represents the capability to manage risks or uncertainty by promptly responding in a proactive or reactive manner to business opportunities or market threats [GT01]. Organizational flexibility is directly proportional to labor flexibility and middle-managers of the organization [Ros10].

Operational Operational decision flexibility is an aggregated flexibility describing choices in the supply chain operations: e.g. the assignment of jobs to machines is changed due to a breakdown, a different bill of material has to be used to produce the finished product, production volumes are assigned to another production facility to exploit economies of scale [ST11]. Operational decision flexibility can also be used to exploit market opportunities, and is related to a broad list of network flexibility issues such as manufacturing process flexibility, workforce labor, and network structural flexibility in operations management. It can be seen as a result of encompassing the operational level decisions from other machine and workshop level's flexibility dimension choices.

2.3.2 Literature support on supply chain flexibility according to the new framework

A lot of reviews exist in manufacturing flexibility, whereas existing works in supply chain flexibility are not quite updated. Even in a review recently published in 2011 [ROW11], the reviewed literature does not cover many works dated in the last decade, and, is mainly limited to descriptive and survey researches.

In this context, we are interested to construct a review table listing all the literature covering papers concerning most dimensions of supply chain flexibility and, especially published in 21th century recently. It is shown in Tab. 2.4 and continued by Tab. 2.5 and Tab. 2.6.

The column on the left of table are dimensions of supply chain flexibility classified in our new framework. Since flexibility can be studied in supplier echelon, manufacturing plant echelon, intermediate locations and rather end-customer side, the second line of table indicates the problem structure over which the research is carried out: S - Supply; P - Plant; I - intermediate locations as distribution centers, warehouses and retailers; C - Customer. For instance, if it is noted as a combination S-P-C in the cell, S-P-C denotes that the study covers a problem with the supplier-plant-customer structure; otherwise, the single P implies the study is limited to the manufacturing plant. The last line of table denotes the supply chain sector the author or authors study on, or particularly the company over which it is specially applied, or the company from whom the author are provided with industrial input data.

As presented in the previous section, the term “flexibility” is very broad, sometimes ambiguous. The inter-related types of flexibility in the literature are based on an amplified and frequently diverse conception. It is one of the reasons why some flexibility dimensions are considered to be major, or less important, and be redefined in this chapter. Our classification helps to establish a standardized understanding with recent literature support, and provides sufficient conditions for the subsequent analysis on flexibility measurements in supply chain.

Flexibility Category	Flexibility Dimension	[Abd06]	[Adl99]	[Arv05]	[Bar03]	[BC07]	[Bay09]	[CC10]	[CEG05]	[CYCS03]	[CYC04]	[Das11]	[DA03]	[DT01]	[ETAMA12]	[FM01]	[FLM11]
Problem Structure		P-C	P	P-I-C	P-I-C	P-C	P	P-I-C	P	P-C	S-P	S-P-C	S-P	S-P-C	P	P	P
Manufac-turing	**Machine**	*	*				*								*		*
	Labor	*		*					*							*	*
	Routing	*					*								*		
	Product-mix	*	*				*		*	*		*				*	
	Volume	*					*		*	*		*					*
	Operation	*															
	Material handling	*															
	Program	*															
	Process	*															
	Product				*												
	New/Launch	*		*						*							
Logistics Chain	**Supplier**							*			*	*	*	*			
	Delivery	*			*	*		*		*		*	*	*			
	Transport routing				*												
	Sourcing												*				
	Partner										*						
	Logistics											*					
	Operational decision																
	Postponement				*												
	Transportation tool				*												
System	**Expansion**	*															
	Information technology			*				*			*						
	Access																
	Organizational			*							*						
	Market	*															
Application Sector			Toyota subsi-diary NUMMI	Swiss econo-my		Nordic tissue producer			Ford motor	Machine tool industry in Taiwan	Hasbro Far East Inc.			Italian manufac-turing		JIT-practicing firms	Daimler AG

Table 2.4: Literature support on flexibility dimensions in supply chain - Part I

Flexibility Category	Flexibility Dimension	[FZ05]	[GA00]	[Gon08]	[GMS05]	[GPN10]	[Goy11]	[GT03]	[HO09]	[HT01]	[HTY06]	[IG01]	[EKD10]	[Lam08]	[LVD05]	[Mac95]	[MSF96]	[NPMB06]
Problem Structure		S-P-C	P	S-P-C	S-P	S-P	P	P	P	P-I-C	P-I-C	P	S-P	S-P-C	S-P-C	P	P	P-I-C
Manufac-turing	**Machine**			*			*											
	Labor		*	*										*		*		
	Routing		*	*														
	Product-mix					*	*		*			*				*	*	
	Volume	*				*			*									
	Operation		*															
	Material handling																	
	Program																	
	Process							*										
	Product																	
	New/Launch					*												
Logistics Chain	**Supplier**					*							*		*			
	Delivery					*												*
	Transport routing									*	*							*
	Sourcing												*					
	Partner				*													
	Logistics														*			*
	Operational decision														*			
	Postponement																	*
	Transportation tool									*	*							*
System	**Expansion**																	
	Information technology			*	*										*			
	Access					*												*
	Organizational													*	*	*		
	Market																	
Application Sector				Foxconn Electro-nics	E-business	UK house building contractor						General Motors		Data from US firms in hospita-lity, trans-port, retail and banks			General motors	

Table 2.5: Literature support on flexibility dimensions in supply chain - Part II

Flexibility Category	Flexibility Dimension	[FLM11]	[OLD04]	[POD+11]	[PA01]	[Rog11]	[SB00]	[ST09]	[ST11]	[SCW00]	[SGM08]	[TH11]	[TK10]	[Uzz97]	[YTN11]	[ZVL03]	[ZCS10]
Problem Structure		P	P	P	S-P-C	P	S-P-I-C	S-P-C	S-P-C	S-P	S-P-C	S-P-C	P	S-P-C	P-I-C	P	P-I-C
Manufac-turing	**Machine**	*		*									*			*	
	Labor	*														*	
	Routing												*			*	
	Product-mix				*	*					*					*	
	Volume	*			*	*	*	*	*	*	*					*	
	Operation																
	Material handling								*							*	
	Program																
	Process									*							
	Product																
	New/Launch				*												
Logistics Chain	**Supplier**									*	*	*		*			*
	Delivery		*		*		*		*		*						
	Transport routing														*		*
	Sourcing										*						
	Partner																
	Logistics										*						
	Operational decision							*	*						*		
	Postponement																
	Transportation tool																
System	**Expansion**					*											
	Information technology										*						
	Access																
	Organizational																
	Market																*
Application Sector		Daimler AG		Food manufac-turing industry				Norwegian meat industry: Nortura	Norwegian meat industry: Nortura			German automo-tive plants					

Table 2.6: Literature support on flexibility dimensions in supply chain - Part III

2.4 Levers of supply chain flexibility

Uncertainties and related flexibility dimensions are not the only important key aspects. Another important key aspect, called *flexibility lever*, receive mass attention from industry at the same time, for the reason that flexibility levers may imply concrete causes and subsequent operations that influence both the flexibility performance and flexibility configuration itself. These levers are detailed operations to implement flexibility in supply chain.

Generally speaking, a lever (or an actuator) of supply chain flexibility serves as one source of flexibility to concretise the flexibility dimension. The two terms "lever" and "flexibility dimension" are not the same. A flexibility lever represents a detailed choice among possible actions, leading to subsequent changes on flexibility performance or on system configurations. The flexibility dimension is a term explaining what are the type and properties of this kind of flexibility, whilst a lever enables a practical action to change the status of flexibility dimension. For example, consider a flexibility dimension "material handling flexibility", its corresponding levers can be "increase/decrease storage space for certain products" and/or "share storage space of certain product for other products" , which are all concrete actions.

Therefore, it must be noticed that a same lever may involve several dimensions of supply chain flexibility, and flexibilities and the levers of the same type do not necessarily lead to the same impact on the other dimensions. For instance, the lever "Homogenize the IT system with suppliers and clients" is connected with supplier flexibility, client flexibility and information technology flexibility at the same time. And the lever "modify the delivery frequency" impacts not only on transport flexibility, but also on delivery flexibility in the downstream of supply chain. Consequently, the choice of a flexibility lever becomes very cautious, depending not only on its impact but also on the easiness and the cost to implement the corresponding flexibility in supply chain.

Moreover, for each practical case, the determination of flexibility lever depends on the environment where the company lives in and the changes it faces. Therefore, it is necessary to build up a list showing all possible flexibility levers and their corresponding flexibility types to be implemented facing possible variations. The determination of flexibility levers can be illustrated in the following diagram Fig. 2.4.

Levers of flexibility vary from industry to industry and by different supply chain echelons. Thus, one lever may stimulate the flexibility in one dimension type and at the same time, lead to a negative impact in another.

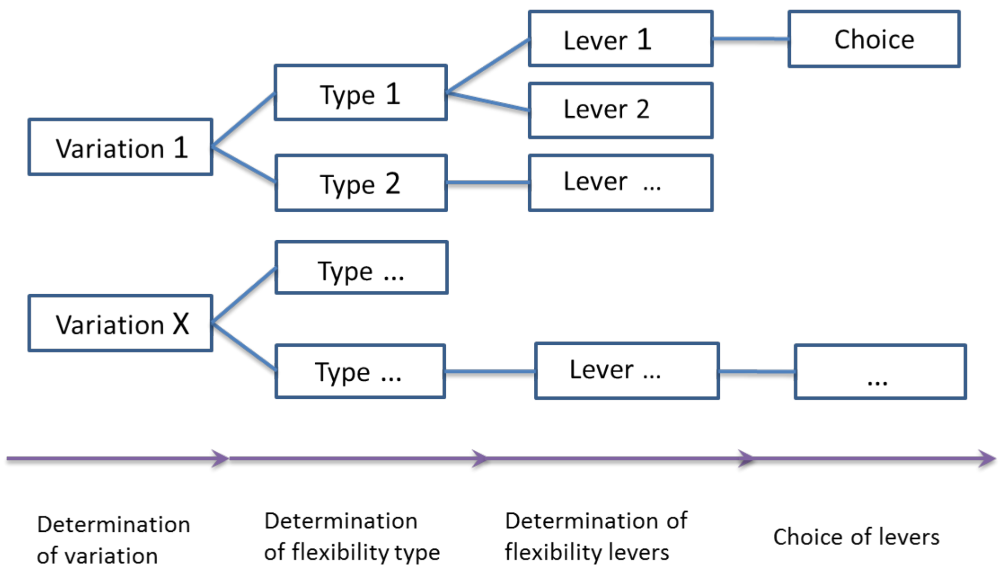

Figure 2.4: Determination of a flexibility lever

It is easy to understand that upstream flexibility levers in supply chain is strongly dependent on suppliers' flexibility. The number of possible suppliers, the variety of suppliers, the contracts through which a firm can negotiate their concerning order quantity and varying due date, and the connection between manufacturers and suppliers, are four important elements to identity flexibility levers in upstream supply chain. Thus, for the supply or replenishment part, flexibility levers in upstream supply chain can act as:

- Increase/Decrease the number of warehouses → Material handling and supplier flexibility
- Utilize the Cross-docking → Material handling and supplier flexibility
- Re-negotiate transport contract services → Transport flexibility
- Mutualize the procurement with another company → Supplier flexibility
- Homogenize the IT system with suppliers and clients → IT and supplier flexibility
- Adopt RFID tags for products or pallets to improve the traceability and order preparations → IT flexibility
- Differentiate the delivery delay of clients → Delivery flexibility
- ...

Meanwhile, most industrial requirements on manufacturing flexibility in a supply chain aim at two main flexibility dimensions: volume flexibility and product-mix flexibility. To tackle with the two requirements, a lot of levers are identified and proposed to solve the problem using machine, routing, labor, process and other flexibility dimension techniques. Apart from that, the choice of lot-size, the internal configuration of production tool and variable lead time are all important parameters to identify flexibility levers in manufacturing sites. Therefore, in manufacturing part of supply chain, flexibility levers could be actions as follows:

- Train workers to be multi-skilling → Labor flexibility
- Take overtime of the opening plant → Machine and labor flexibility
- Sub-contract one part of production goals → Volume flexibility
- Increase or decrease the safety stock → Material handling flexibility
- Centralize the production planning → Organizational flexibility
- Postpone the differentiating steps in manufacturing and assembly lines as late as possible → Routing and operation flexibility
- Rationalize the number of references to keep a simpler logistics → Product-mix and material handling flexibility
- ...

The principal concerns of downstream flexibility levers in supply chain concentrate on storage capacity, delivery quantity, lead time and mix-delivery (the ability of a firm to deliver a variety of products at the same time), which are mainly related to dimensions like delivery flexibility, transport routing flexibility, postponement, etc. Therefore, flexibility levers in distribution echelon can be identified according to parameters as: the number of available transporters, the dependency or relation between product units and delivery points, delivery planning, lead time, etc. At the downstream of the supply chain, flexibility levers regarding distribution activities can act as:

- Increase the synergy between stores of various sizes
- Adapt delivery frequencies
- Deliver punctually and directly to sales point without passing through a distribution center or a warehouse
- Improve the visibility of controls to better manage HR
- Make possible changes to balance inventory levels between different warehouses
- Homogenize the IT system with clients
- ...

Before a flexibility lever is studied and implemented, one or several phenomenons may serve as triggers for the corresponding lever. It is to be noted that a trigger may activate one or more flexibility levers at the same time, and an active flexibility lever incurs consequent effect on various aspects in supply chain. To understand this, consider a flexibility lever “make use of storage space dedicated to certain products to store other products ”.

One of its trigger can be the saturation of storage space dedicated to some types of products. The implementation of this lever may accommodate changes on replenishment cycle and leads to positive effects such as better utilization of warehouses and less stock out. The negative effect is that the warehouse must be adapted to store and handle many types of products at the same time. Not all products can be stored under the same conditions, so the adoption of this lever may incur risks of damaged or deteriorated products.

After the clarification of triggers and effects, the ease to implement a flexibility lever should be attentively investigated. First, the decision level of flexibility lever must be identified, and its implementation, duration of implementation, associated Key Performance Index (KPI), relative costs and returns must be estimated. For instance, consider a flexibility lever in transport: "deliver punctually and directly to sales point without passing a warehouse". The triggers for it are multiple, such as the overstock of upstream centers, too long lead time, or even the risk of stock out in sales points. The lever lies in operational decision level with a short implementation delay, but may require quite a long time (duration) to be implemented. Thus, the cost of punctual and direct delivery is much higher than normal one, with possibly a small return on investment (ROI) if unit profit is not too high. The KPI associated is Leadtime.

In this context, three teams of students in Ecole Centrale Paris have conducted their studies by collecting useful information from partner firms, identifying a number of levers respectively in upstream supply, manufacturing and distribution parts of supply chain. The five firm partners are Carrefour, Danone, Louis Vuitton, PSA and Vallourec of Chair Supply Chain in Industrial Engineering Laboratory of Ecole Cenrale Paris. The first team working on the upstream part of supply chain [LBGH13] has identified 52 levers in function of purchasing, warehousing, transportation, IT, conception, supplier, human resource, forecasting and communication sectors. Another team working on the manufacturing part of supply chain [LMM$^+$13] has explored flexibility levers in machinery, human resource, factory, relation among factories, strategic decision and information system fields. The third team working on distribution [BCFS13] has investigated 49 levers separately in warehousing, transportation, IT, strategic decision, sales outlet, demand, product-mix fields. Finally, the three teams have constructed a table each to help identifying the types of levers and clarifying its effects, its interrelation and its implementation in different criteria.

The three tables have been merged to a whole in order to constitute a helpful tool in decision making concerning flexibility levers in supply chain. A small extract of the table is shown in Tab.2.7. The head of the table lists different criteria on temporal, control, effects, specificity and risk aspects, and the column on the left indicates lever type and the lever itself in detail. From this piece extracted from the whole table, we can easily see that for levers in type Transport and Stocks in Upstream supply chain, all the evaluation descriptions and scores are marked in columns according to different criteria.

Table of flexibility actuators

	Actuator type	Actuators	Observed Trigger	Criteria						
				Temporal			Control			
				Implementation delay	Duration of utilisation	Decision level	Adapted KPI	Cost	Return on investment
Up-stream	Transport	Modify the delivery frequency	Upstream overstock; seasonality	+	++	Tactical / Operational	OTD / OTIF	-	++
	Transport	Deliver Punctually and directly to the sales point without passing a warehouse	Upstream overstock (in cost and volume); Leadtime too high, risk of rupture in store	++	--	Operational	Leadtime	--	+
	Stocks	Make use of storage space allocated to certain products to store others	Storage saturation dedicated to one type of product	+	-	Operational	Utilization rate of warehouse	-	+

Table of flexibility actuators (continued)

Criteria				
Effets			Specificity	Risk
Positive effects	Negative Effects	Influence on the rest of the supply chain	Specificity to an insdustry	Risk
Less upstream stock; Less risk of non-delivery; Smoothing the handling costs	Negotiation; Less transport cost	Scheduling changes	NA	Risk of stockout if bad prediction; Risk of organizational planning
Avoid rupture; Customer Satisfaction	High cost; Flow modification	Mobilization of personnel	NA	Risque of non-tracability
Better usage of warehouses; No out of stock	Adapt to store many types of products	Changes on replenishment cycle and delivery to factories	NA	Risk of products can not be stored under the same conditions

Notation of criteria "closed"	
++	Very good
+	Good
0	Neutral
-	Bad
--	Very bad

Table 2.7: An extract of flexibility levers [BCFS13]

2.5 Conclusion

Definitions and taxonomies of flexibility have been widely studied but no universal consensus has been achieved to date. In this chapter, we first propose a global view of supply chain flexibility and define it together with our industrial partners in Chair Supply Chain as: “La flexibilité est la capacité d’une organization à pro-agir et réagir face aux facteurs externes et internes, et à répondre à la variabilité de la demande avec la maîtrise du coût, sur un horizon donné”. That describes, the supply chain flexibility refers to the ability of an organization to pro-act and respond to internal and external environment factors, and respond to variability in customer demand over a given time horizon especially with cost control.

In order to construct a new framework of supply chain flexibility, we define the *flexibility dimensions* and investigate their relations with environmental uncertainties and between the dimensions themselves. On the basis of these conceptual studies and the existing literature support for each dimension, we construct a framework of supply chain flexibility based on 8-dimension respectively on machine, labor, routing, product-mix, volume, supplier, delivery and transshipment flexibility, which are explicitly defined and analyzed in this chapter.

Furthermore, to implement the flexibility in industrial world, we penetrate into the notion *flexibility lever*, which represents a detailed action and enables the concretization of flexibility dimension in a supply chain. Various aspects of flexibility levers are studied, such as triggers to activate them, durations, positive and negative effects for the rest of supply chain and their adequate or possible costs. These levers are of great value,which may serve as a reference to help firms identity whether it is worthy or not to implement a flexibility operation in their supply chains, that means, to make concrete flexibility decisions.

Throughout this chapter, we have dedicated to “defining the flexibility”. We finally outline a concrete overview of conceptual and qualitative studies on supply chain flexibility, and construct a clear framework to identity the flexibility types and their operations.

3 Measurements and methodologies on supply chain flexibility

This chapter addresses the measurement of supply chain flexibility from a quantitative point of view. This step is necessary to evaluate the possible actions to improve the flexibility, and/or to incorporate flexibility considerations in industrial production and transportation planning problems. We first review the existing literature, and then, we use the mechanical analogy method to assess the effective flexibility in a real life case and establish the evaluation procedure to carry out this method in supply chain.

3.1 Introduction

Due to the hierarchical configuration of manufacturing system and the complexity of the entire supply chain, a focusable measurement of flexibility is always required for different system properties, in order to meet the multidimensional supply chain flexibility.

It there is a generally accepted assessment system for measuring supply chain flexibility, it would be needed to be ideally applicable cross-industries, and be able to release comprehensive and comparable results. Comprehensive research in technical literature has shown a great number of methods for the measurement of flexibility across the manufacturing activities, but a bit less in the supply chain. This implies on one hand a continually growing interest in the subject, on the other hand the lack of a generally accepted evaluation and optimization methodology. However, studies show another good trend, that is with extensive descriptive, empiric and survey documents in literature, some quantitative researches have come up in the last decade, in order to add quantifiable values to different types of supply chain flexibility.

As a result, existing methods can be generally classified into three categories:

- Conceptual and survey researches, which preserve a great part of literature on supply chain flexibility. This kind of articles often gives descriptive analysis, or collects traversal questionnaires among different industrial sectors and penetrates into different internal activities in the studied supply chain echelon to draw conclusions. For instance, papers of [SS90, KM99, Lee04, Arv05, TT07] are all in this category.

- Development of measures and the evaluation of detailed flexibility dimensions pertaining to the supply chain activities, which take a small part of existing studies. Studies in this field as [AMMC05, Rog11, WWL08, Bay09, FLM11].
- Methodologies that investigate a rough or total flexibility performance without subdivision in precise dimension of flexibility, or, encompass some flexibility issues or considerations when exploring other industrial problems (e.g. supply chain management skills, production planning, facility location optimization, ...). These works provide an important part of existing contributions, as work in [XN09, TK10, ZCS10]. Uncertainty term is frequently used in this category, for instance, Vidal and Goetschalckx [VG00] incorporate uncertainty considerations into a mixed integer linear program with some specific stochastic constraints, such as supplier reliability and on-time performance.

Comprehensive descriptive, analysis and survey results are principally mentioned and presented in the previous chapter in sec. 2.2. In this chapter, we pay attention mainly to the second and the third categories, whose studies establish mathematical formulas, models and/or develop effective algorithms to measure and solve problems with supply chain flexibility concerns.

3.1.1 Evaluation of dimensions of supply chain flexibility

Compared with enormous conceptual work talked about in sec. 2.2, quantitative studies regarding supply chain flexibility start to emerge during the last decade. Different authors have proposed proper measures and methodologies to quantify the flexibility in each level of the supply chain system. Among these methods, the *volume flexibility* and *product-mix flexibility* defined by our new classification, are most studied in manufacturing system.

Different methods exist to incorporate the flexibility dimensions into an optimization of production or distribution problems. Most of the studies focusing on some particular flexibility dimensions, are complicated and impossible to present briefly the flexibility measure out of the entire model separately. However, Rogalski [Rog11] proposes a good methodology evaluating the *volume*, *mix* and *expansion* flexibility, in which each of them are incorporated with very simple formula and especially, can be expressed separately without interfering into the analytical model in details. Thus, it is more appropriate to be presented here to show how to evaluate flexibility dimensions in a supply chain. It is presented in the following paragraphs.

Volume flexibility

Volume flexibility is always related to the manufacturing system's capacity. It implies the firm's competitive potential to change production volume in order to meet market demand while remaining profitable. From this definition, we can state that, the profitable limits of the system with the considered period must be respected. Hence, two parameters are important [Rog11]:

- **Break-even-point**: the manufacturing quantity at which the revenues cover the total costs (fixed and variable costs) and the resulting profit is zero.
- **Maximum capacity**: the biggest possible capacity the system is able to reach where still profitable. It is determined by the technical details of the manufacturing facility and organizational measures like flexible man-hour models, e.g., overtime or multi-shift.

The range between the Break-even-point and Maximum capacity is called the ***Flexibility Range***, during which the system remains economical while varying the production output. This is expressed as a relative figure (Fig. 3.1), with a flexibility range representing the volume flexibility, originally in black.

Thus, we could simply calculate the Flexibility Range as $x_{MAX}(S) - x_{BE}(S)$, where S denotes a manufacturing system or one system object, and $x_{BE}(S)$ denotes the Break-even-point. The *Flexibility Range* is an absolute value to characterize the dimension of the economical, object-dependent part of manufacturing. Here the "***system object***" refers to the studied object in the manufacturing system, which can be a workshop, a production line, a production site, any part or total line of the manufacturing site, etc.

In order to compare different system objects, this flexibility range has to be put in a relationship with the Maximum capacity, and the volume flexibility can be formulated:

$$F_{volume}(S) = \frac{x_{MAX}(S) - x_{BE}(S)}{x_{MAX}(S)} \cdot 100\% \tag{3.1}$$

As a result, the bigger the relative deviation between the Break-even-point and Maximum capacity, the higher the volume flexibility for the system or the system object.

Product-mix flexibility

Product-mix flexibility disposes the ability to switch between several products without influencing negatively the optimal system profit. It is often measured by the cost and time of

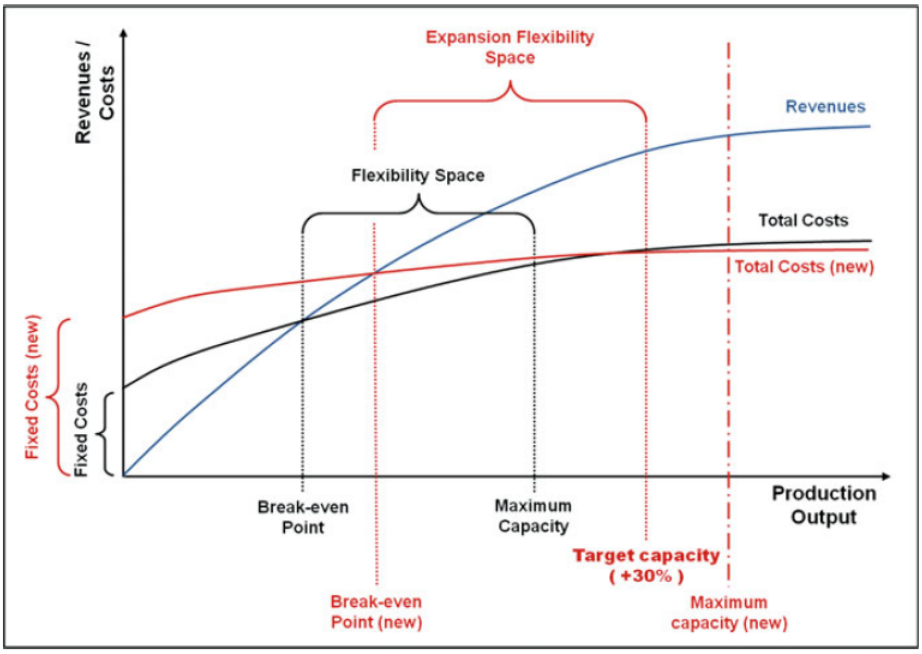

Figure 3.1: Determination of the range of volume flexibility and the cost-benefit ratio of an expansion alternative [Rog11]

switching production between the two products without any major facility modifications. Two parameters are suggested to make it quantifiable [Rog11]:

- **System-optimal production profit**: the maximum profit that a system can achieve with an optimal configuration of its production programming and based on a prescribed time line. Product type and volume are considered.
- **Product-restricted optimum profit**: the maximum profit that a system can achieve under the restriction of excluding one of the products which is usually manufactured on-site.

The product-mix flexibility of a system can be expressed as a ratio, called Average production profit deviation. Analogue to the *standard deviation*, Rogalski proposes to calculate the *root mean square* of the System-optimal production profit, which provides detection of any threats and will not be composed of the *arithmetic means* of the individual deviations. It is then formulated:

$$\triangle G_a(S) = \sqrt{\frac{1}{n_M(S)} \cdot \sum_{MI \in S} \left(G_1(MI, S) - G_{opt}\right)^2} \tag{3.2}$$

where:

$n_M(S)$ Number of different kinds of products M of system object S

$G_1(MI,S)$ Product-restricted profit optimum of product MI in system object S

G_{opt} System-optimal production profit of the whole system

$\triangle G_a(S)$ Average production profit deviation in system object S

In order to compare different system objects or different production systems, the Average production profit deviation must be put in a relationship to System-optimal production profit. The flexibility of product-mix can be formulated:

$$F_{Mix}(S) = 1 - \frac{\triangle G_a(S)}{G_{opt}} \cdot 100\% \tag{3.3}$$

From this formulation we can see if there exists only one single-product fabrication, the product-mix flexibility will take the value of 0. Subsequently, the value 1 stands for the complete product-mix flexibility.

Expansion flexibility

Expansion flexibility is a long-term flexibility and related to the easiness of adding more or new capacity to an existing system. Consequently, it is assumed to be quantity-related to the maximum capacity in the previous determined phase. Before the determination of the expansion range, we first calculate the target capacity for system object of a manufacturing system. This target capacity has to be multiplied with the maximum capacity that relates to product-mix flexibility in the previous phase.

$$TC(S) = (1+e) \cdot x_{MAX}(S) \tag{3.4}$$

where:

$TC(S)$ Target capacity of system object S

$x_{MAX}(S)$ Maximum capacity for system object S

e Given expansion capacity of system object S in per cent, specified by the user

Depending on the system object concerned, a specific alternative problem that maximizes the capacity can be solved using a simplex-algorithm. Afterwards, the alternative-specific Break-even-point, noted as x_{BE_A}, has to be calculated using the same logic during the determination phase of volume flexibility. The calculation procedure for the whole system and for subsystems should be distinguished, and for each valid alternative point, the related adequate linear programming problem have to be slightly reformulated and solved. Afterwards, with the knowledge that the original flexibility range may arise when calculating the volume flexibility, it's time to consider the expansion flexibility.

The expansion-based flexibility range depends on the Break-even-point of the individual expansion alternatives, which is colored in red in Fig. 3.1. The original flexibility range of the system is in black, between the original Break-even-point and Maximum capacity generated within the limits of the Volume flexibility.

Thus, the expansion-based flexibility range for different system objects can be expressed as $TC(S) - x_{BE_A}(S)$. The closer an alternative comes to reaching this point, the larger its expansion-based flexibility range and therefore the bigger its influence on the Cost-Benefit ratio of the system.

Thus, the expansion flexibility for different system objects can be calculated from:

$$F_{Expansion}(S) = \frac{TC(S) - x_{BE_A}(S)}{x_{MAX}(S) - x_{BE}(S)} \cdot 100\% \tag{3.5}$$

As a result, the expansion flexibility of a manufacturing system is dependent on the expansion alternative with this highest **Cost-Benefit ratio**. The bigger the relative deviation between its Break-even-point and its Target capacity, the more flexible expansion the system.

Apart from the evaluation of several particular flexibility dimensions, Rogalski also defines a Cost Accounting Reference Frame in his book [Rog11]. These flexibility dimensions are integrated into the frame in order to form and perfect a complete methodology.

Among the existing literature, *volume flexibility* and *product-mix flexibility* have received vast attention in the literature on manufacturing system flexibility studies. Goyal and Netessine [GN11] work over a single firm with two products, facing the choice of selecting one of the four strategic flexibility technologies: D (not flexible), V (volume flexible), P (product-mix flexible) or VP (both volume and product-mix flexible). They formulate four models whose objective functions with or without volume or product-mix flexible technologies and highlights that adding the P to V is not always beneficial. They argue that the volume flexibility value is a function of demand correlation between products, and the product-mix flexibility value decreases in demand correlation. They then underscore the necessity of analyzing volume flexibility with more than one product and emphasize the opposite with product-mix flexibility.

In a smaller supply chain scale, *machine flexibility* is the most studied in manufacturing workshop. Baykasoğlu [Bay09] propose a new approach based on digraph theory and matrix algebra to quantify machine flexibility. Wahab et al. [WWL08] provide a generic approach to measuring machine flexibility in manufacturing systems. Francas et al.[FLM11] propose a two-stage stochastic program with recourse to study the investments on labor and machine capacity, under uncertain demand and a given network configuration while anticipating the deployment of labor flexibility. They investigate the impact of labor flexibility on machine and labor capacity and its interplay with machine flexibility, and show that personnel transfers are more effective in larger manufacturing networks.

3.1.2 Measures and methods of supply chain flexibility

Probabilistic approach: Penalty of Change method (POC)

This is a general probabilistic measure used to measure flexibility of a manufacturing system, which determines the flexibility by its sensitivity to changes. This method can be easily extended to whole supply chain. And, the lower the sensitivity is, the higher the flexibility is. High flexibility or low sensitivity to changes can bring advantages to a supply chain system at least in product-mix, operation and volume flexibilities in our defined framework.

The measure is based on evaluation of additional costs in case of potential change, called penalty cost, and the probability of potential change. It works as an index "Penalty of Change" (POC) [Chr96], where change is a transition from one "state" to another. If the considered change within a system can be solved and handled without incurring any further costs, we say the system holds maximal flexibility so that the POC-value is zero. Chryssolouris [Chr96] goes back to the concept of Event Tree, with what he calculates penalty costs on the basis of occurrence probabilities of future scenarios.

Both penalty and probability can be viewed as functions of a discrete random variable X, which represents potential change. For instance, in three possible states A, B and C, the possible values of X are $X_1\,(A,A)$, $X_2\,(A,B)$, $X_3\,(A,C)$, $X_4\,(B,A)$, $X_5\,(B,B)$, $X_6\,(B,C)$, $X_7\,(C,A)$, $X_8\,(C,B)$, and $X_9\,(C,C)$. Here, the combination (A,A) indicates the system stays in the same state A, and (A,B) refers to a transition of system state from (A,A) to (A,B). The penalty of change (POC) can be then defined as:

$$POC = \sum_i Pn\,(X_i) \cdot Pr\,(X_i) \tag{3.6}$$

where:

X_i the i^{th} potential change

$Pn(X_i)$ penalty of the i^{th} potential change

$Pr(X_i)$ probability of the i^{th} potential change

The calculation of POC can be also viewed as a procedure of single-attribute decision making under uncertainty. If X_i stands for possible future scenarios, $Pn(X_i)$ represents the attribute values for each future scenario and $Pr(X_i)$ interprets the probabilities of occurrence of the scenarios.

Furthermore, consider the most general case that a system may not process a finite set of discrete state-changes but a continuous range of state-change couples, the formula 3.6 can be changed to a continuous integral form with continuous distribution $Pn(X)$ and $Pr(X)$ in function of continuous variable X. Consequently, the scenario with the lowest cost is considered to be the best.

The flexibility evaluation on the basis of the “Penalty of Change” is possible to include all processes from workplace to plant and supply chain scenarios as well. It specially makes sense for the evaluation of different options or expansion alternatives in regard to costs. The first crucial disadvantage is the distinct dependence on occurrence probabilities of scenarios and corresponding costs. The second default is one must provide a complete list of the possible changes and make a right anticipation of all the potential costs against the changes. This need of data collection and especially the anticipation of data, may be quite a difficult requirement for firms, which limits the application of the measure.

Alexopoulos et al. [AMMC05] present a study of flexibility for the punching department in a commercial refrigerators manufacturing system, where three technology solutions for the punching department under different sets of production requirements are considered. They investigate the flexibility of punching manufacturing system with the use of POC method, and give a good picture of the flexibility characteristics for alternative solutions of the punching department.

DCF analysis: Design of Systems for Manufacture (Desyma)

Design of Systems for Manufacture (DESYMA) is a flexibility evaluation method developed at the Greek University of Patras to assess the flexibility of a manufacturing system statistically. With different demand insecurities, it refers to the evaluation of alternative design solutions of manufacturing systems.

In this method, flexibility is considered by using a “**Discounted Cash-Flow**” (DCF) analysis. This is a statistical analysis of discounted estimations of the Cash-Flow, where all future cash flows are estimated and discounted to give their present values (PVs) - the sum of all future cash flows, both incoming and outgoing, is the net present value (NPV), which is taken as the value or price of the cash flows in question. Present value may also be expressed as a number of years' purchase of the future undiscounted annual cash flows expected to arise.

Afterwards, the life cycle time of a considered production system is evaluated with different market scenarios in a certain time period. Based on the distribution of DCF values, the flexibility evaluation in the supposed market environment occur afterwards. The correlation between the DCF and the flexibility implies that, the smaller the distribution of DCF values are, the more flexible the production system is, and the more stable life cycle costs are [AMMC05].

The DCF can be calculated for each market scenario and the spread of the DCF scores may represent the flexibility of the system in the given market environment. Consequently, the dispersion of DCF-values leads to a kind of "collective flexibility" and involves costs for different market scenarios, thus, some particular costs (for measuring adaptation, for instance) can be evaluated cross-industrially on the basis of sales expansion.

In another aspect, the scenario related part of this method turns out to be disadvantageous, and, the quality of results depends on the subjective user's judgment. The long-term expansion flexibility of a production system can be deduced from DESYMA method, whilst the volume and product-mix flexibilities are hard to deduce from this method.

Alexopoulos et al. [AMPC07] propose a backward optimization algorithm implemented in Visual Basic for Excel, as a part of the overall DESYMA method. Both expansion and contraction of a system are considered in this paper, using DCF values to compare the flexibility of alternative manufacturing systems. Results prove that this algorithm releases accurate solutions and runs faster than normal DESYMA design method. An application of this method to a production investment case study is carried out with data derived from the automotive industry.

Dynamic modeling approach: Mechanical vibration analogy

A production line can be viewed as a mechanical vibration mechanism [APM+08]. The demand expressed in quantities of products at a certain production duration, can serve as the input data to the adequate mechanical mechanism; the delivery expressed in quantity of products and lead times, can be interpreted as the output of the mechanical mechanism. This kind of analogy is cited as the ζ-analogy method [Chr96], where ζ indicates a dimensionless damping factor of the mechanical system. Hence, the damping factor ζ is considered to represent the insensitivity to environment change. This approach is further described in details in sec. 3.2.1.

FLEXIMAC

Other than the traditional mechanical system analogy, another way of evaluating flexibility is the FLEXIMAC method. It overlaps to some degree the early ζ-analogy method, and goes back to the analogy of dynamic properties between a mechanical system and a production system. The ability to react to potential changing in a mechanical system is characterized by the damping factor ζ, that can be deduced and calculated under certain circumstances using a transfer function [APM+07]. The same logic applies to a production system, where the system flexibility can be evaluated with the ability of reaction in regard to the dynamic input excitations.

The input could be processing time of a production system, which is necessary to produce a required varying quantity and type of products. The output may be represented as actual flow time, which is normally longer than the supposed processing time, due to variable waiting time during the production with incidences such as accidents, lack of raw materials, lack of human resources, etc. In the ideal case, input and output should be identical without delay.

It is necessary to divide the predicted period length in equal time intervals, and collect the data on processing time as well as the flow time. The concrete FLEXIMAC value is calculated from the arithmetic mean of the ten highest amplitudes in the spectrum, as expressed in formula 3.7, where Q_i is the amplitude corresponded to the eigen frequency. The higher the FLEXIMAC value for a production system is, the more flexible it is, the less sensitive towards input variations.

$$FLEXIMAC = \frac{1}{10}\sum_{i=1}^{10}\left(\frac{1}{2Q_i}\right) \tag{3.7}$$

The great advantage of FLEXIMAC-method is the non requirement of explicit internal variables and data gatherings. The only need is input and output data, neglecting all the system and organization configurations. These relevant data can be easily gathered from working data or Enterprise Resource Planning (ERP) Systems. The second advantage is its independence from subjective assessments and reference scenarios, as it is transformed by a mechanical view. Furthermore, evaluation of flexibility can be executed cross-industrially on all relevant levels, starting at the machine level, workplace level to the point of the factory and supply chain level.

There are also disadvantages. In applying this method, concrete conclusions regarding expansion flexibility is completely impossible, because it disregards completely the macro measures such as total costs, total revenue to integrate in the method, so that the evaluation of volume and product-mix flexibility are hard to derive or only possible in a limited way. With this great disadvantage, the mechanical analogy method can evaluate the flexibility of the system only in a general sense, rarely for a special small flexibility dimension.

3.1.3 Methodologies with supply chain flexibility considerations

Synthesizing instrument: Toolbox Approach

Developing an instrument to help decision making is another way of facilitating flexibility evaluation between firms. A simple toolbox can help supply chain managers to easily find out the bottleneck of their supply chain and to alter available operational alternatives rapidly. Georgoulias et al. [GPMC07] propose a toolbox approach for flexibility measurements in diverse environments. They build a flexibility assessment platform consisting of a flexibility evaluation toolbox module, the data collection module and a change management framework module. The overall software platform is shown in Fig. 3.2.

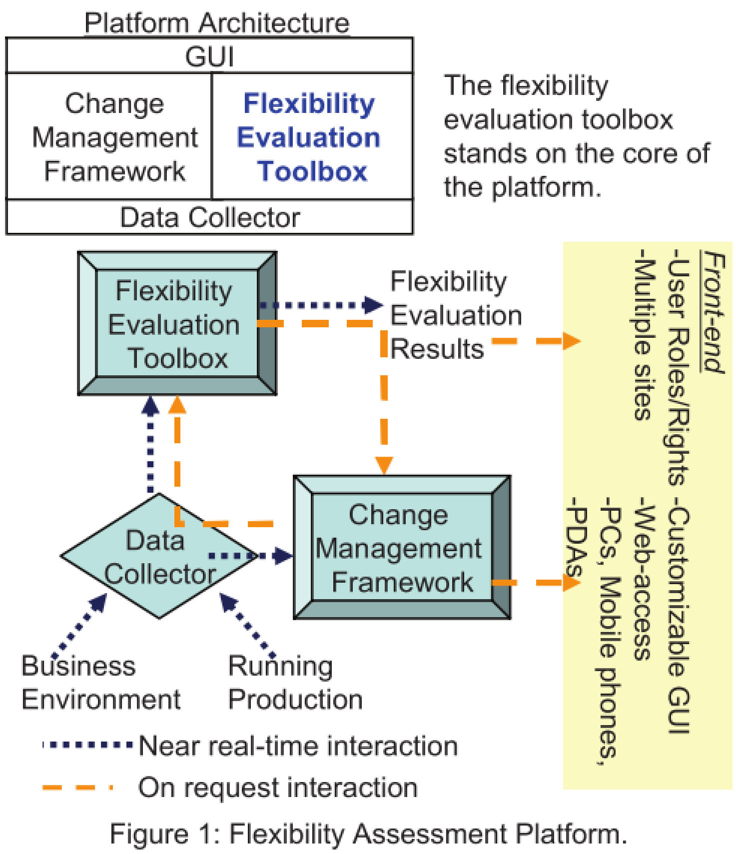

Figure 3.2: The toolbox software platform for flexibility assessment [GPMC07]

In this toolbox evaluation module, five individual flexibility measures are integrated into the flexibility evaluation toolbox:

- Penalty of Change
- ζ - analogy method
- Desyma
- FLEXIMAC
- Reaction-time analogy

The platform firstly sorts the enterprise level criteria and the flexibility types that could be measured, then examines the required data complexity from current IT systems to aggregate possible flexibility measurements of lower levels. The easiness of application of each flexibility measures is noted and recommended to import to the change management framework. The approach overcomes the limitation of using a single flexibility measure, and provides the opportunity for managers to select from a broader set of several flexibility measures.

Simulation based on Petri nets

Petri nets are a class of modeling tools originally proposed by Petri [Pet76]. A Petri net is a directed graph consisting of places, transitions, and arcs. The nodes denote transitions, representing events that may occur, signified by bars or boxes; the places are drawn as circles, representing possible states or conditions. Arcs run from a place to a transition or vice versa, never between places or between transitions. The relationships between places and transitions are linked by a set of arcs in either direction. The places from which an arc runs to a transition are called the input places of the transition; the places to which arcs run from a transition are called the output places of the transition. And, the dynamic behavior of the system can be represented using tokens which graphically appear as black dots in places.

Simulation of manufacturing activities or supply chain activities can provide estimation of the required times for a system to adapt to various environmental disturbances. The time can be interpreted as a kind of responsiveness, and can be used as flexibility measures [BS88].

Furthermore, a flexible manufacturing system (FMS) is a discrete-event system, where a discrete number of parts or components are processed and assembled by controlled machines, computers or robots and a number of resources shared to reduce the production cost. Viswanadham et al. [VNJ90] investigate the use of Petri net (PN) models in the prevention and avoidance of deadlocks in flexible manufacturing systems, and propose a Petri net-based on-line controller.

Tüysüz and Kahraman [TK10] present a complex time critical and dynamic system, modeled in stochastic Petri nets with fuzzy parameters for a flexible manufacturing cell containing nine places and five transitions. El-Tamini et al. [ETAMA12] choose Petri nets for measuring and analysis of the FMS performance, integrating machine flexibility and routing flexibility in their model. The authors conducted an example FMS in its Petri net model, AweSim model (Visual Slam AweSim to run simulations) and a mathematical model. They conclude their method works well for the studied case, but for a complex system, they suggest using simulation techniques instead of mathematical reformulation.

Other models and methodologies in supply chain flexibility

Chan et al. [CBW07] provide a simulation study for the flexible manufacturing system, using Taguchi's method to analyze physical and operating parameters with flexibility range. The Taguchi's method [Ran90] allows the analysis of experimental results to estimate the relative contribution of individual factor and interactions with other factors, in percentages. The results show that an increase of routing flexibility (RF) may not always lead to expected benefits, and could be counterproductive under certain environment, if variations are above certain limits. The conclusion is useful for decision maker to distinguish the flexibility level up to which can be increased in a set of varying physical and operating parameters, and still retains the profitability.

An economic evaluation model across the entire supply chain is proposed by Gong [Gon08]. The author adds systemically machine flexibility, labor flexibility, routing flexibility and information technology to construct the supply chain model. The objective function leads to a probabilistic average profit, as an economical index. These dimensions of flexibility are constructed and integrated by adding specific probabilistic distributions to corresponding factors. For instance, they use β_i to represent the time with a probability distribution needed by team j to finish one unit of product i, which is multiplied with the team worker output to form a labor capacity, which represents the labor flexibility. Results are obtained through Matlab. The author provides a sensitivity analysis as well, which supports that only several flexibility dimensions in certain teams, certain products and certain routes are the main factors that affect the most system flexibility.

Swafford et al. [SGM08] conduct an empirical study to determine the effect of IT integration on the SC process-specifically in regards to SC flexibility and SC agility. Their question is mainly about "How IT flexibility can influence the supply chain flexibility as a whole?" Based on data analysis, they conclude that IT integration improve SC flexibility and SC agility as well, but argue that SC flexibility and agility are two distinct concepts. They use Confirmatory Factor Analysis (CFA) as the tool to examine the relationship between flexibility types. CFA is used to examine whether the proposed measures of a construct are consistent with a researcher's understanding of that construct (or factor), mostly used in social research. Thus, the objective of CFA is to test whether the data fit a hypothesized measurement model [Jör69].

Apart from studies on information dimension, Liu and Cetinkaya [LÇ09] adopt a game theoretic modeling approach to explore the supply contract flexibility from the perspective of a bilateral setting, and address on leadership between the two sides. The authors consider a buyer-driven policy and derive an optimal methodology with information asymmetry for three different types of contracts: "under a two-part linear contract, the impact of information asymmetry depends on the buyer's estimation accuracy; a two-part linear contract, it depends on the buyer's estimation accuracy; a two-part non-linear contract, it increases the buyer's profit margin." They conclude that the buyer-driven channel shows more efficiency than supplier-driven underone-part linear contract, and the partner without accurate information may not benefit from having leadership even for a good two-part non-linear contract, in other words, sometimes one can forfeit the leadership in the supply-buy relation and still gain higher profit.

Xu and Nozick [XN09] propose a supply chain design model for supplier selection. They consider supplier capability disruptions to be a risk to the SC process, look for good choice between taking a trade-off based on cost and the risks of selecting suppliers in various categories, or taking the optional contracts. Erhan Kesen et al. [EKD10] consider the case where the buyer releases a fixed period replenishment order to the supplier under a supply contract in three parameters: (i) supply price per unit (ii) minimum order quantity and (iii) order quantity reduction penalty. Their work suppose there is no penalty for not placing an order. They then suggest a model to select supplier by minimizing the procurement plus lost sales cost. A key buyer decision is Q_{lost}, the order or replenishment quantity level below which no order is placed and sales are lost. Authors consider the flexibility of inventory replenishment under a contract, while optimizing costs and avoiding inventory risks based on the optimum value of Q_{min} (minimum order quantity) and Q_{lost}.

Zhu et al. [ZCS10] work on a two-stage serial supply chain in which a retailer and his supplier are operating in make-to-stock environments, with the uncertain demand problem faced by retailers. Their model consider a decentralized supply chain with a so-called periodic flexibility, where retailers could order any quantity in one period of the cycle, based on contract conditions that they would receive a fixed quantity from the supplier during other periods. The results demonstrate that periodic flexibility improves the supply chain performance by about 11% on average and highlight the centralization control. This periodic flexibility can be viewed as a supplier flexibility, the sourcing quantity flexibility and a delivery flexibility. Moreover, the information communication plays an important role in their case. Chan and Chan [CC10] propose a two-echelon SC inventory cost model to study the supplier capacity and delivery flexibility in a make-to-order (MTO) supply chain. The work employes an agent-based simulation to get the results, and also conclude both the flexibility for MTO and the adaptability would provide better cost than order-up-to policy model costs.

Das [Das11] tries to develop models to integrate volume, product mix, distribution and supply flexibility in a strategic level. A mixed integer supply chain planning model is then proposed as a way of addressing demand and supply uncertainty, as well as considering various market scenarios. Based on the product mix flexibility, the model selects an optimal number of products from fast moving and extended product range options, then confirms a quick response to a changing marketplace by considering transport and supply lead time along with the stock out probabilities, with supply and distribution flexibility. The author proposes a scenario-based stochastic approach for estimating the demand increase towards capacity flexibility planning, and provide a step-by-step procedure for solving the model and applying the flexibility measures.

3.2 Application of the mechanical analogy method to a practical case

3.2.1 Introduction on mechanical analogy method

3.2.1.1 General introduction

In this method, a manufacturing system can be viewed as a mechanical system, whose input is excitation force and the output is displacement or the movement of the mechanical system. Inside the mechanical vibration box, a simple mechanism generally consists of an elastic spring, a damper, a mass and their oscillatory interactions. In the same logic, a manufacturing plant system is composed of several manufacturing resources (machines, labor, raw materials, ...) and production activities. Outside the manufacturing system or a workshop in a manufacturing system, the input may often be the fabrication order expressed in quantities of products with a certain estimated processing time; the output can be the finished order expressed in quantity of products and real flow time. This is shown in the left part of Fig. 3.3.

Nevertheless, the analogical notion can be easily extended to the whole supply chain and applied to different echelons in/of a supply chain. For example, the analogical input data to a supply chain or to an echelon of supply chain can be symbolized as client demand, which could be expressed in quantities of products with estimated lead time or an agreed due date; the output can be presented as delivery operations expressed in quantity of products and real delay time. This is shown in the right part of Fig. 3.3.

For a mechanical vibration system, excitation force and mechanism displacement vary over time, and so do the fabrication orders and delivered orders of an manufacturing system. Therefore, a manufacturing system may exhibit strong dynamic behavior, which is difficult to be described with mathematical curve and often nonlinear. On the other hand, flexibility is well defined for a simple dynamic mechanical system, representing its insensitivity to external excitation. Thus, the flexibility of manufacturing system can be obtained with the help of the appropriate mechanical damping factor [Chr96].

Moreover, by studying properties of a supply chain, we consider this damping concept able to be extended to whole supply chain and could be adapted to different echelons in a supply chain. The flexibility of supply chain system can be also obtained with the help of mechanical damping factor, as a supply chain can be also viewed as a system composed of several supply chain resources (suppliers, production plants, transportation vehicles, ...) linked by several supply chain operation activities, as well.

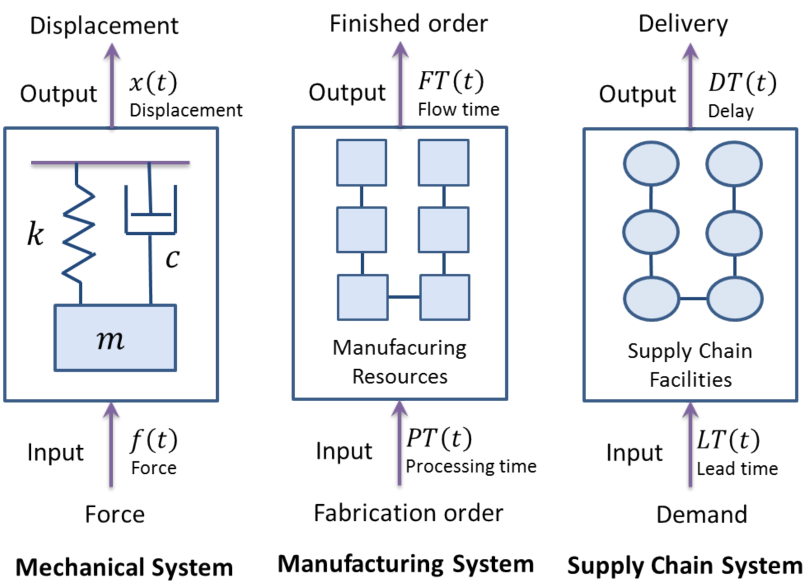

Figure 3.3: Analogy between a manufacturing and a mechanical system [Chr96]

3.2.1.2 Methodology

Before stepping into the detailed methodology, we start by identifying a simple mechanical oscillatory system.

All concrete bodies possessing mass and elasticity in the world are capable of vibration, that can be further distinguished into two vibration classes - free and forced vibration [TD98]. *Free vibration* takes place when a mechanical system oscillates under the action of inherent forces in system itself, and leaves the body vibrate alone at one or more natural frequencies, which are linked with the intrinsic properties established by the distribution of its mass, stiffness and damping (if it has a damper). *Forced vibration* takes place under the excitation of external forces, where the body is forced to vibrate at the excitation frequency (if the excitation exhibits a frequency).

A mechanical system may oscillate in different modes, described by its number of independent coordinates, called *degree of freedom*. For example, a rigid dust floating in a vacuum room is capable to vibrate in three degrees of freedom. Besides, all oscillatory mechanism subjects to damping effects to some degree, because there exists always the energy dissipation by heat radiation, friction and other resistances.

For the mechanism of a single-degree freedom with known mass, elasticity and damping properties, the damping factor can be easily calculated, noted as ζ. The following expression shows the relationship between damping factor and other attributes of the mechanical oscillator system :

$$\zeta = \frac{1}{2}\sqrt{\frac{c^2}{km}} \tag{3.8}$$

where:

c	the damping of the mechanical system
k	the stiffness of the mechanical system
m	the inertia of the mechanical system
ζ	the damping factor representing the system's ability to respond to changes in the excitation

The mass is considered to be measured in SI system [Cox58] as kilograms kg or g. The linear spring follows Hook's law[Hoo78], $F_k = kx$, where the stiffness k is measured in newtons/meter n/m. A simple viscous damping is described proportionally to the velocity $F_c = c\dot{x}$, where the damping coefficient c is measured in newtons/meter/second $n \cdot s/m$. The damping factor ζ is dimensionless.

Naturally, if we make use of nominal attributes to achieve the analogy between mechanical oscillator and corresponding supply chain, the four attributes become as follows:

c	the damping of the supply chain system
k	the stiffness of the supply chain system
m	the inertia of the supply chain system
ζ	the damping factor representing the system's ability to respond to changes in the input/excitation

For a mechanical oscillator system, the damping factor ζ can be estimated from the frequency spectrum in an approximate way, as follows:

$$\zeta \approx \frac{1}{2Q} \tag{3.9}$$

where Q is the amplitude corresponding to the fundamental natural frequency in its frequency spectrum, which will be detailed in the following paragraphs. This is the core relation of our method.

Consider any mechanical system solicited by a time-varying force $f(t)$ with $f(t=0) = \bar{F}$, and reacted by a movement $x(t)$. The differential equation that describes the vibration motion of simple-degree system undergoing the excitation $f(t)$ at time $t = 0$ is:

$$m\ddot{x}(t) + c\dot{x}(t) + kx(t) = f(t) \tag{3.10}$$

recall:

m	the mass coefficient of the mechanical vibration system
c	the viscous damping coefficient of the mechanical vibration system
k	the stiffness coefficient of the mechanical vibration system
$x(t)$	the displacement of the mechanical vibration system
$\dot{x}(t)$	the velocity of the mechanical vibration system
$\ddot{x}(t)$	the acceleration of the mechanical vibration system

The response $x(t)$ of a damped single degree of freedom mechanical system subjected to an impulse excitation at time $t = 0$ could be then deduced and expressed by Eq. (3.11)[Tho93](recall $f(t = 0) = \bar{F}$):

$$x(t) = \frac{\bar{F}}{m\omega\sqrt{1-\zeta^2}} e^{-\zeta\omega t} \sin\sqrt{1-\zeta^2}\,\omega t \tag{3.11}$$

where:

ω	the circular frequency of the mechanical system, given by $\omega = \sqrt{\frac{k}{m}}$
ζ	the damping factor representing the mechanical system's ability to respond to changes in the input, given by $\zeta = \frac{c}{2m\omega}$

When an excitation $f(t)$ is applied at time $t = 0^+$, the initial velocity of movement is given by relation:

$$\dot{x}\left(0^+\right) = \frac{\bar{F}}{m} \tag{3.12}$$

Thus, if the initial velocity and the force are all known, the mass can be directly estimated. That means the nominal value m of the supply chain system, can be determined by the following:

$$m = \frac{\bar{F}}{\dot{x}(0^+)} \tag{3.13}$$

In order to numerically record the time-varing force and the displacement of the mechanical system, the couple $x(t)$ and $f(t)$ can be both discretized and sampled in length N:

$$f_n = f(t_n) \;\; x_n = x(t_n), n = 0, 1, 2, ...N-1 \tag{3.14}$$

where $t_n = n\triangle$, $\triangle$ is the sampling interval, as what we have presented in sec.3.2.1 to study its transfer function in the frequency spectrum.

The transfer function between the input and output of a supply chain system could characterize the way the system responds to changes in the input, such as variations in orders of different products in different volumes and due dates.

This transfer function can be expressed in the frequency domain. For a continuous range of frequencies, the variable ω denotes the circular frequency in radians/sec. For the DFT (Discrete Fourier Transforms) series, the discrete frequencies are all multiples of a specific frequency ω_0, called the fundamental frequency. Therefore, the transfer function of the system can be expressed as:

$$H(\omega) = \frac{X(\omega)}{F(\omega)} \tag{3.15}$$

where :

ω given by the relation $\omega \in \{h\omega_0 \mid h = 0, 1, 2, ...N-1\}$, set $\omega_0 = 2\pi/N$ for x_n of length N.

$X(\omega)$ the Discrete Fourier Transforms (DFTs) of x_n: $X(\omega) = \sum_{n=0}^{N-1} x_n \cdot e^{-j\omega n}$

$F(\omega)$ the Discrete Fourier Transforms (DFTs) of f_n: $F(\omega) = \sum_{n=0}^{N-1} f_n \cdot e^{-j\omega n}$

The transfer function of mechanical system contains basic information concerning the intrinsic characteristics independent of initial conditions or excitation. The transfer function $H(\omega)$ depends exclusively on the interconnectivity and magnitude of system internal components. The plot of $H(\omega)$ in a frequency spectrum of the system contains eigenvalues Ω_i, which are a set of invariant system's natural frequencies characterizing this particular system's configuration. The amplitude at Ω_i in the spectrum , noted as Q_i, depends only on the system's damping properties and changes the phase angle sign at Ω_i . If there is only one vibration mode with one fundamental natural frequency Ω and one corresponding Q, we may directly apply the relation (3.9) to calculate the approximate damping factor.

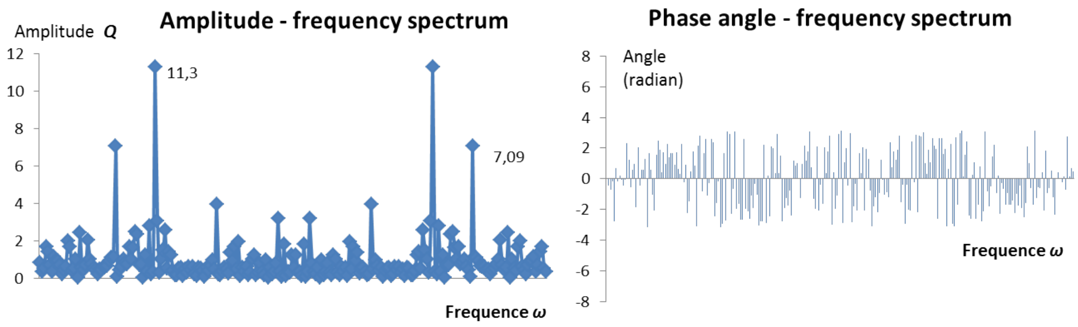

Figure 3.4: Frequency spectrum of the transfer function

Similar to the mechanical system, a manufacturing system can use, for instance, a sequence of orders and their anticipated processing times (length of time from the placement of an order to its accomplishment if everything goes well), as the excitation to the mechanical system, while the real lead time as the output. At the same time, a supply chain system can also use sequence of demand and their anticipated lead time or agreed due date by clients, as the excitation to the mechanical system, and the real delivery operations as the output.

The input and the output data can form a Discrete Fourier Transform to get the frequency of eigenvalues Ω_i and the corresponding amplitude Q_i in the frequency spectrum. Then the damping factor - the insensitivity - can be estimated with Eq. (3.9). Fig.3.4 is an example of frequency response spectrum for one sales store in LV, from the figure we can see it is symmetrical so just consider the half of figure. The amplitude point 11.3 corresponds to its primordial frequency, and there are other subordinate frequencies Ω_i, such as the plot point with amplitude 7.09. At their frequencies Ω_i , the phase angle changes the sign, which helps to identify the Ω_i value. The application will be presented in the next sub-section.

It must be noted that estimation in formula (3.9) is valid only when the damping factor lies in the range of $0 < \zeta < 2^{-1/2}$, otherwise the system is over damped and the peak of amplitude disappears. The higher the damping factor ζ is, the less sensitive is the response of the system to changes in the input. The lower the value of ζ, the more sensitive is the response of the system to changes in the input. Therefore, the value of damping factor indicates the system's ability to respond to changes in the input to the system and the insensitivity to changes in the input, hereby construct itself as a flexibility measure. If we interpret the system flexibility as the insensitivity to environmental changes, the higher the value of ζ, the more flexible the system is.

The FLEXIMAC-method take the same logic and calculate the arithmetic mean of the ten highest amplitudes in the frequency spectrum with Eq. (3.7).

3.2.1.3 Advantages and drawbacks

As described above, we investigate the feasibility of this analogy method and conclude this method of great advantages, such as:

- Great independence of subjective assessments and resource scenarios.
- Great indifference to all other internal configuration data and operations in the "black" mechanism box. The only required data is the input (e.g. demand) and the output (e.g. delivery).
- The required data of input and output is generally simple and easy to acquire, in manufacturing and in supply chain as well. The data can be rapidly gathered from working data or Enterprise Resource Planning (ERP) Systems.
- The evaluation of flexibility can be executed cross-industrially on all relevant levels, starting at the machine level, workplace level to the factory plant and supply chain level, as long as the input and output data are gathered.

In spite of these merits, several disadvantages must be identified.

First, if the variation of excitation input changes too radically, the response of system may go out of reach. Therefore, either the system is damaged, or the amplitude of Q_i at the natural frequency Ω_i becomes impossible to anticipate and the relationship exploited to calculate the damping factor could not be held any longer.

Secondly, if the system is over damped, it would be impossible to find the correct high amplitude Q_i, thus impossible to identify its natural frequency and hard to estimate its damping factor.

Thirdly, when adding the first and the second disadvantages as a whole, it is not clear if the different pattern of input data does have an impact on the output data.

Moreover, measure of damping factor only evaluates the system flexibility in a total or general sense. It would be difficult to identify and to separate different flexibility dimensions from this total measure. Particularly, an evaluation of expansion flexibility is not at all possible in this case, because it is hard to make an exact mechanical analogy with input and output data for expansion phenomenon.

For a mechanical system with more than one degree of freedom, in a more general case, there will be several primordial natural frequencies in different modes of freedom. In Fig. 3.5, we observe different modes of displacement when there are more than one possible degree of freedom. For this spring with one extremity fixed to the wall, it can oscillate in the longitudinal direction (forward and backward), the perpendicular direction (up and down), or the mix direction that forms a spiral circle. In fact, among all these possible movements, there are always one or more primordial displacements which dominate the vibration, and other subordinate modes which are less important. Whereas, if the subordinate modes also lead to high dynamic response and are not such sub-ordinated, the highest corresponding amplitude may be no more adequate to represent the system attribute, and thus no more adequate to calculate the mechanical damping factor. Neither the ten highest amplitudes in FlEXIMAC are adoptable. In this manner, we may arrive at an estimation of the system flexibility with quite a large deviation away from the intrinsic values, that means, it represents no more the real system's characteristics.

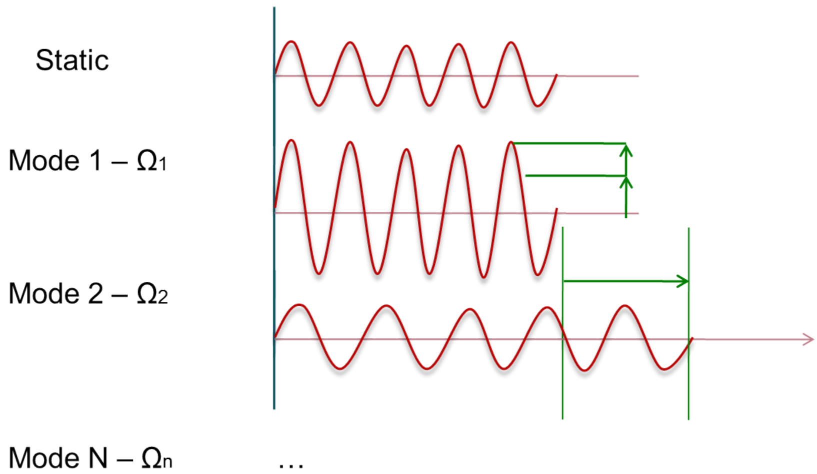

Figure 3.5: Vibration modes of a spring in multiple degrees of freedom

Nevertheless, it must be noted that this mechanical oscillator analogy method has not been widely tested and studied to date, and never been adapted and implemented into supply chain. It is applied only once to a manufacturing case in an aluminum workshop [Chr96], in which the estimated processing time of production acts as the input, and the real flow time of the products production acts the role of output. This is a simple and rough case that did not detail the product family and the product time cycle.

Whereas in the context supply chain, the real situation is more complicated according to different echelons and most time volatile; for example, the input data (client demand for instance) is often stochastic and difficult to anticipate. Other than the mentioned manufacturing case with relatively stable production input data and well defined internal configurations, a supply chain exhibits sometimes a great volatility and complexity. Therefore, how to enlarge the mechanical analogy and adapt it to be carried out to supply chain, becomes our next concern. In the next sub-section, in order to explore how to implement the method in supply chain, we settle up to conduct a case study in the downstream of supply chain; i.e. outlets and stores level, to investigate and implement the analogy method into supply chain.

3.2.2 Mechanical analogy application for flexibility in Louis Vuitton problem

3.2.2.1 Problem Identification

The problem to be studied lies in Louis Vuitton (LV), a French fashion company founded in 1854 by Louis Vuitton. The company produces a variety of products ranging from luxury trunks and leather goods to ready-to-wear, shoes, watches, jewelry, accessories, and sunglasses. For LV, the flexibility problem principally lies in the production level, where the labor flexibility such as skilled and experienced workers are of most importance, due to a great number of hand-made operations in the factory.

Generally, LV reaches quite a good client service level, up to 95%, relatively high. One of the reasons is that the replenishment of articles to regional warehouses and to stores is sometimes indifferent to transportation prices. If the required luxury products retains a high price level, the delivery or emergent delivery by planes in views of LV is not unacceptable. However, even the service level of LV is pretty good, there is still some space left for consequent improvements.

In this background, we started out to estimate the flexibility performance in order to provide an evaluation list for products and stores for LV. In adopting mechanical analogy method, we set about to evaluate some simple echelons in its supply chain. Since the measurement in this method is uncomplicated to understand, and easy to carry out only with the help of some input and output data, there is no need of collecting tremendous detailed information inside the organization. In this case, we expected to acquire basic results as: (i) the evaluation of the flexibility performance of different products; (ii) the evaluation of the flexibility performance of different stores; (iii) possible indications on why they exhibit such flexibilities.

To start off, the downstream of the supply chain in LV is studied and illustrated in Fig. 3.6. It consists of the plants of fabrication (F), central warehouse or distribution center (C), a number of regional warehouses (R), outlets and stores in grand commercial centers or grand stores (M), and then final customers (V).

This case study lies in the downstream part of supply chain and focuses on the store level (M), specifically for the stores of LV in Japan.

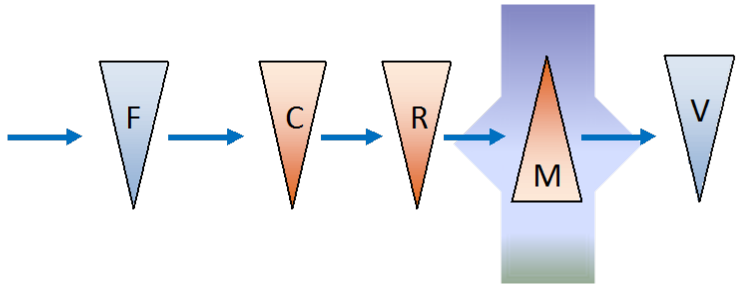

Figure 3.6: The supply chain and the studied problem field of LV

Furthermore, the replenishment activity in LV is demand-driven. In the store level, LV stores sell a variety of products to clients, and then command the corresponded replenishment quantity from regional warehouses to replenish and fill its physical inventory. Thus, the input and output data source for this problem is explicit and clearly observed:

- **Input** - Excitation: Sales in LV stores per product reference per store per day
- **Output** - Response: Delivery of product orders from regional warehouses to stores per product per store per day

Before utilizing the mechanical analogy method in LV problem, we first identify if the considered problem coincides to some degree with disadvantages expressed in mechanical analogy in sec. 3.2.1.3:

1. The first disadvantage does not affect the studied problem, because LV nowadays places a good service level and due to the nature of "luxury" product, its excitation (demand of final clients) appears with less ability to incur a drastic increase in a short period.
2. Secondly, LV achieves a good service level but it can still be improved. Even the existing service level could be improved from time to time via some expensive operations, e.g. transport by plane. So, there is still a perfectible space to improve the profitability while maintaining or even improving the service level.
3. Thirdly, we concentrate on the overall flexibility of store level, and do not pay much attention to expansion flexibility or to study seperately the volume flexibility and product-mix flexibility.
4. In case of different patterns of input data, with the knowledge that client demand in store level does show a great uncertainty, we propose to classify different periods in the next sub-section to distinguish the time length during which the system may exhibit similar performances.
5. It is almost impossible to specify how many corresponding degrees of freedom exist in the supply chain system. However, the primordial degree of freedom for a me-

chanical system is always the basic one with the biggest amplitude shown in the frequency spectrum, corresponding to its primordial vibration mode. Some secondary peak values in the spectrum indicates other important secondary frequencies. After tests with several stores and products, we found that just three frequencies are enough for the scale of the considered LV problem.

3.2.2.2 Period classification

We are quite aware of the interference of different periods during which the system may present different configuration and behaviors. Thus we propose to classify the different business periods before extracting the results of LV from the analogy method. Two reasons support this point of view:

On one hand, disadvantages (1), (2) and (3) listed in the previous sub-section imply that, the pattern of input data does have consequences in the response type of the system. Although the interference of the input data is not yet clear, we are inclined to exclude any possible interconnections which may influence the flexibility calculation. Thus, we choose to distinguish heterogeneous periods with evident differences in distribution of input data, that means, in daily sales in LV stores per product reference per store.

On the other hand, the logistics properties of the considered LV stores regarding opening hour, labor force, promotions and decoration, do not remain the same all along the business year. That implies during different periods, the LV stores retain different system configurations and plan to make small modifications for the next period, such as promotions, employment of salesman, new arrangement of stores, etc. Though demand of final clients may not have a drastic change pic due to the product nature of "luxury", the sales to final clients demonstrate differences between low season and high season. For time interval closed to special holidays like Adults Day or Christmas Day, configuration of stores are certainly modified, and moreover, managers may place anticipated orders to regional warehouses to make enough stock in advance. In these periods, stores manifest different intrinsic attributes of its own.

To solve this focus, we develop an algorithm to detect the evident differences in input data, and add additional weight to special periods. A moderate weight is put on the input data, with a heavy weight added to the great feasts and extended holidays, and a slight one added to small parts and weekends. At last, we combine and merge overlapping portions to form a rational long period. The weighting index is illustrated in the following figure.

As a result of this weighting and detection algorithm, we finally obtain a list of "**special periods**" in Tab. 3.1, which must be distinguished out of the normal main branch "**principal**

Figure 3.7: Weighting system for period classification of LV

period". Important days in these special periods are listed in the last column to understand if it is rational. Due to the small amount of data inside each of the special period, the results may exhibit high deviation from the real world, so it is suggested to merge these periods to a single period called "special period" together with the "principal period" to be studied on.

2010		2011		Principal cause
02/01/2010	11/01/2010	02/01/2011	11/01/2011	New Year+ Adults Day
11/02/2010	14/02/2010	11/02/2011	15/02/2011	National birthday + Saint Valentin
24/04/2010	05/05/2010	23/04/2011	05/05/2011	Birthday of emperer Shōwa +Constitution+ Children's day+Extended holiday
14/08/2010	24/08/2010	06/08/2011	15/08/2011	Festival Tanabata + Day of the deads +Extended holiday
18/09/2010	23/09/2010	19/09/2011	25/09/2011	Mid-automn day + Oldmen's day
23/12/2010	01/01/2011	23/12/2011	01/01/2012	Emperor Birthday+ Noël + Extended holiday

Table 3.1: Period classification for the mechanical analogy of LV

3.2.2.3 Flexibility behavior analysis for stores and products

To obtain the damping factor (flexibility indicator) for a store for all products, we collect the data and make use of the equations (3.9), (3.14) and (3.15). Considering the period differentiation phase above, we calculate and plot the frequency spectrum for the "all periods", "special periods" and "principal period". The frequency spectrum for the store V8 with a low annual sales volume 3268 (number) in 2011 is shown in Fig.3.8. The horizontal axis is the circular frequency and the highest amplitude corresponds to the system's fundamental frequency. We use the first five natural frequencies to calculate the arithmetic mean of damping factor each, they are respectively 0.0432, 0.1928 and

0.0442 for all periods, special periods and principal periods. The peak of special periods is explicit.

With these results, it is observed that the flexibility manifested in special periods are significantly higher than those in all periods and principal period. This is mainly because of i): The company anticipates better responsive behavior and may have planned better modification of configuration in special periods; ii) The sampling points of special periods data are not as enough as the normal periods, therefore, the results may be not representative to compare that of special periods with those of all periods and principal period. However, in case of ii), it remains reasonable to compare the flexibility results of special periods with those of other stores, since they are all based on the same period length of sampling data.

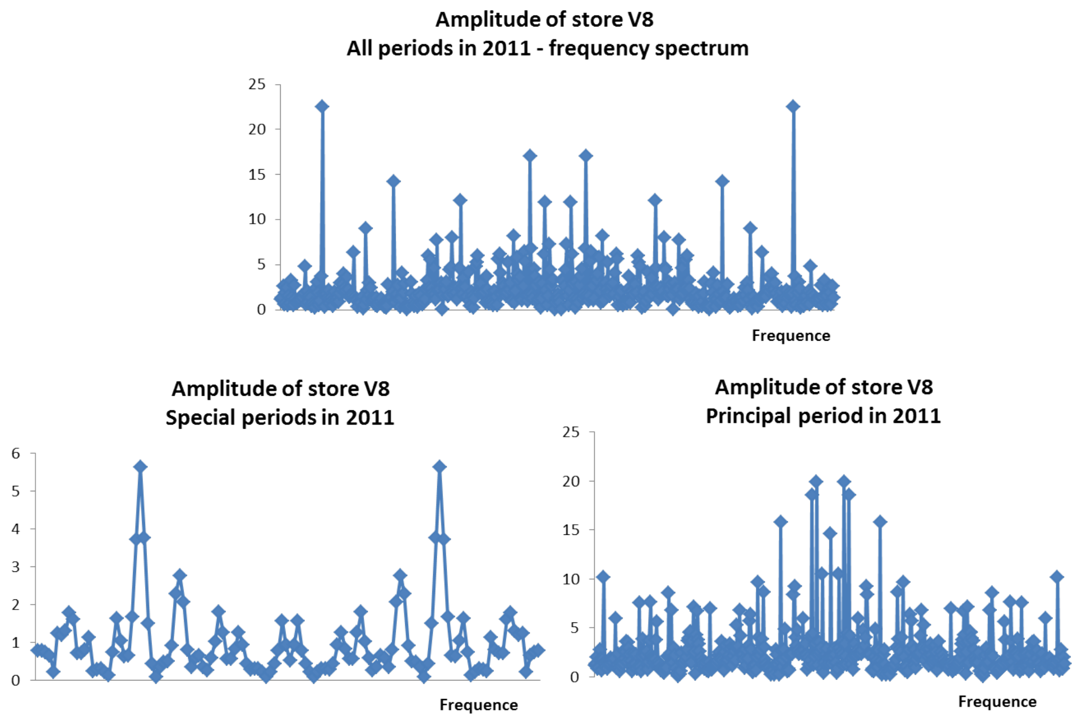

Figure 3.8: Frequency spectrum for store V8 in LV

This is only the results for one store V8 with all products, and it is of great value to compare flexibility results with those of different stores. The frequency spectrum of store V36 with a higher annul sales volume 43107 (number) in 2011 is presented by three periods in Fig.3.9. Its flexibility damping factors are respectively 0.1147, 0.2495 and 0.0999 for all periods, special periods and principal period. Thus, compared with results of store V8, the V36 manifest better flexibilities. It is noticeable that sales volume of V36 is greater than V8, implying to a question that, does the stores of bigger volume have better flexibility performances in LV? Does the stores of smaller volume provides lower flexibilities? These are inevitable further questions to answer in this study.

As a result, in order to analyze the flexibility behavior for different stores, we propose to classify these stores in different groups as “Very Important”, “Important”, “Normal” and “Less Important” according to adequate criteria. Multiple criteria can be used to classify them:

- Annual sales volume of the store
- Size (surface) and number of employees of the store
- Status of the store (independent store or integrated into large commercial stores)
- ...

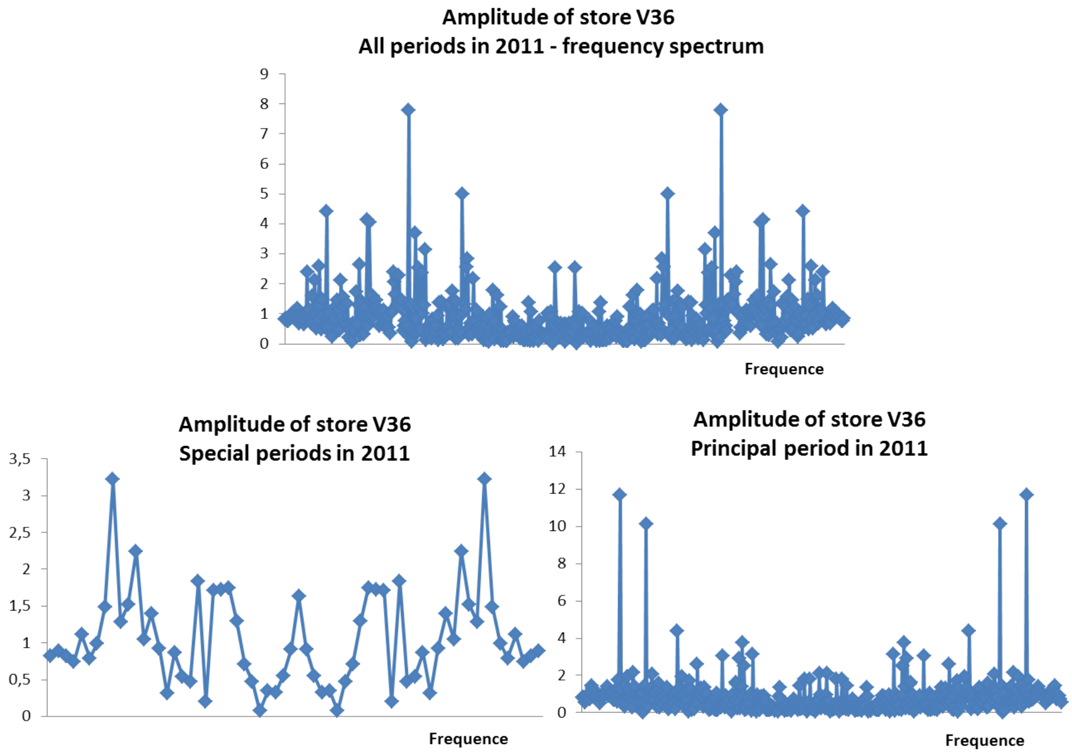

Figure 3.9: Frequency spectrum for store V36 in LV

Due to lack of information, we simply propose to classify the stores of LV by the annual sales volume, that is, the category of **stores 3, 2, 1, 0** with upgrading sales volume.

Same to the classification of stores, the product references can should be prudently classified as well. They are supposed to be classified as "Very Important", "Important", "Normal" and "Less Important". Multiple criteria can be used to classify them:

- Annual sales volume of the product
- Net profit compared to sales volume of the product
- The sales stability during the business year of the product

LV has already a rough classification of their products: Seasonal, Slow, NP, Uni-sex, Women, Men and EndLife. But this classification is not really always representative of the product nature, for example, certain products in Men are massively sold to women, and the border among Slow, Uni-sex and Men are not clearly defined. In this case, we are agreed to classify them in this study briefly by the ranking of sales volume of each product, as **class A, B, C, D, E, F**.

With this combined classification of stores and products, we finally obtain a result table of damping factor, which indicates the flexibility in each combined category in the following table.

	Product	Stores 0	Stores 1	Stores 2	Stores 3
A	M61734, N62665, ...N60015	0.2417	0.2182	0.2234	0.2016
B	N62631, M62631 ... R04240	0.2279	0.2465	0.1962	0.1873
C	N63024, N63074 ...N62659	0.1387	0.1540	0.0930	0.0822
D	N63084, N51205 ...M62693	0.0867	0.0798	0.0831	0.1003
E	N41158, N41158 ...N62669	0.0656	0.0719	0.0588	0.0449
F	M60240, M41528 ...M93493	0.0471	0.0402	0.0378	0.0351

Table 3.2: Flexibilities for stores and products in LV

From the Tab. 3.2, we can see that the "*important product* [**A**]" provides the best flexibility for all stores and almost the best compared with all products. Particularly, the "*important product* [**A**]" in "*important store* [**0**]" manifests a flexibility factor of 0.2417, colored in red, and it is almost the highest value in the table. This may be explained by better operational planning, more adequate strategies of replenishment and more products placed in inventory or in regional warehouses for this category of products and stores. We observe the "*important product* [**A**]" manifests better flexibilities in whatever store, whereas the "*important store* [**0**]" does not lead to better flexibility for all the products.

The significant tendency is that, for stores in less volume and products in less volume, flexibilities go down gradually along with their sales volumes. Meanwhile, we have observed some exceptions for "*important store* [**1**]", the store group with second sales volume, whose flexibilities in "*important product* [B], [C] and [E]" are a bit higher than that in "*important product* [**A**]". This result may be a little strange, but not difficult to explain. It is very likely that the "*important store* [**0**]" has attracted too much attention of clients for the most demanded *product* [**A**], and partakes quite a lot part of pressions for *store* [1]. Consequently, *store* [1] could provide better flexibilities under less demand pressions. And it must be noted that, the "*important product* [B]" in "*important store* [**1**] exhibits the best flexibility in value 0.2465 among all products and stores.

Another exception occurs for "*important product* [D]", classified into [D] claims its unimportance. Whereas, unimportance + unimportance may not always sum up to unimportance, the *product* [D] achieves better flexibility (colored in blue) in *store* [2] and *store* [3], which are both store groups with quite minor sales volumes. This phenomenon is understandable: while other important stores and important products have stuck into fierce and complex situation, *product* [D] remains in peace and receives clients in *store* [2] and *store* [3] in tranquility. And it is not the only one, the same happens to *product* [E] in *store* [1], colored in orange, with 0.0719 a bit higher than 0.0656 in *store* [0]. But, unfortunately, for the last "*important product* [F]", no miracle have come to this category: it exhibit bad flexibilities for all stores, and *product* [F] in *store* [3] has shown the worst flexibility among all products and stores.

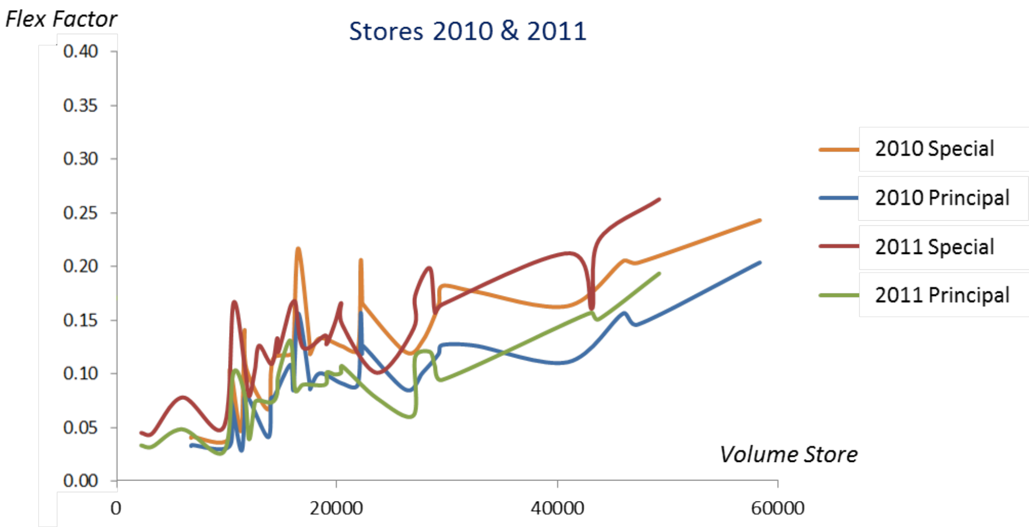

Figure 3.10: Comparison for flexibility curve in principal and special periods

By comparing flexibility behaviors and the flexibility evolution during two years for different stores by volume in Fig.3.10, we observe that a store with bigger annual sales volume presents relatively higher flexibility. These stores has shown generally less important sensitivity to environmental changes and consequently, become more flexible. It is clear that for stores with lower annual volume of sales around 20000, its flexibility curve turns out to be not quite smooth. These stores are generally more sensitive to external excitation (demand) mainly for each group of products. From this curve, we can conclude their flexibilities are generally lower and not as stable as the bigger stores, which coincides with the real situation of the company.

The sharp jump near the volume 40000 is an exception, possibly due to an accident or other emergency in the store's configuration. Moreover, we can see that the evolution value of flexibility in 2010 is generally higher than the year 2011, which implies, either the strategy of the year 2010 is more flexible than the year 2011, either the configuration in stores themselves became more flexible (e.g. new inventory and replenishment policies). Or, if there were a lot more new stores opened in Japan, they may share demand flexibilities and partake demand pressions. In this case, flexibility in each single store may be not satisfiable temporally, but the overall flexibility of all the Japan division would be better in the long term. Normally, the more stores opened, the more buffers (damping) would appear.

3.2.3 A procedure to implement the mechanical analogy evaluation in supply chain

In the previous section, we have exploited the mechanical analogy method to obtain flexibility evaluations from the damping factor in stores' level. The implementation of this method in supply chain is not difficult, but a little different from the manufacturing case mentioned in sec. 3.2.1.3, with a new phase called period-differentiation and more detailed analysis in our study.

In this part, we try to extend this method to be applied to whole supply chain, and establish a procedure to carry out this flexibility assessment.

Supply Chain is a widely defined notion consists of a set of necessary resources and facilities including manufacturing resources. In Fig. 3.6, flexibility assessment using the analogical method, can take place not only in every single stage but also in multiple echelons in distribution. For example, end-customer demand as input, and order of regional warehouse from central warehouse as output; or orders from store to regional warehouses as input, and orders from regional warehouse to central warehouse as output. In every echelon and for multiple echelons, this method is always applicable.

Nevertheless, in the LV application, the "demand" talked about is the end-customer demand specified in order quantity. In fact, the "demand" can be also characterized by time, that means, by the order's real processing time. In the distribution echelon, one can take the estimated lead time as input data, and the real processing time (delay) of delivered orders as output data. In this case, orders are characterized in *"time"* instead of *"quantity"*. As a result, researchers must collect input and output data specified in time length. However, this change of data type does not lead to inconveniences, because nowadays, with the help of Radio Frequency IDentification (RFID) technology, more and more products are immediately recorded by their step-by-step delivery operations. Consequently, the data recorded in time is not difficult to acquire. Therefore, on condition that products are recorded for each stage or for major stages (e.g. in Fig. 3.6), the distribution level can also adopt the time data to implement the flexibility evaluation.

For manufacturing, Chryssolouris [Chr96] considers a manufacturing system producing aluminum profiles. He adopts the estimated processing times of finished aluminum profiles as input data, and real flow times of the production as output data (response). This manufacturing system consists of different stages of extrusion process, heat treatment, transit buffer, chemical surfaces treatment and packing operations. However, on one hand, Chryssolouris only evaluates the overall flexibility at the stage of finished aluminum profiles. Flexibility assessment in using the mechanical analogy, can take place in various echelons of distribution and also in different stages of manufacturing. The analogy method is applicable to any single intermediate stage and multiple stages of the manufacturing system. For example, one can take the estimated processing time of combined “heat treatment - transit - chemical surfaces treatment” as input, and real flow time of the combined “heat treatment - transit - chemical surfaces treatment” as output. On the other hand, it is noticed that input and output data in this case are only time data. If times can be recorded, their production quantities should be easily derived as well, and probably, already recorded with their times at the same time. Thus, in the analogy evaluation of manufacturing flexibility, the input and output data can be both specified in manufacturing quantities as well. That means the inverse direction of data type *“quantity”* to data *“time”* is possible as well as in manufacturing echelon.

Other than manufacturing and distribution activities, the supply echelon has not been covered by any existed flexibility study with analogy method. However, its evaluation could be conducted in the same way. In manufacturing sites, the accomplishment rate of production orders counts well for production planning; whereas in distribution echelon, the delivery service level for clients anounces its performance. And in supply echelon, service levels provided by suppliers vs industrial clients (e.g. manufacturer, assembler, components manufacturer...) in terms of time, quantity and cost, counts well for the selection of suppliers. Furthermore, different suppliers may co-exist to offer various raw materials and semi-finished articles in a multiple-stage structure. Thus, this analogy method is still applicable to supply echelon: one can compare the flexibilities among different articles offered by only one supplier, and among several suppliers providing the same article. In the same way, the results of analogical flexibility assessment would be understandable for suppliers, and can be conducted in every single stage and multiple stages of the supply echelon. In addition, *“time”* and *“quantity”* remain as two regular data types for input and output data in order to evaluate the flexibility in supply echelon.

To extend this method to each stage of supply chain, we propose to define a new term: *finished rate*. This *finished rate* aim at being the notion of “service level for clients” in distribution echelon, the notion of “fulfillment of production orders” in manufacturing echelon, and the notion of “satisfactory rate of industrial clients to their suppliers” in supply echelon.

Generally, it describes the accomplishment situation of any orders in any stage of supply chain (supply / production / distribution) in terms of time and quantity. That means, it depicts the order accomplishment regardless of different supply chain echelons. This is an important term, indicating whether it is appropriate to exploit mechanical analogy method to evaluate the flexibility performance of the studied problem. It is detailed in the following paragraphs.

In conclusion, we consider the mechanical analogy method appropriate to be exploited regardless of various supply chain echelons (supply / manufacturing / distribution / or small stages among them).

Before carrying out the evaluation, a lot of preparation works need to be done. The *fin-*

ished rate is only one data provided from industrial world. For this, we propose to outline and establish a complete evaluation procedure, which would be useful for all further work to be applied in supply chain:

(I) Appropriateness checking

The initial phase to identify whether the studied system is appropriate to be assimilated to a vibration mechanism and evaluated by the analogy method. This checking phase goes in three steps:

- Study the supply chain situation of the company;
- Check the *finished rate* and make sure if there exist relatively drastic increases in input data within quite a short period;
- Check whether the *finished rate* reaches 100%;

If there exist too many drastic changes leading to a very low service level, it may be of no value to make use of analogy method for the studied problem. The reason is that the analogical response of corresponding vibration system, may frequently jump out of reach and lead to distorted, meaningless results. Here "the studied problem" can be either for a whole supply chain, or in one echelon, one small stage and for several multiple stages of supply chain. In the following paragraphs we just use "the studied supply chain" for short.

If the *finished rate* of the studied supply chain achieves or closely approaches 100%, the analogical mechanical system is probably over damped, so that the corresponding frequency spectrum of the mechanical vibration system could not arrive at any meaningful results.

Fortunately, these two situations are rarely seen in most part of industrial world. Generally, firms in the market may exhibit a good finished rate but still can be improved.

(II) Data preparation

The preparation phase to carry out the mechanical analogy method for the studied problem. It is followed in three steps:

- Identify the input data: type of data (time/quantity), physical meaning with analogy to excitation force of mechanical system;
- Identify the output data: type of data (time/quantity), physical meaning with analogy to vibration response of mechanical system;
- Prepare the required input and output data;

The data required in analogy method is not difficult to gather from the industrial world, as explained in sec. 3.2.1.3.

However, it is of great importance that input and output data must be understandable and passable for its appropriate physical meaning in supply chain. For example, in the previous LV application, the input is considered to be “sales quantity in LV stores per product reference per store per day”, the output as “delivery product quantity from regional warehouses to stores per product per store per day”. This input and output can not be changed to the inverted sense, because stores of LV do work mainly in a order-driven mode, that means products are first sold and demanded in stores, and secondly, stores place commands in regional warehouses to receive sufficient replenishment. Thus, the input data is “sales in LV stores”, serves as the analogical excitation to system, which coincides with the physical meaning in the studied supply chain.

(III) Period classification

The second preparation phase in order to carry out the mechanical analogy method for the studied problem, is concerned with period issues:

- Prepare all the data in all working/opening periods of the studied supply chain;
- Check if the company retains the same internal configurations among different periods during a business year;
- Check if the input data shows the same pattern during a year;
- Classify heterogeneous periods;

The opening periods of a company differ from supply department, manufacturing department and distribution department. For example, for a great part of holidays (e.g. Saturday) some manufacturing sites and warehouse centers do not continue to work, whilst stores in distribution echelon may keep open for clients. Therefore, the period information must be provided by distinguished input and output periods.

Moreover, in industrial world, a company intends to plan various promotions in periods to pre-stock for future occasions and to recruit temporary employees. As a result, the internal configuration in a company could not remain the same. So does the input data, which is rarely distributed in the same pattern over a year. And, if the company does not maintain regular activities during holidays, the results will be more different.

In this way, we suggest the researcher to lance an appropriate and complete period-classification table before flexibility evaluation, not only in use of analogical method, but also for other methods, because all changes of internal configuration will impact on flexibility evaluation methods and lead to different flexibility behaviors. The researcher is recommended to list and highlight all the unusual periods with time length by internal configuration changes, and also by different input data patterns, as what we have constructed by a weighting system in Fig. 3.7 and Tab. 3.1.

(IV) Object classification

Before the data computation and consecutive analysis, researcher is suggested to identify the studied objects by different criterion on which he intends to study and analyze, in order to assess the right flexibility, and make meaningful comparisons.

- Identify the studied objects;
- Group the studied objects by different criterion;

In the LV case, flexibility assessment is carried out for two study objects: *stores* and *products*. *Stores* can be concreted and distinguished as smaller groups by its sales volume, size, number of employees, independent status, etc., while *products* need to be classified and grouped by multiple criteria, such as sales volume, net profit, sex aimed by the product, sales stability, etc.

In order to conduct understandable results for industrial use, the classification of the studied objects by groups in appropriate criteria is of great value. With this classification, flexibility evaluation could be carried out by different groups of input and output data, leading to any indications relating to their intrinsic properties, which may be further linked with internal configurations in the company.

(V) Data computation

- Calculate the analogical damping factor;
- Analyze flexibility behaviors by object groups.

Data computation is the last and core phase of the mechanical analogy procedure.

Input data and output data of the studied supply chain are receptively entered to algorithm, waiting to be transformed to Transfer Function in the frequency domain. Afterwards, response of vibration system in the frequency spectrum are recorded, and damping factors reflecting system's flexibility are derived.

In adopting this procedure, the researcher can easily arrive at a comprehensive assessment on flexibility on studied objects by groups in periods, and draw conclusions by object characteristics. It is claimed that flexibility behavior is closely related to object property and company's internal configuration, thus, if the object properties of the studied problem are explicitly known, all flexibility behaviors can be consequently well reasoned. And if company operations to change the internal configuration in the past are known as well, various flexibility behaviors can be directly linked to its operations, and thus fully reasoned. Therefore, it is a good method to identify consequent flexibilities according to different strategic operations.

3.3 Conclusion

This chapter addresses supply chain flexibility from a quantitative point of view. We first review the existing evaluation methodologies on supply chain flexibility, and confirm that quantitative studies are now booming but still quite limited.

In order to clarify the methodology to integrate some precised flexibility dimensions, we have presented the method of Rogalski [Rog11] , which incorporates volume flexibility, product-mix flexibility and expansion flexibility respectively into the model, and can be expressed separately without interfering too much in details. Other measures and methods as Penalty of Change, Design of Systems for Manufacture, Mechanical Analogy, Simulation based on Petra nets, Toolbox Approach and methodologies involving flexibility considerations are reviewed.

Among these different methodologies, we consider *Mechanical Analogy* method quite useful and practical to evaluate the flexibility performance in supply chain. It does not require numerous data in detail or hard to collect, and is interested and appreciated by our industrial partners. As the method was rough and has never been applied to supply chain level, we start off to investigate its feature, assess its advantages and drawbacks, and establish a complete procedure to implement this method in supply chain. We discover that the period classification is inevitable because the system may take reconfigurations in different periods.

By exploiting this method, we conduct a case study in Louis Vuitton to evaluate the flexibility for stores and products in Japan. The results lead to the conclusion that flexibility of a small store is generally lower, and not as stable as the bigger stores during a year, whereas the products in bigger volume exhibit a general better flexibility throughout the whole year. These results coincide with the real situation of the firm. As a result, a general evaluation procedure to carry out this method in supply chain is detailed in this chapter.

Although the mechanical analogy concept could be exploited to calculate corresponding damping factor, in order to assess the flexibility of a supply chain system (a supply chain or part of supply chain), the detailed logic on how the analogy concept impacts the modeling of supply chain remains unclear. As described in sec. 3.2.1, a simple mechanical vibration system of a single degree of freedom, consists of a mass m, an elastic spring k and a damper c, including three main intrinsic attributes of a mechanical system: its inertia, damping and stiffness. It is of little difficulty to draw damping factor as the flexibility measure, but the attributes of inertia and stiffness are also important keys to understand the supply chain's behavior. We can see that the mass m of system could be calculated from 3.12, which make it possible to be deduced from the flexibility, but the relation of stiffness k and damping c is still hard to derive. This is a good research subject to be investigated in future researches.

4 Integrated production and transportation planning with given flexibility

Industrial planning problems arise in different circumstances, so does incorporated flexibilites. Planning problems are frequently encountered in each echelon of supply chain and influence directly or indirectly facilities' performance, while flexibility issues may occur in each stage of supply chain. It is known that two primary goals in both production and transportation planning are to satisfy the customer demands and to bring in the lowest cost. However, the problems synchronizing the production plan and the transportation plan with some detailed flexibility issues, have received little attention in the prior literature and applications in practice.

In this chapter we concentrate on how to exploit and to manager the flexibility in industrial planning problems. We propose to solve an integrated production and transportation planning problems with given flexibility considerations, with data provided by the water company Evian. To start off, we first present a short introduction to production planning and transportation planning literature respectively. Afterwards, literature on synchronized or integrated production and transportation planning problems is comprehensively reviewed in sec. 4.2, as a contribution of literature. In the following, we present an entire case study for the French mineral water company in sec. 4.3, with special consideration on given flexibilities. This integrated problem has been developed and solved in two cost-based combinatorial optimization models which are slightly different and respectively described in sec. 4.4 and sec. 4.5. The next sec. 4.6 concludes this part of thesis.

4.1 Introduction to industrial production and transportation planning problems

4.1.1 Production planning

To appropriately make use of limited resources in order to meet industrial goals, manufacturers have to make decisions on allocating resources and scheduling their activities over a planning horizon. Production and scheduling planning in a supply chain is viewed as the planning of the acquisition of different production resources and raw materials, as well as the planning of the production activities of staff to the ability to release accurate delivery times for the customer. It prepares a detailed plan in production process to achieve production goals economically.

Generally, production planning provides answers to three following major questions:

- What work should be done?
- How much time will be taken to perform the work?
- Which resources (site, machine, labor, ...) are needed to carry out the work?

Thus, solutions of production planning will decide the ways and means of production activities that affect several organizational echelons mainly grouped into three broad categories:

- Strategic level, involving capital investment, policy formulation, and location design of physical facilities in a long term
- Tactical level, dealing primarily with aggregate production planning in medium term
- Operational level, concerning detailed production scheduling issues in short time horizon

The three categories of production decisions differ largely in terms of level of management responsibility and its interaction, length of the planning horizon needed to assess their consequences, level of the required information and also the degree of uncertainties inherent in each decision.

An ideal hierarchical production structure is illustrated in Fig. 4.1, where the system operates and allocates resources and client orders in a centralized manner, separates several distinct planning areas defined into organizational units and coordinates them with a few controlled interfaces. It utilizes the natural time-structure of the planning process and requires the aggregation of data. Thus, a perfect hierarchical structure conveys production decisions fluently by decision level, decreases incidents and chaos in sub-problems and enables most important problems to be visible and traceable. However, an ideal hierarchical production planning is difficult to achieve due to enormous work on data aggregation and cooperation among departments, especially if the company did not design and implement such a framework in the first place.

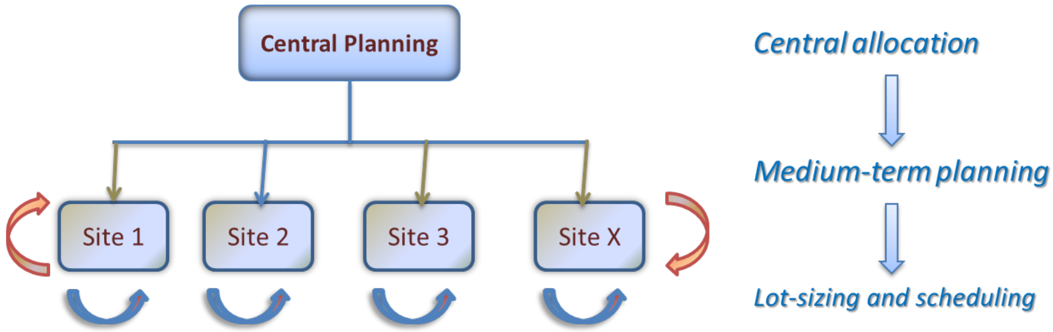

Figure 4.1: Hierarchical production structure

This structure interests the partners in our Chair Supply Chain. The steel tube production company Vallourec takes on a central planning department to allocate client orders to production sites, with some special quotas reserved for several sites, which is already a typical centralized and almost hierarchical production planning system. Furthermore, the company has tried to reorganize its existent distinct and disperse production planning process in different sites in order to convert into an ideal hierarchical structure. The company inclined to implement an uniform planning tool (APS - advanced planning and scheduling system) across the planning structure, but was confronted with the situation where each site utilizes its own tool or methods. Due to enormous information and complicated cooperation among departments, especially because the sites have accustomed to their own planning process from the beginning, the perfection and standardization of its hierarchical organization leads to a pretty high cost which would be not at all worthy. In this context, the company has finally abandoned its project on APS to reform and standardize its production structure.

In academic field, a lot of investigations have been done on production planning problems. When focusing on tactical and operational production plannings, we could say first studies in this field started with constant demand, continuous time and infinite horizon. If there is no obvious capacity constraints, the classical economic order quantity model is useful for a single-level production process [Har13, Wil34]. Furthermore, models with dynamic demand, discrete time and finite horizon, are generally referred to as dynamic lot sizing, seeking a minimum cost plan that meets all constraints over a finite horizon, which is often formulated into mixed integer programs (MIP).

In this context, the simplest form of dynamic lot sizing problem is called *single item lot sizing problem* (SILSP). Wagner and Whitin [WW58] describe a dynamic programming (DP) recursion for the uncapacitated SILSP, and then various versions of production planning problems have been investigated. Wagelmans et al. [WHK92, AP93] propose further algorithms to reduce the computational complexity in comparison with the initial Wagner-Whitin algorithm. Van Hoesel and Wagelmans [VHW01] provide a theoretical underpinning for fully polynomial approximation schemes for SILSP.

The senior level of SILSP is *multi item lot sizing problem* (MILSP), initially viewed as a multiple summation of SILSP. However, practically, multi-item problems are much more complex than the single-item counterparts, because the great quantity of items may bring in a larger number of variables, as well as the complex interrelation between these items, parts and machines, etc. In particular, even the general models involving inventory capacity of continuous SILSP are already proved to be NP-hard [Flo80, BY82]. With inventory capacity, some single-item problems are proved to be solved in polynomial time [CCZ+12, CCZY13, CC08, CC07]. Chen and Thizy [CT90] state clearly that multi-item capacitated lot-sizing problem (MCLSP) with setup times is strongly NP-hard. Consequently, efficient methods need to be explored and developed.

Generally, the objective function of a cost-based production optimization model for a manufacturing site in medium term with production, inventory and labor costs, can be formulated as below:

$$Min: Z = \sum_{t}\left(\sum_{i} q_{it}Q_{it} + \sum_{i,i\neq j}\sum_{j} st_{ijt}\cdot y_{ijt} + h_tH_t + l_tL_t\right) \tag{4.1}$$

where

- q_{it} represents the variable production / backorder / subcontracted / inventory quantity, of product i or product family i produced in period t in regular time / overtime, and Q_{it} is the corresponding cost;
- y_{ijt} the binary variable indicating whether a changeover is needed from product or product family i to j in period t, and st_{ijt} as its cost;
- h_t and l_t respectively the labor time of workers hired and laid off for period t ($person \cdot hour$) with their costs H_t and L_t.

In this simple form, the objective Z can minimize the sum several types of cost as regular production, overtime production, subcontracted production, inventory holding, backorder, production changeover and labor resource costs. y_{ijt} can only be the value 0 or 1. Therefore, this is a mixed integer problem (MIP) and difficult to solve in a small amount of time.

In order to solve the MIP problems efficiently, a variety of approaches have been investigated, from exact mathematical programming methods to heuristic approaches. Many exact mathematical methods attempt to strengthen the original formulation by adding valid inequalities [BVRW84, PW94] and by extending model reformulations [EM87, Wol02].

Since real-world problems are computationally difficult, different heuristic methods are proposed to tackle them. Among the different heuristics in the literature, we can generally classify them into simple heuristics and iterative ones. The simple heuristics are usually one-pass "constructive" (greedy) heuristics, which starts with no solution and tries to construct one in a step-by-step manner. The other iterative heuristics are usually so called "improvement" heuristics, starting with a feasible solution and trying to improve the current one in an iterative manner. This type of heuristics has been carried out mainly in two categories: meta-heuristics such as Genetic Algorithms [HK96], Tabu Search [GDS01] and Simulated Annealing [SKW93]; relaxation techniques that relax capacity constraints to decompose the initial problem into single-item uncapacitated subproblems.

Furthermore, problem-specific heuristics are proposed to solve individual problems. Maes and Wassenhove [MW88] provide an early review on problem-specific heuristics. Further Lagrangian-based decomposition is also developed [TD96] and Local Search method is frequently mentioned [SE05]. Among these heuristics, Tian et al. [TWK11] suggest an iterative approach to jointly optimize the tactical safety stock level and production planning. Apart from various problem-specific heuristics, the generalized MIP heuristics are comparatively few. Pochet and Wolsey [PW06] provide a general review of MIP heuristics, such as LP-and-fix and relax-and-fix. Allaoui and Artiba [AA06, AA14] study a hybrid flow shop scheduling with machines that are not always available due to stochastic breakdowns and preventive maintenance. They propose dynamic programming to solve two-machine flow shop, a branch and bound algorithm to solve the two-stage hybrid flow shop, and three heuristics for the worst-case performances.

In addition, for some models involving multiple objectives, one can associate a weight with each of these objectives to merge them into a single objective function. Different approaches are explored for multi-objective models with different working assumptions, such as, artificial neural network [McM01, GFG06, SV09], fuzzy simulation [MM08, JS09], genetic algorithm [CH05, SV09], problem-specific and random search heuristics [KNK12], etc.

4.1.2 Transportation planning

Transportation planning plays a linkage between each two steps of supply chain, taking all transport functions and sub-functions into a system of commodities movement. Companies are traditionally involved in different steps [FW81] such as production/manufacturing plants, storage, warehousing services, merchandising establishments, transportation, wholesaling, and retail sale. According to the 23rd annual CSCMP States of Logistics Report presented by Wilson [Wil12], transportation costs in 2011 in the USA represented 64% of the total logistics costs, inventory costs 33% and administrative costs 4%. Around one third to two thirds of the expenses of enterprises' logistics costs are spent on transportation, playing a vital role in the determination of product price.

Besides, costs of transportation vary from different industrial sectors [TYT+05]: for those products with small volume, low weight and high value, transportation cost accounts for only a tiny part of sale and is less regarded; for those products with big volume, heavy weight and mainly low unit value, transportation occupies a very big part of sale and affects profits more, and therefore it is more regarded.

The transportation problems discussed here mainly refer to distribution problems in a supply chain. On the downstream side of supply chain, distribution activity consists of transfer movements of multiple commodities from plants to demand markets directly or indirectly, the latter concerned with intermediate transshipment via some additional facilities such as warehouses or distribution centers (DC). Usually, storage volume may be planned for high value commodities whose market demand is difficult to forecast, while the other fast-moving items may be hold in inventory at the DCs to achieve a better responsiveness. These intermediate locations between plants and final customers facilitate the consolidation of shipments from different supply plants to meet the demand market through accumulated product inventories, in order to achieve lower transportation costs in a shorter response time. Two further tasks are usually performed at distribution centers and warehouses, namely *consolidation* and *split* (break-bulk) operations. Consolidation consists of combining shipments of similar or different delivery from several origins, while split goes the opposite side through which a large load from a given source is split into several smaller deliveries [TOG01].

The transportation problems also differ one from another according to decision level and planning horizon, and can be further classified in to strategic, tactical, operational problems in the literature. With increasing intermediate components added into the downstream side of supply chain, the transportation system is quickly extended to N-echelon network ($N \geq 2$) and the 2-echelon case is mostly studied. The N-echelon location routing problem and the inventory routing problem are the two well-known tactical distribution problems. In the operational planning phase, vehicle routes and schedules are periodically generated based on available resources, supplier and customer locations and product demands. Research attention have been mainly attracted on strategic and tactical planning, and most operational optimization approaches for N-echelon transportation system are extensions of methods for the classical vehicle routing problem. Economical savings by using N-echelon transportation network are also partly due to different sizes of vehicles at different levels. Haul trucks are assigned to move end products from factories to intermediate facilities and vehicles with lower capacity transfer loads between intermediate facilities and the final destinations. Distinct modes of transportation may vary from truck, air, rail, ships in the water, pipeline and the intermodal manner which combines various transportation modes in different steps.

Geoffrion and Graves [GG74] are the first to study the two-stage version of multi-commodity transportation problem, considering a *multi-plant, multi-commodity, multi-DC* structure. This is a MILP problem using Bender Decomposition procedure to get LP subproblems. To understand the N-echelon transportation problem, we could illustrate below a simple 2-echelon transportation routing network by a graph $G(I,A)$ in Fig.4.2. Generally, in the node set I at least three types of nodes are considered: (i) source nodes IS, such as manufacturing storage sites where vehicles only pick up finises items; (ii) intermediate nodes IM, like regional warehouses or distribution centers where vehicles turn to carry out pickup or delivery operations; (iii) destination nodes ID, such as consumer locations where vehicles come to accomplish their deliveries. In the arc set A, every arc $(i, j) \in A$ between the nodes is characterized by a distance-based or a time-based transportation cost c_{ij} and a journey time t_{ij} served by some vehicles V_i. It is assumed that the triangle inequality must be satisfied that $c_{ij} + c_{jk} \geqslant c_{ik}$, where $(i, j, k) \in I$.

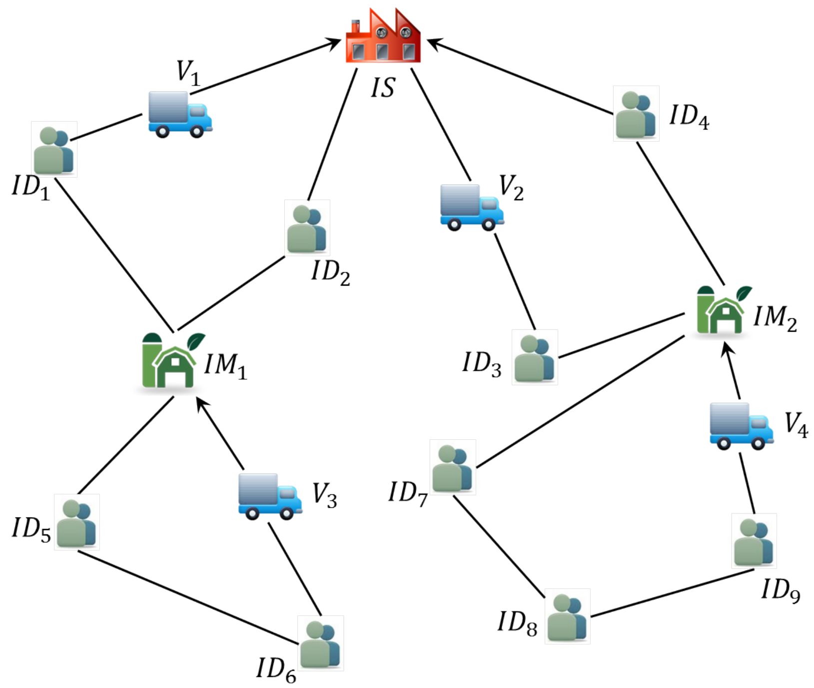

Figure 4.2: A two-echelon distribution network

Transportation operation is costly. It is frequently studied by two parts: fixed cost and variable cost. A basic assumption asserts that transportation cost is directly proportional to the number of product units transported [Dia91], thus, some studies consider a purely proportional quantity dependent distribution cost. Apart from this assumption, many practical transportation and distribution problems can be modeled as a fixed charge transportation problem [AK99, EEP06, AKVL07], in which there exist two kinds of cost: (i) a continuous variable cost that linearly increases with the quantity transported between a source and a destination, and (ii) a fixed charge, which may represent a cost of renting a railway train, landing fee at an airport or toll charges on a high way, incurs if a nonzero quantity is transported between a source and a destination. Hirsch and Dantzig [HD54] are among the first to explain and formulate the fixed charge transportation problem (FCTP), and Balinski [Bal61] proposes a heuristic method to solve this type of problem. A broad body of literature has started on this category and proposed solution techniques to solve the one-echelon FCTP [PKZ90, AADRR09], which is NP-hard if we solve it with exact algorithm [SAMD98]. Sun et al. [SAMD98] and Gen and Cheng [GC00] propose using metaheuristics such as tabu-search or genetic algorithms to solve the fixed charge transportation problem.

While solving the problem in exact algorithm is comparatively hard, the mathematical model construction is not complicated. A simple form of *multi-plant, multi-commodity, multi-DC, multi-customer* and *two-echelon* transportation problem at tactical level can be easily formulated together with a set of mutual constraints, see Annex I for details.

Researchers have attempted to solve multi-echelon transportation problems using exact algorithms and heuristics (e.g. [PJ98, THR00]). Syarif and Gen [SG03] describe a double spanning tree-based hybrid genetic algorithm with a chromosome for each echelon represented by Prüfer numbers. In combinatorial mathematics, the Prüfer numbers (also Prüfer code or Prüfer sequence) of a labeled tree is a unique sequence associated with the tree, which has length $n-2$ for a tree of n vertices and can be generated by a simple iterative algorithm [Prü18]. When taking the opening cost of a DC into consideration, Gen et al. [GAL06] propose a genetic algorithm using a priority-based encoding procedure to solve the two-stage transportation problem, with limited number of opened DCs. Such two-stage transportation problems are NP-hard [GAL06]. Jawahar and Balaji [JB09] present a genetic algorithm considering a chromosome to represent a candidate solution from DCs to customers and the other part of solution by applying the Least Cost Method (LCM), which makes use of a cost called equivalent cost, per-unit transportation cost and the fixed cost associated with a route. Later, Balaji and Jawahar [BJ10] develop a simulated annealing algorithm to solve the same problem, compared with the solution obtained by a LP using an approximate per-unit transportation cost, they provide a better solution. Antony Arokia Durai Raj and Rajendran [AADRR12] provide genetic algorithms to solve a two-echelon transportation problem with two different scenarios, where the first is similar to that of [GAL06] and the second considers the opening cost of a DC similar to [JB09]. They also present a methodology to represent the two-echelon transportation problem into a single-echelon fixed charge transportation problem and solve the resulting problem using their proposed genetic algorithm.

Besides the warehouses and DCs, another important type of intermediate stage is the *cross-dock* facility, also called *satellite platforms* or satellites. Consolidation and split operations are executed in this stage. Cross-docking consists of unloading materials from an incoming railroad car or truck and loading them directly into outbound trailers, trucks or rail cars, with little or no storage in between. This may be done to change types of conveyance, to sort commodities intended for different destinations and to dispatch them to destinations in outgoing vehicles without delay. It reduces inventory costs, storage space occupations and cycle time of the order, and accelerates the cash flow [CGM05]. Cross docking systems work well for industries with frozen foods [Boy10], refrigerated pharmaceutical products, perishable products in needs of preservation of quality and product freshness.

In N-echelon network problems, *vehicle routing* has mainly been treated in an implicit or simplified way, and studies on cross-docking with vehicle routing choices are relatively few. A closely related problem is the *vehicle routing problem with cross-docking* (VRPCD). The VRPCD considers the transportation of commodities from a set of suppliers (pickup nodes) to a set of customers (delivery nodes) via a single cross-dock without intermediate storage. Thus, the problem involves vehicle route design and consolidation at the cross-dock facilities. Lee et al. [LDCO06] are the first to study the VRPCD problem. They assume all the vehicles coming from suppliers reach the cross-dock simultaneously to avoid vehicle waiting time at the cross-dock. Since this integrated MILP is NP-hard, they develop a heuristic algorithm based on tabu search to solve the problem. Afterwards, Liao et al. [LLS10] provide a new tabu search algorithm for the VRPCD and solve it in less computation time.

Dondo et al. [DMC11] provide a mixed-integer linear programming (MILP) formulation for the N-echelon multi-item vehicle routing and scheduling problem with cross-docking and time windows (NE-VRPCD). They consider multiple commodities network where more than one item could be delivered via either direct shipping or intermediate facilities. Two or more vehicles can visit a given manufacturer site to carry out pickup and/or delivery operations, and the vehicle routes may perform several stops and multiple tours at the same site. Moreover, some customers can be pre-assigned with a given depot point. They formulate a MILP model and solve it through a branch-and-cut algorithm instead of using heuristic procedures. Ma et al. [MMLR11] introduces a two-stage approach, which treats first a reduced transportation problem for a full truckload plan and afterwards, solves the remaining less-than truckload problem iteratively by using a metaheuristic approach.

4.2 Review of integrated production and transportation problems

4.2.1 Introduction of integrated production and transportation problems

A typical supply chain starts from raw material input flow, followed by corresponding production to make finished items and deliveries to different distribution centers until reaching final customers. The cost of a product come up not only from factory resources to convert raw materials to end products but also from resources to deliver the product to customers, make corresponding sales, configure the inventory holding and services to customers. The composition of these operational term in total costs varies largely by industry, while the production cost is proved to be the largest part of all costs in almost all the industries [Che97]. Production and transportation operations can be easily decoupled if a sufficient amount of inventory is permitted between them. Many companies manage the two functions independently with little or no coordination without further consideration, which may lead to higher holding costs and longer lead times through the whole supply chain. The two activities are usually studied separately not only in the industrial field, but also in academic researches, mainly for reasons: $a)$ each problem itself is already difficult to solve, therefore the combined problem seems intractable and $b)$ different departments in an organization deal with each activity [EEP06].

On one hand, firms in the last decades have recognized that there would be a greater opportunity to manage supply chain in a coordinated manner than in improving individual function areas separately to save the cost. Nevertheless, reduced inventory may result in closer linkages between production and distribution functions. Production and distribution operations have often been considered as two separate operational functions in a supply chain. To achieve optimal operational performance in a supply chain, it is therefore suggested to integrate these two functions and plan them jointly in a synchronized way.

On the other hand, a synchronized production and transportation plan is one of fundamental needs to firms who provide mainly make-to-order products to the market or manufacture some kind of time-sensitive products (perishable and seasonal goods, etc.). As the number of companies continues to increase in changing themselves to make-to-order business models, such as assemble-to-order, build-to-order, design-to-order, direct-sell e-business models, the products become customer-made or must be delivered to customers within a very short lead time. In some practical cases, products should even be delivered directly from the factory site without any intermediate location transfer. A no-wait situation occurs in many real working environments, mainly because of limited storage capacity: if products cannot be all transported and delivered, the production quantity would have to decline. Thus, implementation of an effective transportation plan is also one of the most important factors to reach good performance of a supply chain. It leaves few or no finished item in inventory in their supply chain so that production and transportation activities are intimately linked to each other and must be scheduled and optimized in a synchronized manner, in order to reduce the costs and to achieve a desired delivery service. Consequently, the coordination of production and distribution operations becomes critical in order to maintain a high customer service level, and to speed up the cash flow by decreasing the inventory holding costs.

Chandra and Fisher [CF94] show empirically the value of integrating production and transportation decisions in an environment involving only a single production facility and multiple customers. Gains ranging from 3% to 20% are reported in this work by integrating the production lot sizing plan and the vehicle routing plan (local delivery routing problems) in a heuristic algorithm. This work has investigated the value of coordination between these two functions over a multi-period horizon in a single plant, multi-item, multi-retailer supply chain environment.

Chen and Vairaktarakis [CH05] and Chen and Pundoor [CP05] prove that adopting the optimal integrated production-distribution schedule can bring a significant benefit compared to the schedule generated by a traditional sequential approach in the models they consider. Integration of these two functions may lead to substantial saving in global costs. Thus, the basic idea behind this approach is to simultaneously optimize decision variables of different functions (e.g. purchasing, production, distribution, and storage) in the supply chain that have traditionally been optimized sequentially.

In this context, researches in this area has been mainly conducted and referred to as *Integrated Production-Distribution models*, *Aggregate Production-Distribution Planning* or *Coordinated Production-Transportation Planning*.

Normally, the strategic and tactical integrated production and transportation problems are investigated in order to evaluate a firm's expansion, contraction, facility relocation, plant capacity, transportation channels, associated production tasks and customer assignments to each facility. At the lower production level, short-term planning is carried out on a daily or weekly basis to determine the assignment of tasks to units and the sequencing of tasks in each unit, referred to as scheduling. In this detailed scheduling level, researches are mainly done in the last decade, attempting to optimize jointly the detailed production and delivery scheduling decisions by taking into account relevant revenues, costs, and customer service levels at a detailed individual order level [Che10].

Several surveys on such models appeared in the literature [OD98, Che10, BF12] and most of them are at the strategic and tactical planning levels [ESV06, GVD02, BO04]. Flexibility issues are also mentioned, but are often considered as a few given intervals or fuzzy constraints in the model construction.

4.2.2 General classification of integrated production and transportation planning problems

Consider a supply chain structure in multiple levels illustrated in Fig.4.3, where the inputs to various manufacturing plants consisting of raw materials can be sourced from a set of suppliers, and the output of finished items can be transported to different warehouses and distribution centers and then to different outlets or to final customers. In this structure, production facilities can be multi-leveled, and so do distribution ones. For a production-transportation problem in a supply chain, the integrated problem can occur at each linkage and each micro or macro bloc in this chain structure.

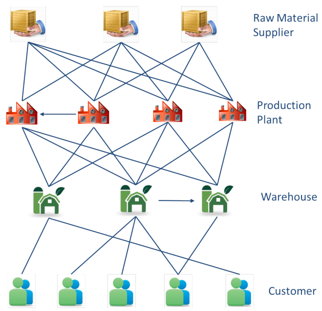

Figure 4.3: Multi-facility supply chain structure

A macro block problem in the structure Fig.4.3 is often referred to as a production-transportation, facility location-allocation problem. A great deal of study has been carried out to develop models and exact algorithms in this area, see [RL96, RE05] for a review. Here the term "*facility*" is expressed in its broadest sense, including entities such as factories, distribution centers, warehouses, retail outlets, computer terminals, schools, hospitals, day-care centers, etc. If each facility is limited to a certain capacity, the problem is then referred to as capacitated facility location problem. The single-source, capacitated facility location problem is the simplest form and is a special case of the capacitated facility location problem in which each customer can only be supplied from exactly one facility. The further extension of the location problem leads to multi-level or multi-echelon facility location problem. These are mainly strategic and tactical decisions: the former indicating facility location, capacity and network structure; the latter focusing on how much to ship in a time period, how much inventory to keep, how long a production/distribution cycle should be, etc.

A micro block problem in the structure Fig. 4.3 is related to explicit production-distribution problems in operational level, involving detailed scheduling level decisions such as: when and on which machine to process a job, when and by which vehicle to deliver a product, what the vehicle routing should be, etc. We can then classify the integrated production and transportation problems into three main categories:

- (A) Cross-facility, production-transportation, facility location-allocation problems across multiple stages of the supply chain
- (B) Explicit scheduling level, production-supplier problems integrating the inbound transportation and production
- (C) Explicit scheduling level, production-distribution problems integrating the outbound transportation and production

The problem class (A) and (C) are reviewed successively in the next sections.

The integrated production and inbound problems (B) are often aggregated as a material control subproblem in problems (A) and thus will not be widely reviewed in this work. We just make a short introduction for problems of class (B) here: an integrated production and inbound problem (B) treats problems of production and delivery of raw material from suppliers. A manufacturer purchases raw material from some suppliers, uses the raw material to manufacture finished products and ships them to customers. Thus, a (B) class problem contain mainly four components: (i) distribution cost for delivering raw material from the supplier to manufacturer plants; (ii) inventory cost for holding raw material at manufacturer side; (iii) production cost at manufacturer side; (iv) inventory cost for holding finished products at the manufacturer. Therefore, the (B) problems turn out to look for a joint cyclic ram material delivery and production schedule in an optimized manner. Works on (B) problems can be seen in papers [MT82, Hil97, Fre06, PVK06, EJSD14].

Apart from this rough classification (A-B-C), the integrated production-transportation problems differ one from another in function of their inherent parameters, which depict the problem structure and the algorithm complexity :

- Single/multiple periods (during infinite horizon with constant demand or finite horizon with dynamic demand)
- Single/multiple facilities (multiple manufacturing sites, warehouses, regional distribution centers,...)
- Single/multiple retailers
- Single/multiple levels (multi-echelon)
- Single/multiple commodities (products)
- Homogeneous/heterogeneous vehicles (trucks, trains, boats, planes, ...)

Tab. 4.1 shows study features of some main academic researches and their practical applications.

Literature	Suppliers	Facility	Retailer/ Customer	Level	Commodiy	Vehicule	Period	Application
Armstrong et al. [AGL08]		*	**	*	*	*	**	
Chandra and Fisher [CF94]		*	**	*	**	*	**	
Chen and Wang [CW97]	**	**	**	**	**	*	*	
Cohen and Lee [CL88b]	**	**	**	**	**	*	*	
Cohen and Lee [CL89]	**	**	**	**	**	*	*	PC manufacturer
Chen and Pundoor [CP06]		**	*	*	**	*	**	
Dhaenens-Flipo and Finke [DFF01]		**	**	**	**	*	**	Metal manufacturing
Dogan and Goetschalckx [DG99]	**	**	**	**	**	*	**	
Eksioglu et al. [EE06]		**	**	*	**	*	**	
Ertogral et al. [EWB98]		**	**	*	**	*	**	
Geoffrion and Graves [GG74]		**	**	**	**	*	*	Hunt-Wesson Foods
Jackson and Grossmann [JG03]		**	**	**	**	*	**	
Jayaraman and Pirkul [JP01]	**	**	**	**	**	*	*	Health-care products manufacturing in US
Jayaraman and Rose [JR03]		*	**	**	**	*	**	Chemical retailing of Walgreens in US
Koc et al. [KTS13]		*	**	*	**	**	**	
Lee and Kim [LK02]		**	**	**	**	*	**	
Ozdamar and Yazgac [OY99]		*	**	*	**	*	**	Production and distribution of liquid and powder detergents in Turkey
Park [Par05]		**	**	**	**	*	**	
Sabri and Beamon [SB00]	**	**	**	**	**	*	*	
Stecke and Zhao [SZ07]		*	**	*	*	**	**	PC production and distribution of Dell
Wu and Golbasi [WG05]	*	**	**	**	**	*	**	
You and Grossmann [YG07]	*	**	**	**	**	*	**	Polystyrene resins producer
Zuo et al. [ZKM91]		**	**	*	*	*	*	Seed corn production and distribution

*: single for Supplier, Facility, Retailer, Level, Commodity, Period; homogeneous for Vehicle
**: multiple for Supplier, Facility, Retailer, Level, Commodity, Period; heterogeneous for Vehicle

Table 4.1: Literature on integrated production-transportation problems

4.2.3 Models and Methods

4.2.3.1 Production-transportation, facility location-allocation problems (A)

In a multi-plant production structure with multiple product items, the adequate assignment of production orders to plants determines the production performance. Higher efficiency can be achieved through proper coordination of material, financial and information flows across the supply chain [Sta05, VRBP07]. Location-allocation decisions involve a substantial capital investment and result in long-term constraints on production and distribution process. A facility location-allocation problem (FLAP) not only seek the optimal locations of facilities, but also attempts to assign optimally facilities to customer zones in order to meet client demands. A simple *single-level, multi-facility and multi-customer model* is presented by [RS70], see

Therefore, a simple *single-level, multi-facility and multi-customer model* of $[PF1]$ is as follows [RS70]:

$$[PF1] \qquad Minimize\, Z = \sum_i \sum_j c_{ij} y_{ij} \tag{4.2}$$

subject to:

$$\sum_j z_j = P \tag{4.3}$$

$$\sum_j y_{ij} = 1 \qquad \forall i \in I \tag{4.4}$$

$$z_j \geq y_{ij} \qquad \forall i \in I,\ \forall j \in J \tag{4.5}$$

$$z_j = \begin{cases} 1 & \text{if candidate node } j \text{ includes a facility} \\ 0 & \text{otherwise} \end{cases} \qquad \forall j \tag{4.6}$$

$$y_{ij} = \begin{cases} 1 & \text{if candidate node } j \text{ provides service} \\ & \text{to demand node } i \\ 0 & \text{otherwise} \end{cases} \qquad \forall i \in I, \forall j \in J \tag{4.7}$$

This problem minimizes the total costs incurred by the allocation of clients to facilities, where I is the set of demand nodes, J is the set of candidate locations where facilities may be sited and c_{ij} denotes the cost of assigning customer i to facility j. Relation (4.3) ensures that exactly P facilities can be opened. Relation (4.4) certifies that each node is assigned and (4.5) ensures that only opened facilities are allowed to be assigned to demand nodes. Relation (4.6) and (4.7) are sets of binary variables.

Badri [Bad99] propose to adopt Analytic Hierarchy Process and multi-objective goal-programming methodology as aids in making location-allocation decisions, and has applied to a real life problem. Capacitated location-allocation problems under limited capacity of facility, cost, time are further developed and multi-commodity situation can be taken into account. One can refer to [Sul01, MNSdG09, BF12] for more information.

For a great part of problems (A), the production-transportation location-allocation network can be viewed as four regions in general: supplier, primary manufacturing, further finishing facility and customer zones [DG99, GVD02]. For a two-echelon facility location problem, deliveries are made from first-echelon facilities (e.g. plants, warehouses) to second-echelon facilities (e.g. warehouses, distribution centers) and to final customers, shown in Fig.4.4. It is commonly referred to as the capacitated plant location problem [THR00].

For a typical production-transportation, facility location-allocation problem across multiple stages of the supply chain, decision variables and parameters in different echelons must be taken into account. Consider a simple multi-supplier, multi-plant, multi-level, multi-commodity, single-period and homogeneous vehicle problem, on condition that a warehouse serves only one customer zone, noted as [*PF2*], the problem can be easily formulated as a cost-based minimization model. Mathematical description for problem [*PF2*] is relatively longer than the problem [*PF1*], see Annex II for details.

The problem formulation [*PF2*] in Annex II can be further extended to multi-period model with inventory flow conservations backlogged or not, between any two adjacent periods. For example, the warehouse assignment constraints can be quickly modified in order to serve more customer outlets. For the sake of taking heterogeneous vehicles into account, we make modifications on unit transportation and purchasing cost, noted as ts_{skr} , with index from supplier s to plant k for raw material r. This cost can be further splitted into

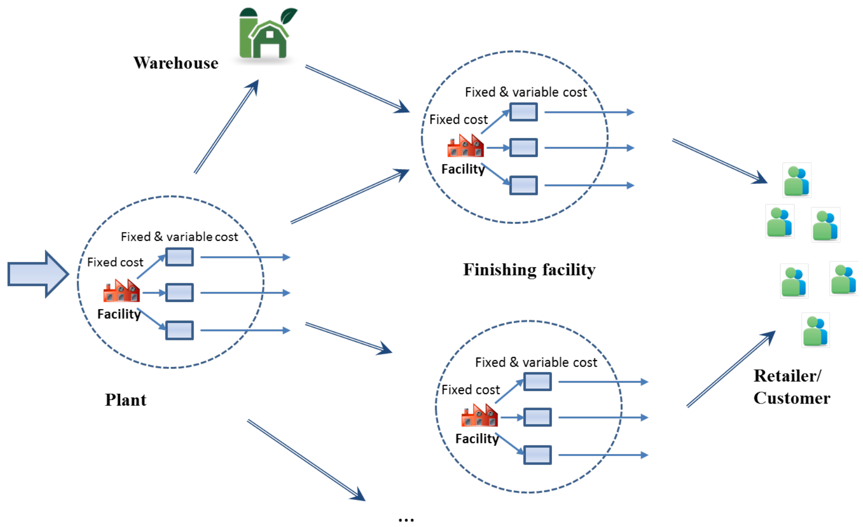

Figure 4.4: Overview of two-stage production-transportation network [DG99]

multiple costs ts_{skrv} with heterogeneous vehicles $v = 1, 2, ..., V$, if the costs are vehicle-independent. Meanwhile, we designate the unit transportation cost by tw_{ijkl}, with index for product l from plant k via warehouse j to customer zone i, which can be transformed in the same way: tw_{ijklv} with independent vehicle modes $v = 1, 2, ..., V$. On condition that vehicle utilization cost is dependent one to another, ts_{skr} and tw_{ijkl} are forced to be functions of the existing vehicle modes $ts_{skr} = ts_{skr}(v_1, v_2, ..., v_V)$ and $tw_{ijkl} = tw_{ijkl}(v_1, v_2, ..., v_V)$. And, the vehicle velocity, volume and loading limits can be also studied for a more detailed formulation.

To solve the [*PF2*] problem, the use of conventional mixed-integer linear programming tools is limited due to a large amount of decision variables and constraints, and also the complexity of the problem structure. A simplified [*PF2*] without supplier connection considerations can be reduced to a capacitated location problem, which is already NP-complete [GJ79]. It is unlikely to adopt a standard mathematical programming package to look for an optimal solution in a reasonable amount of time. Heuristic seems a common choice to solve the problem. Since there are no obvious heuristic procedure that can be adapted to all models according to each situation in the problem itself, efficient solution procedures still need to be developed.

Geoffrion and Graves [GG74] are among the first to solve a problem similar to [*PF2*] that is characterized by multi-commodity, capacitated multi-plant and multi-warehouse, product flow and customer assignments. They use Bender Decomposition to obtain a set of linear programming subproblems and decompose it into several independent transportation problems. Fixed cost for plant possession and operation cost are not considered in this paper. Lee [Lee93] also expresses some inherent disadvantages in conventional techniques: Bender Decomposition methods exploit only the primal structure of the problem and Branch and Bound techniques require considerable amount of time.

Chen and Wang [CW97] study a three-stage (*multi-supplier, multi-plant and multi-customer*) problem with deterministic demands for products, linear raw material purchasing cost and linear transportation cost. Its production cost consists of a fixed part and a variable part, the latter depending on the production amount. The problem is formulated as an LP and solved using an LP software package. Cohen and Lee [CL88] gives also an early review concerning similar supplier-plant-retailer structure.

Lee and Kim [LK02] study a *multi-plant, multi-item, multi-retailer and multi-period* problem in developing a hybrid analytic-simulation procedure. The model is formulated as a linear program minimizing the overall costs of production, distribution, inventory holding and shortage costs, subject to operation time constraints. Operation time in an analytic model may not represent correctly the dynamic behavior of the real operation time, it is then considered as a stochastic factor and adjusted by the results from independently developed simulation model, which includes general production-transportation characteristics. The simulation model is developed by using the simulation tool ARENA.

Park [Par05] discusses a *multi-plant, multi-item and multi-period* environment and solves the mixed integer problem by a heuristic method consisting of two phases: a tentative integrated plan in the 1st phase and improvement phase by consolidating small deliveries into full truckload shipments in earlier periods, reducing the stockouts at retail outlets, etc. [EEP06] study an integrated production and transportation planning problem in a *multi-facility, multi-commodity, multi-period and two-stage supply chain* with fixed charge costs. No production or transportation capacity constraints are imposed and a primal-dual based heuristic that generates upper and lower bounds and runs in polynomial time is applied. The quality of the upper and lower bounds is tested on a large set of randomly generated problems.

You and Grossmann [YG07] propose a mixed-integer *non-linear programmin*g (MINLP) to consider simultaneously the economics and responsiveness of *multi-plant, multi-echelon, multi-period* process supply chain networks. The problem is formulated as a bi-criterion optimization in which the objectives are to maximize the net present value (NPV) and to minimize the lead time. An ε-constraint method has been adapted to produce a Pareto-optimal curve, establishing trade-offs between NPV and lead time. Jackson and Grossmann [JG03] describe a multi-period *nonlinear programmin*g model for multi-commodity multi-plant case where each production plant is represented through nonlinear process models. Based on Lagrangian decomposition, spatial and temporal decomposition schemes are proposed to enhance computational performance and tighter bounds to the optimal solutions.

The *Lagrangian relaxation* scheme has been successfully applied in various planning problems and provides good bounds to the original problems [Fis04]. The work of [JP01] exploits heuristics that uses the solution generated from the Lagrangian relaxation subproblems to solve a multi-supplier, multi-plant, multi-level, multi-commodity of [*PF2*] problem. Zhu et al. [ZCS10] propose a heuristic solution procedure based on Lagrangian relaxation, to solve a problem called the capacitated plant location problem with customer and supplier matching (CLCSM). The paper merges a distribution trip and a supply trip into one triangular trip for saving allocation cost, and vehicles from plants visit a customer and a supplier for each trip.

Other methods are investigated by researchers as well. Jayaraman and Ross [JR03] suggest a simulated annealing methodology to design a production and distribution system characterized by a *central plant, multiple product families, multi-retailer and multiple cross-docking* sites for the chemical retailing operations of Walgreens in US. Vidal and Goetschalckx [VG00] incorporate uncertainty considerations into a mixed integer linear program with some specific *stochastic* constraints, such as supplier reliability and on-time performance. Dhaenens-Flipo and Finke [DFF01] model a *multi-plant, multi-warehouse, multi-item, multi-period* production and distribution problem in the form of a network flow problem with relatively few additional 0-1 variables describing the linking constraints between periods. The model is formulated as a MIP, solved using CPLEX and applied successfully to a metal industrial problem.

4.2.3.2 Integrated production and outbound distribution scheduling problems (C)

The problem class (C) of integrated production and transportation planning problems steps into the explicit scheduling level, studying on production-distribution problems integrating the outbound transportation and production, that means the production echelon plus the downstream distribution echelon.

To interpret this problem, we first take a glance at a simple example. Consider m production plants coded with i, n customers coded with j, and the single product is produced in quantity x_i and shipped in quantity y_{ij} to customers with a concave production cost $f(x_1, x_2, ..., x_m)$ to meet demands d_i but limited by production capacity s_i, an objective function to minimize the production and transportation-distribution cost could be formulated as below:

$$[PF3] \qquad Minimize\, Z = f(x_1, x_2, ..., x_m) + \sum_i \sum_j c_{ij} y_{ij} \tag{4.8}$$

subject to:

$$\sum_j y_{ij} = x_i \qquad \forall i \tag{4.9}$$

$$\sum_i y_{ij} = d_j \qquad \forall j \tag{4.10}$$

$$x_i \leq s_i \qquad \forall i \tag{4.11}$$

$$x_i, y_{ij} \geq 0 \qquad \forall i, \forall j \tag{4.12}$$

This is a concave minimization problem and constraints (4.9), (4.10) and (4.11) are linear supply and demand constraints similar to those in the classical transportation problem.

The majority of studies in this field are concerned with a separable concave production cost function and assume that the demands are deterministic. Kuno and Utsunomiya [KU96] consider a function $f(x_1, x_2, ..., x_m) = g_1(x_1) + g_2(x_2) + ... + g_m(x_m)$ with concave sub-functions g_1, g_2, ..., g_m and proposed a Lagrangian based branch and bound algorithm and worked on a different structure with which there is a head production plant which can deliver goods to all customer zones. Hochbaum and Hong [HH96] propose a polynomial time algorithm and show that the problem [$PF3$] is NP-hard even if the concave production cost function $f(x_1, x_2, ..., x_m)$ is separable, symmetric and even if all the elements in the transportation cost matrix are set to a constant. Youssef and Mahmoud [YM96] consider a special separable function $f(x_1, x_2, ..., x_m) = \sum_{i=1}^{m} a_i x_i^{b_i}$ for the *[PF3]* problem where $b_i \in (0, 1)$ and provide an iterative procedure, based on a non-linear programming model of the transportation problem under production economies of scale, in order to solve the uncapacitated production and distribution problem under concave cost function in a centralized way. A more general structure than [$PF3$] with $m-2$ warehouses and 2 production plants is presented in [KU97], in which a pseudo-polynomial time primal-dual algorithm is suggested. However, no production and no warehousing cost has been considered in that work.

Apart from these deterministic demand researches, Pyke and Cohen [PC94] develop a Markov-chain model to solve the integrated production-distribution system, consisting of a single plant, a stockpile of finished item and a single retailer. Holmberg and Tuy [HT99] propose a stochastic demand problem where a convex penalty must be paid for each unmet demand. This paper provides a branch and bound algorithm capable of solving problems with 100 plants and 500 customers.

However, different from the conventional cost-based optimization measures, most production and outbound distribution scheduling problems emphasizes the time-based and revenue-based measures as well. A comprehensive review of existing integrated production and outbound distribution scheduling problems is provided by [Che10]. These measures and additional related parameters are listed in the next page as follows:

Time-based objective measures	
D_{max} = maximum delivery time of orders, i.e. $max\{D_j \mid j \in N\}$	
$\sum_j D_j$	total delivery time of orders, i.e. $D_1 + D_2 + ... + D_n$
$\sum_j (w_j) D_j$	total (weighted) delivery time of orders, i.e. $D_1 + D_2 + ... + D_n$ (or $w_1 D_1 + w_2 D_2 + ... + w_n D_n$)
L_{max} = maximum delivery Lateness of orders, i.e. $max\{L_j \mid j \in N\}$	
$\sum_j (w_j) T_j$	total (weighted) delivery tardiness of orders, i.e.
$\sum_j (w_j) O_j$	(weighted) number of late orders, i.e.
$\sum_j (w_j) E_j$	total (weighted) delivery earliness of orders, i.e.
Time-related parameters	
r_j	release date when the order j arrives and is ready for processing
d_j	delivery due date for the order j to its customer, possibly violated with a penalty
fd_j	fixed delivery time at which the order must be delivered to its customer
$\widehat{d_j}$	deadline before or at which the order must be delivered to its customer
$\left[\underline{d_j}, \overline{d_j}\right]$	delivery time window within which the order j should be delivered, possibly violated with a penalty
Cost/Revenue-based objective measures	
$\sum_j R_j$	total revenue of the orders processed and delivered
$\sum_j CP_j$	total production cost of orders
$\sum_m CT_m$	total transportation cost of all incurred individual delivery trips
$\sum_k CV_k$	total transportation cost of vehicle utilization
Revenue-related parameters	
R_j	revenue of order j if it is successfully processed and delivered to its customer at a desired time, e.g. before or at the deadline $\widehat{d_j}$, within the time window $\left[\underline{d_j}, \overline{d_j}\right]$),
P_j	penalty cost of the unmet order j if a penalty is imposed to order system

Table 4.2: Objective measures and related parameters for integrated production and transportation planning problems of class (C)

In the scheduling level, existing models in the literature could be further distinguished by their different delivery modes [Che10], and we classify the model with fixed delivery departure method as the 6th mode, listed as below:

- (C.a) Individual and immediate delivery
- (C.b) Batch delivery to a single customer by direct shipping method
- (C.c) Batch delivery to multiple customers by direct shipping method
- (C.d) Batch delivery to multiple customers by routing method
- (C.e) Batch delivery with split delivery method
- (C.f) Fixed delivery departure dates

For models with (C.a) individual and immediate delivery mode, orders need to be delivered individually and immediately after its completion. First studies on individual and immediate delivery methods are mostly inspired by [Pot80], in which a modified Schrage's heuristic algorithm [Sch70] is developed to solve a sequencing problem with n jobs on one single machine and no delivery time window. Woeginger [Woe94] studies a more general version of the problem where there are a set of parallel machines in the plant and gives some heuristics with constant worst-case error bound guarantee. Liu and Cheng [LC02] consider a single-machine scheduling problem with job release dates, delivery times, preemption penalties and job-dependent setup. The paper proves that the problem is strongly NP-hard and presents a dynamic programming algorithm and a polynomial time approximation scheme. Studies of [GH02, WL05] adopt both the branch-and-bound exact algorithm to solve the problem. These mentioned works all concern individual and immediate delivery problems without time windows. In some problems, a delivery window is imposed in the way that each order j has a fixed delivery time fd_j or a delivery time window $\left[\underline{d_j}, \overline{d_j}\right]$. With this delivery time window, Garcia and Lozano [GLC04] propose an exponential-time network based exact algorithm to solve a problem with several parallel machines at each plant. They also propose a tabu-search based heuristic to solve the problem.

For models with (C.b) batch delivery to a single customer by direct shipping method, orders come from a single customer zone and each delivery takes the same shipment route - from the plant to the customer and goes back. Therefore, each shipment takes the same delivery route and incurs a same transportation trip time and cost. Chen [Che96] studies a case where a single machine, a common due date shared by all jobs and to minimize the total weighted earliness and tardiness of jobs and total delivery cost. He considers jobs with identical weight respectively on their earliness and tardiness, and provides a polynomial time dynamic programming algorithm. Sched [Sch01] investigates various problems with a combination of several parameters or conditions: (i) the plant has a single manufacturing machine, a set of parallel machines, or flow-shop; (ii) the number of vehicles is limited; (iii) each vehicle can process one or more jobs; (iv) the objective is to minimize either the time when all the delivery jobs are completed (makespan), or the total delivery time of jobs. Many problems are shown to be NP-hard and are commonly solved with different heuristic approaches, e.g. the problem of [CP06] with a sufficient number of vehicles, that of [WC07] with a limited number of vehicles. Some others are shown to be solvable in polynomial or pseudo-polynomial time by dynamic programming algorithms, e.g. the problem of [HP03] with an unlimited number of vehicles and that of [HP05] with a limited number of vehicles. The literature mentioned previously in this paragraph treats the delivered batch in equal size, and quite few papers study problems with generally different batch sizes [CL04, ZDT07].

Unlike models in (C.b) where each shipment can deliver orders only to one customer, for problems in the multi-customer category (C.c), different shipments may have different transportation routes and costs. This is a more general case than the (C.b) class. Hall et al. [HLP01] study integrated production-transportation scheduling problems with batch delivery in an arborescent supply chain where a supplier makes deliveries to several manufacturers, and manufacturers also make deliveries to customers. Hall and Potts [HP03] solve a (C.c) problem with sufficient vehicles and equal batch size in polynomial time and Li et al. [LVL05] study a one customer subproblem with limited number of vehicles.

Little literature reviewed so far considers vehicle routing decisions. For (C.d) category of batch delivery to multiple customers by routing method, only a handful of papers discuss (C) problems involving routing methods. In this category, a shipment is allowed to visit multiple customer zones and it is necessary to determine the route for each shipment. A routing problem contains already the strongly NP-hard traveling salesman problem (TSP) [Kap72] as a subproblem, consequently, (C.d) problems are intractable in many cases.

For problems in the category (C.d), Hurter and Van Buer [HVB96, VBWO99] consider a joint production and distribution scheduling problem in a newspaper industry. In this case, different newspapers are quickly printed in a plant facility during night and then immediately delivered to drop off point waiting for delivery carriers to pick them up in the every early morning. A setup time must be paid between prints of different types of newspapers. Demand at each drop off points for different newspapers are known and a delivery deadline $\widehat{d}_j$ is given, e.g. 6:30 AM the next morning. The objective is to find a production (printing) schedule and a delivery route for each delivery van involved and the amount of different type of newspaper to be carried by each delivery van in order to minimize the number of used vans. Under the assumption that each delivery van can only be used once, Hurter et al. [HVB96] propose an iterative heuristic to determine the number of vans and routings, then based on the routing decisions look for a production schedule. Under the assumption that each delivery van can be used repeatedly. Further, Van et al. [VBWO99] suggest a local search based heuristics to solve the problem. Li et al. [LVL05] provide a dynamic programming algorithm with deliveries to multiple customer locations. Armstrong et al. [AGL08] consider a simple problem where all the orders are processed on a single machine and delivered in a single shipment in a prespecified sequence and each order must be delivered within an individual time window $\left[\underline{d_j}, \overline{d_j}\right]$. The objective is to determine a subset of orders to be delivered so that the total demand of the delivered orders is maximized. The authors show that their problem is at least ordinarily NP-hard, and give a branch-and-bound exact algorithm and a heuristic.

Problems in (C.e) batch delivery with split delivery are less explored in existing literature. The study field is, to some extent, superposed to other five classes. Different from the "consolidation" indicating whether different orders can be bundled and shipped together in the same vehicle, "split" indicates whether an order is allowed to be split and then delivered in multiple batches. Thus, splitting refers to delivering the portions of an order at multiple points in time and may lead to reduced inventory, improvement on service levels and mitigating the loss or damage during loading and unloading operations. Contrarily, customers may want their orders to be delivered as a whole rather than split, reported by Chen and Pundoor [CP06]. Stecke and Zhao [SZ07] consider a problem in a make-to-order computer manufacturer Dell with two cases : (i) splittable delivery; (ii) non splittable delivery. The authors show that with split mode the problem becomes a cost minimization flow problem and is polynomially solvable. With a non-split delivery policy, the problem becomes strongly NP-hard and a heuristic is chosen to solve it. Koc et al. [KTS13] examine a manufacturer's integrated planning problem with three considerations: (i) consolidation; (ii) split; (iii) size of orders in terms of vehicle/container capacities such as full truck load or general load delivery; (iv) heterogeneous vehicles where vehicle type I is available in unlimited number in all periods and vehicle type II only available at certain period t. The authors propose a dynamic programming running in pseudo-polynomial time.

For the last category, models with (C.f) fixed delivery departure dates are investigated by a few papers [WL05, LGS05, LGS06, SZ07]. In this situation, the delivery departure time of each order is no more a part of decision, but a part of input data. Wang and Liang [WBJS05] study a coordinated mail processing and distribution scheduling problem at a mail processing and distribution center with heterogeneous vehicles. The objective is to minimize the total un-used truck capacity. Some dispatching rules are proposed and the problem is solved by heuristics. Stecke and Zhao [SZ07] consider also the problem of a make-to-order situation where each order is limited with a delivery time deadline. Heterogeneous vehicles are taken into account with a decreasing shipping time and a linear function of order size. In their problem, a number of delivery modes exists but vehicles have fixed departure dates.

4.2.4 Further prospects

We have reviewed existing models on integrated production and transportation problems by three macro categories (A-B-C), and six sub class for the third class (C) of integrated production and outbound distribution scheduling problems. These classes of the literature address various practical situations in the production-transportation area and provide useful problem-solving methods. The majority of the work was done in the last decades, indicating a growing interest in this study field.

Besides, much more research is needed for further studies and for some relatively new areas:

- *Problems with heterogeneous vehicles.* Only a handful of papers [WL05, SZ07, KTS13] consider heterogeneous vehicle issues in their work, while the heterogeneous vehicle delivery mode occurs in many applications and deserves more research attention. Different kinds of vehicle may have the same or different capacity with different delivery speeds and costs, and many package delivery services offered by third party logistics (3PL) may provide overnight, one-day, two-day delivery with different costs. The problems with heterogeneous vehicle are worth more research attentions because of its practical relevance.
- *Problems with stochastic demand.* Most existing results consider deterministic models where product demand is known in advance to satisfy with or without backlogging. However, many products in practice does not figure in this field. For products having a large variety with short life cycle, the customer demand is of high uncertainty and difficult to predict. In this case, stochastic demand or with a certain distribution may be more realistic to reflect the industrial world.
- *Problems with non-linear costs.* Most production-transportation problems reviewed in this section involve linear transportation costs, which may be unrealistic in industry. The transportation cost is normally nonlinear in practice (e.g. fixed charge plus variable nonlinear charge). Thus, problems with non-linear costs are well worthy of further investigations.
- *Value of coordination.* The coordination between production and transportation is important but has a cost. Quite few papers [CF94, FV99] have studied the value of coordination between production and distribution phases. If one can quantify theoretically the value of coordination for some general models, we can decide whether it is worthwhile to optimize production and transportation jointly, and if yes, to which extent they can be coordinated.
- *Integrated scheduling problems with routing decisions.* In our review, this class of problems is referred to as problem class (C.d) “batch delivery to multiple customers by routing method” and is difficult to solve. Most reviewed studies involve unlimited number of homogenous vehicles, and it would be worthwhile to provide studies with multiple and number-limited vehicles. Furthermore, many companies practice JIT manufacturing policy and require frequent delivery of small quantities. With multiple customers locating in different zones, it would be necessary to consolidate

orders of some customers to save transportation cost. Therefore, it is worthwhile to consider routing methods involving different destinations across multiple transportation stops. To solve such problems, it is important to exploit problem structure to reduce the algorithm complexity. Fast and robust solution algorithms need to be developed for large scale problems.

4.3 Problem description for Evian

We propose models and algorithms to solve the integrated production and transportation planning problem, with a particularity of incorporating several given flexibilities. In the literature mentioned above, few literature incorporates the flexibility consideration directly into the model. But nowadays, it is important for firms to arrange their industrial activities to achieve the final commercial goal, also commonly under some certain flexibility tolerances, which may be contracted with supply chain partners or stemmed from their internal decisions. For this, we put our eyes here inside a case study with the French mineral water company, Evian.

Evian is owned by Danone Group, a French multinational company. The brand Evian is that of luxury mineral water coming from several sources near Evian-les-Bains of department Haute-Savoie, on the south shore of Lake Geneva. Evian water is the most sold in France, UK, Belgium, Switzerland, well placed as imported water in the United States and especially in Japan.

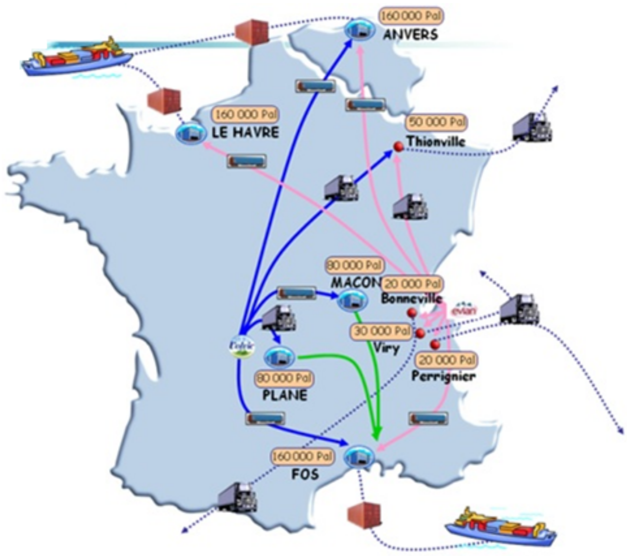

Figure 4.5: Warehouses in Evian problem

In Evian itself, the manufacturing activity studied in this work starts from producing bottle pre-forms, then blowing them in various formats, bottling water and getting packages finished in several production lines until completing the palletization. This can be totally regarded as a continuous production activity, while the stock keeping unit (SKU) is defined as a combination of bottle format and market zone. Stock is held by various warehouses (most warehouses are near ports) and no stock on-site, as shown in Fig. 4.5.

Therefore, finished goods must be rapidly transferred by trains or trucks to warehouses after production (so called “deployment”), waiting to be dispatched to corresponding regions. In Evian case, there are 14 production lines, 9 warehouse destinations and about 420 SKU. The flexibility problem also lies in transportation activity with trains and trucks, because trains must be reserved 3 months before departure according to contracts with train operators. Any exceeding or cancellations may generate a prohibitive cost. Besides, available trucks are also limited. Thus, we are quite aware of heterogeneous vehicles used in our problem. This transportation deployment is shown in Fig. 4.6.

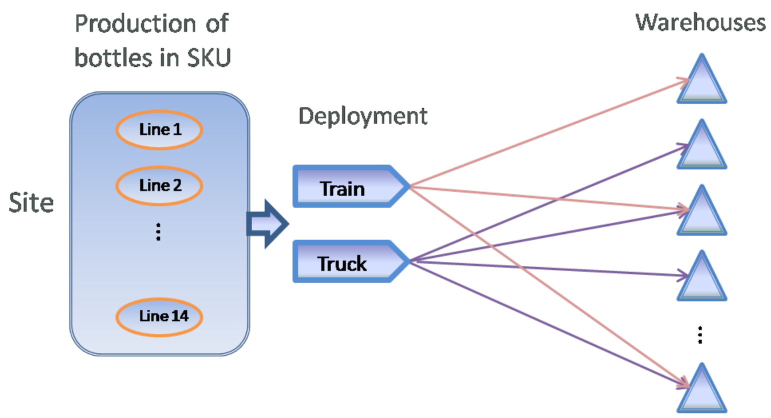

Figure 4.6: Production and transportation activity in the mineral water company

The close linkage between production and transportation, and the deployment of products by two transportation modes lead to a great need of possible modifications in production planning to meet the transportation constraints. Indeed, some fluctuation is possible for the train reservation, but only a small scale of flexibility is allowed. Though train transportation does manifest this or that disadvantage, the advantages are clear and strong. First, cost of railway transportation is relatively low compared with truck prices, particularly if a railway track is already built up between two locations. Secondly, the final products of Evian are bottled water in different formats, which are still heavy and must be delivered in a large amount. Thus, a truck may leave the production site with only one third of its volume filled up, for the reason that its weight reaches the maximum allowance of highway. Thirdly, train is a mode of transportation with less emission of CO_2, therefore, cleaner and greener than other freight transportation modes. This is very important, because Evian prefer to show that its water production is clean and green and does not lead to too much pollution to the environment. Fourthly, all the train wagons waiting on the railway track can serve as storage area, store bottled water and ship them away directly. Therefore, in the Evian case, we appreciate and put priority to train transportation.

In this problem, two goals are expected by the company manager to be simultaneously achieved:

- Bring inventory level for each SKU over all warehouses to their target interval, in order words, as close as possible to an interval [stock Target ~ stock Max]
- Coordinate production plan and transportation plan as close as possible and give priority to train transport, which indicates that the fill rate of train wagons may be efficiently maximized

To achieve both main goals, we propose a cost-based model to include the minimization of inventory penalty, which is different from inventory holding cost. This penalty is the additional cost for each SKU for any deviation from the stock target, with a cost structure illustrated in Fig. 4.7. C_-, C_0 and C_+ in the figure are linear penalty coefficients to be set respectively for the inventory level under target value, in the interval of target-maximum or beyond the maximum value. In this way, the cost structure aims at penalizing heavily the deviation from the flexible target interval and slightly the inventory holding above the target minimum value.

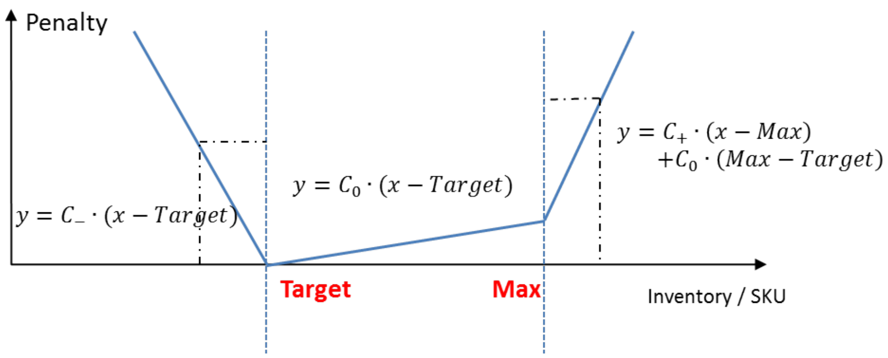

Figure 4.7: Penalty curve for the inventory policy

Among all production lines, some are capable of producing more than one SKU or several families of SKUs. Therefore, changeover is allowed but requires quite a long time to switch between SKUs. Except for some special SKUs, changeover (setup) cost must be paid for each batch if a changeover occurs between different families. Only the setup cost and time among SKUs within a same family could be considered to be negligible.

So the objective of this study is to provide a production and transportation plan in details, respectively described as follows:

Production plan

- Quantity of SKU to produce on production line k in period t

- Changeovers between SKUs on production line k in period t

Transportation Plan

- Number of trains used in direction of warehouse l in period t
- Number of trucks to direction of warehouse l in each period t

This study concentrates on medium/short-term planning, but does not work on scheduling details. That means, changeovers for SKUs i, j at a time period needs to be determined and specified but will not be determined in a detailed time period and in a determined sequence in our solution. This work consider that all data are deterministic. Other assumptions for the studied problem are listed as below:

1. Forecast (demand) is assumed to be accurate and deterministic for each planning period consisting of demands per SKU
2. Production capacity for each production line of the plant is a deterministic value in each planning period
3. Inventory level taken into account in the model of product i is the summation of inventory over all warehouses for each SKU i
4. Unmet demand is backordered with a penalty and the inventory level turns negative
5. Products in transit (in transportation) is counted for inventory level
6. Initial inventory at t_0 is set to the minimum target value
7. Each SKU can only be packed and transported in proper pallet, coded with the same index
8. There may be more than one changeover between SKUs for each production line k in a period
9. Changeover from each specific SKU i to another specific SKU j on specific line k can only occur once in each period, which is consistent with the real situation of the company

Particularly, flexibility considerations in this problem could be listed as below:

1. Inventory target interval is flexible [*stock Target* ~ *stock Max*] with a certain variable cost
2. Transport allocation of SKUs among warehouses has certain flexibility
3. Various pallets of different dimensions can be transported in the same wagon or the same truck
4. A limited degree of flexibility for the number of trains is available in each planning period

4.4 Model with average transport cost (ATC) to solve Evian problem

4.4.1 Mathematical formulation

In this section, the problem at hand is formulated mathematically into a mixed integer linear program. The first objective is to minimize the total cost generated from production changeover, inventory holding and train and truck utilization, with an average transport cost per pallet taken into account. If more than one solution with the same value of objective function are found, the one which deploys the fewest trucks will be chosen. This indicates the priority on train utilization and less stocks in transit by trucks. This model with Average Transport Cost, can be indexed as model ATC for short.

According to contracts with the third part transporters of Evian, no other fixed cost is considered if the number of trains is kept in $\left[\underline{W}_{lt}, \overline{W}_{lt}\right]$ for destination l (warehouses or direct market zones) and period t, which can be fractionated to several wagons. And due to lack of information, only the average transport data by pallet proposed by the studied company is available for transportation cost by train $CostT_l$, and transportation cost by truck $CostC_l$ for destination l. The average quantity for pallets per wagon and per truck is adopted to keep the model in linear form, which coincides with statistics of the studied company. Furthermore, for each produced SKU, it can be transported to l destinations in a fluctuated percentage, varying in an interval $\left[\underline{P}_{il}, \overline{P}_{il}\right]$. All these constitute the main given flexibilities of the problem.

Decision variables and parameters are listed as follows:

Decision Variables	
x_{ikt}	production quantity of SKU i on production line k in period t
z_{ilt}	quantity of SKU i transported to warehouse l in period t
y_{ijkt}	binary variable indicating whether a setup is needed from SKU i to SKU j on production line k in period t
I_{it}	inventory amount for SKU i at the end of planning period t
NW_{lt}	number of wagons to reserve in direction of warehouse l in period t
NC_{lt}	number of trucks to order in direction of warehouse l in period t

Table 4.3: Decision variables for integrated production and transportation planning problem

Parameters (input data)	
D_{it}	demand forecast of SKU i for planning period t
C_{kt}	capacity of production line k (expressed in number of shifts) in planning period t
R_{ikt}	production rate: quantity of SKU i that can be produced on line k during a shift (8 hours) in period t
$\underline{I}_{it}, \overline{I}_{it}$	expected inventory interval of SKU i for all planning periods
$\underline{W}_{lt}, \overline{W}_{lt}$	allowed interval for the number of trains to warehouse l in planning period t
$\underline{P}_{il}, \overline{P}_{il}$	allowed interval of the fluctuated percentage of SKU i to be transported to warehouse l
Q_i	amount of SKU i in its proper pallet
NWm	Average number of pallets in a train wagon
NCm	Average number of pallets in a truck
$\overline{NC}_t$	maximum number of trucks available in a planning period t
s_{ijk}	setup time from SKU i to SKU j on production line k expressed in number of shifts of 8 hours, so decimal fraction is possible
$CostI_i(\cdot)$	inventory cost function for SKU i in a planning period
$CostChange_{ijk}$	changeover cost from SKU i to SKU j on production line k
$CostT_l$	transportation cost by train per pallet to warehouse l in average
$CostC_l$	transportation cost by truck per pallet to warehouse l in average
M	a big positive number

Table 4.4: Parameters for integrated production and transportationplanning problem

Then the formulation of objective function in two levels follows:

$$\begin{aligned} Min: Z_1 = &\sum_t \sum_l (CostT_l \cdot NWm \cdot NW_{lt} + CostC_l \cdot NCm \cdot NC_{lt}) \\ &+ \sum_t \sum_k \sum_j \sum_i \left(y_{ijkt} \cdot CostChange_{ijk}\right) \\ &+ \sum_t \sum_i CostI_{it}(I_{it}) \end{aligned} \tag{4.4.1}$$

$$Min: Z_2 = \sum_t \sum_l NC_{lt} \tag{4.4.2}$$

subject to constraints:

$$I_{i(t-1)} + \sum_k x_{ikt} - I_{it} = D_{it} \qquad \forall i, \forall t \qquad (4.4.3)$$

$$\sum_i (z_{ilt}/Q_i) \leq NW_{lt} \cdot NWm + NC_{lt} \cdot NCm \qquad \forall l, \forall t \qquad (4.4.4)$$

$$\sum_i [(1/R_{ikt}) \cdot x_{ikt}] + \sum_i \sum_j \left(y_{ijkt} \cdot s_{ijk} \right) \leq C_{kt} \qquad \forall k, \forall t \qquad (4.4.5)$$

$$x_{ikt} \leq M \cdot \sum_j y_{jikt} \qquad \forall i, \forall k, \forall t \qquad (4.4.6)$$

$$\sum_k x_{ikt} = \sum_l z_{ilt} \qquad \forall i, \forall t \qquad (4.4.7)$$

$$\underline{W}_{lt} \leq NW_{lt} \leq \overline{W}_{lt} \qquad \forall l, \forall t \qquad (4.4.8)$$

$$\begin{array}{l} z_{ilt} \geq \underline{P}_{il} \cdot \sum_k x_{ikt} \\ z_{ilt} \leq \overline{P}_{il} \cdot \sum_k x_{ikt} \end{array} \qquad \forall i, \forall l, \forall t \qquad (4.4.9)$$

$$\sum_l NC_{lt} \leq \overline{NC}_t \qquad \forall t \qquad (4.4.10)$$

$$y_{ijkt} = \{0, 1\} \qquad \forall i \neq j, \forall k, \forall t \qquad (4.4.11)$$

$$x_{ikt}, z_{ilt}, NC_{lt} \geq 0 \qquad \forall i, \forall j, \forall k, \forall t \qquad (4.4.12)$$

In Eq. (4.4.1), the objective Z_1 minimizes the sum of four types of cost for train plan, truck plan, production changeover plan and inventory penalty values.

In particular, corresponding to the stock penalty structure in Fig. 4.7, costs in the fourth term $StockCost = \sum_t \sum_i CostI_i(I_{it})$ of Z_1 is formulated from the piecewise function to a maximum group (4.4.13), which adds penalty cost to stocks deviating from the target interval. C_-, C_0 and C_+ are cost coefficients for the inventory level respectively under target value, in the interval of target-maximum or beyond the maximum value. For the Evian case, we have decided to configure $C_- = -2$, $C_0 = 1/4$ and $C_+ = 2$, and thus form a penalty curve presented in Fig. 4.7.

$$CostI_{it}(I_{it}) \geq \left\{ \begin{array}{c} C_- \cdot (I_{it} - \underline{I}_{it}) \\ C_0 \cdot (I_{it} - \underline{I}_{it}) \\ C_+ \cdot \left(I_{it} - \overline{I}_{it}\right) + C_0 \cdot \left(\overline{I}_{it} - \underline{I}_{it}\right) \end{array} \right\} \quad \forall i, \forall t \quad (4.4.13)$$

The second objective, marked as relation (4.4.2), minimizes the utilized trucks and claims the priority of transportation allocation by train if there are alternative solutions found for objective value (4.4.1). This also interprets less stock in transit by trucks. If other solutions with similar objective value are not found, (4.4.2) can be omitted referring to algorithm step 1) in sec. 4.4.2. Inventory flow conservation per SKU is shown in relation (4.4.3), where backorders are allowed instead of lost sales with a negative value in I_{it} during T planning periods. It is noticeable that in this formulation, I_{it} does not distinguish between physical stock in each warehouse and stock in transit (in transport to warehouses); so $\sum_k x_{ikt}$ just bring the two into consideration. Flow conservation by warehouses per SKU is expressed in (4.4.4), which sums up total numbers of SKU's pallets transported by trains and by trucks. It also indicates that all production of any SKU i in any period t must be transported to warehouses during the same period, this express the fact that there is no on-site storage area. Capacity constraints are expressed in relation (4.4.5) to ensure that time length consumed by SKU production and SKU changeover, does not exceed the capacity of any production line. For the SKUs cannot be produced on line k in period t, value 0 is assigned to their production rate R_{ikt}. Eq. (4.4.6) determines if a SKU is produced in period t on line k, the corresponding setup must be paid. If changeovers cannot occur on line k, a big positive value M is assigned to their setup times s_{ijk} and costs $CostChange_{ijk}$ to prevent from setting up. Eq. (4.4.7) ensures the sum of production quantity x_{ikt} of SKU i on production line k is identical to that of production quantity z_{ilt} of SKU i transported to warehouse l in each period.

Flexibility is always in our concern. The fluctuation range for train is declared by relation (4.4.8) to restrict the number of trains into a flexible interval. Different train may contain different number of wagons. Furthermore, to transport products to destinations, the company allocates the delivery of SKU i to different direction l in a percentage, within a fluctuated interval $\left[\underline{P}_{il}, \overline{P}_{il}\right]$, expressed in Eq. (4.4.9). Eq. (4.4.10) claims the maximum number of trucks available in each planning period, including round trip trucks. These are all involved in flexibility considerations. In the end, constraints (4.4.11) and constraints (4.4.12) are to show the feasibility conditions of variables.

When production and transportation plans are determined, fill rates $Tfill_{lt}$ of train and $Cfill_{lt}$ of truck can be approximately calculated. If NpT_i denotes the maximum quantity of pallets of type i in a wagon and NpC_i for that in a truck, fill rates could be formulated as below:

$$Tfill_{lt} = \sum_i \frac{\sum_k x_{ikt} \cdot NWm}{Q_i \cdot NpT_i \cdot (NWm \cdot NW_{lt} + NCm \cdot NC_{lt})} \qquad \forall l, \forall t \tag{4.4.14}$$

$$Cfill_{lt} = \begin{cases} \dfrac{\sum_i \left[\sum_k x_{ikt}/(Q_i \cdot NpC_i)\right]}{NC_{lt}} \cdot 100\% \\ \qquad if \;\; NW_{lt} = 0, NC_{lt} > 0 \\ \sum_i \dfrac{\sum_k x_{ikt} \cdot NCm}{Q_i \cdot NpT_i \cdot (NWm \cdot NW_{lt} + NCm \cdot NC_{lt})} \cdot 100\% \\ \qquad if \;\; NW_{lt} > 0, NC_{lt} > 0 \end{cases} \qquad \forall l, \forall t \tag{4.4.15}$$

4.4.2 Solution algorithm - heuristic

In the previous review on integrated production and transportation planning problems, this kind of capacitated mixed-integer problem is proved to be complicated in solving, and may require a great amount of computation time to find an optimal solution with traditional branch-and-bound algorithms. In this work, a problem-specific heuristic algorithm based on “Improvement” logic is proposed to solve the problem, and proved to be efficient to find the solution in a reasonable amount of time.

First, to accelerate the computation of the proposed heuristic, the maximum costs $CostI_i(I_{it})$ in group relation (4.4.13) are discarded, which are only used to program with CPLEX in order to compare with the proposed algorithm. In our heuristic, the cost $CostI_i(I_{it})$ is turned into a piecewise function (4.4.16) in order to calculate the inventory cost directly with different thresholds, while the old one remains in relation (4.4.13) to calculate solutions with the help of CPLEX.

$$CostI_{it}(I_{it}) = \begin{cases} C_{-} \cdot (I_{it} - \underline{I}_{it}) & I_{it} < \underline{I}_{it} \\ C_0 \cdot (I_{it} - \underline{I}_{it}) & I_{it} < \overline{I}_{it} \\ C_{+} \cdot \left(I_{it} - \overline{I}_{it}\right) + C_0 \cdot \left(\overline{I}_{it} - \underline{I}_{it}\right) & I_{it} \geq \underline{I}_{it} \end{cases} \qquad \forall i, \forall t \quad (4.4.16)$$

In a summary, the proposed algorithm can be divided into two parts: *Construction - finding the first feasible solution*, and *Improvement - searching for a near-optimal solution*. In the construction phase, we first generate an initial production and transportation plan according to the demand on different SKU, and adopt the first plan with minimum value on number of trains. This initial solution may be infeasible because the capacity of train and the capacity of truck can be violated. The next step is to adjust this plan with respects to concerning constraints to obtain the first feasible solution. In this context, the core element is that the initial plan is set with minimum train numbers in different direction (destination), which guarantees a starting point at objective value Z_1 as low as possible and leads to a fast solution exploration. After that, we focus on objective function (4.4.1) and look for the big terms with big coefficients in order to reduce big costs to reach better solutions. Finally, we proceed into the comparison phase to terminate this solution exploration. The objective value Z_2 is used to compare with other solutions if there exist more than one solution with similar cost on objective value Z_1.

This algorithm is generally illustrated in Fig. 4.8 in the next page. In the next subsections, we describe all the small loop of our heuristic in detail.

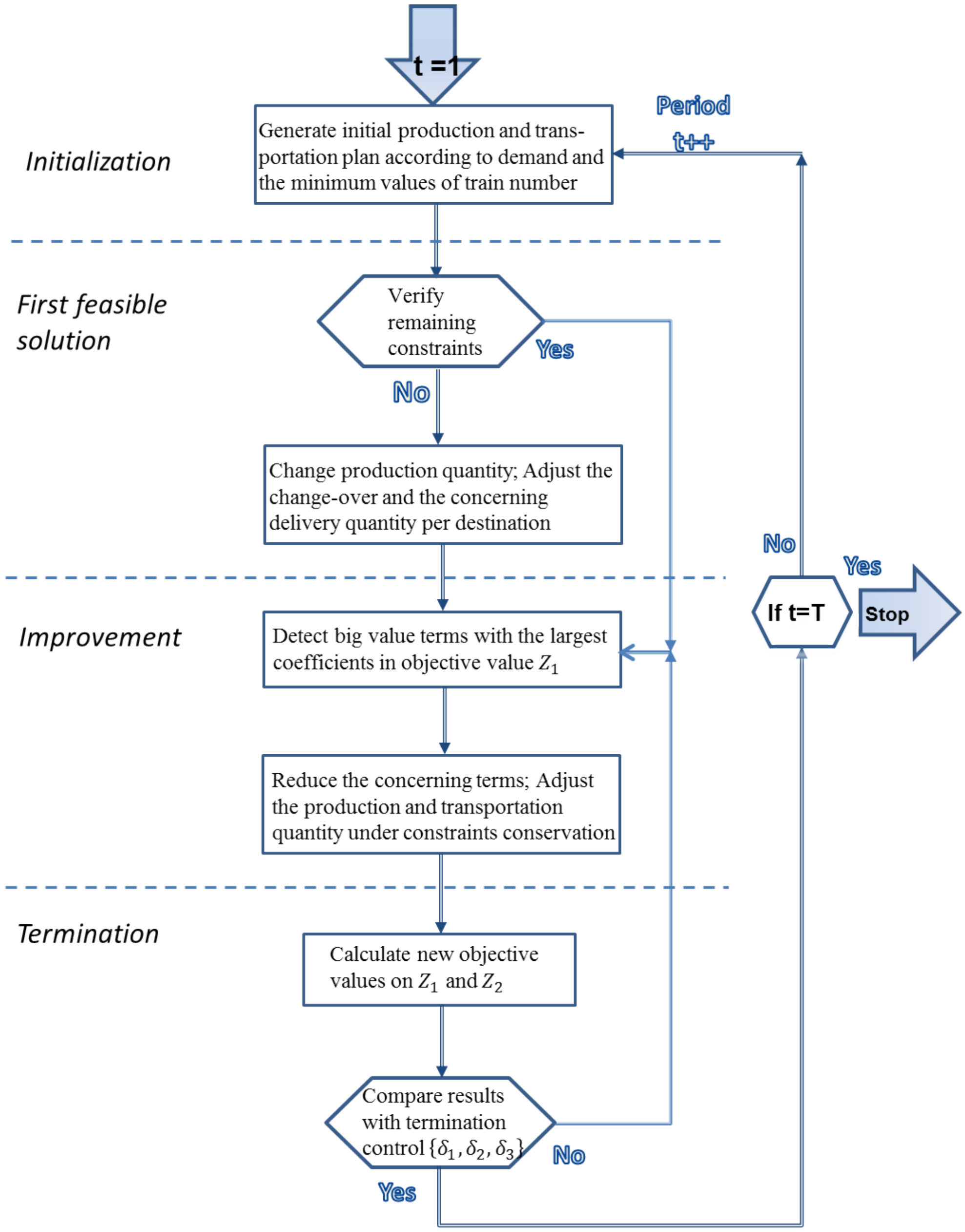

Figure 4.8: General algorithm of the heuristic to solve the integrated production and transportation problem - model ATC

4.4.2.1 Construction: first feasible solution

To obtain a feasible solution as the starting point, we first generate an initial plan which is not necessarily feasible. After that, the concerning constraints which have not been used to generate the initial plan are examined, in order to adjust the production and transportation decision variables to feasible ones.

After the adjusting operations, constraints are reviewed to check whether all conditions are met; if not, go back to the adjusting phase; otherwise, a feasible solution is found and is stored, indexed as Sl_0 in the solution collection $\sum$. All variable values are stored and the objective values Z_1 and Z_2 are calculated as upper bound for the next step. This is detailed in Fig. 4.9.

In Fig. 4.9, the key idea of construction phase is to generate an initial production plan in a rough and set all trains to their minimum numbers. This process is extremely fast, based on good knowledge of the problem-specific data properties. For the products that can not be transported by inital numbers of train wagons, we first seek help from available trucks to transport them. If train numbers are well within reach (remaining in $[\underline{W}_{lt}, \overline{W}_{lt}]$), the feasible initial transportation plan comes out directly; if not, the algorithm turns back to modify train numbers (incrementation only). If the train and truck maximum values are all reached and violated, try to change the delivery distribution $[\underline{P}_{il}, \overline{P}_{il}]$ in different direction (destination) to balance the transportation. And if the delivery balancing could not give out a satisfied transportation plan, the corresponding production quantity x_{ikt} is to be adjusted. Normally, we go quite fast to acquire the first feasible solution.

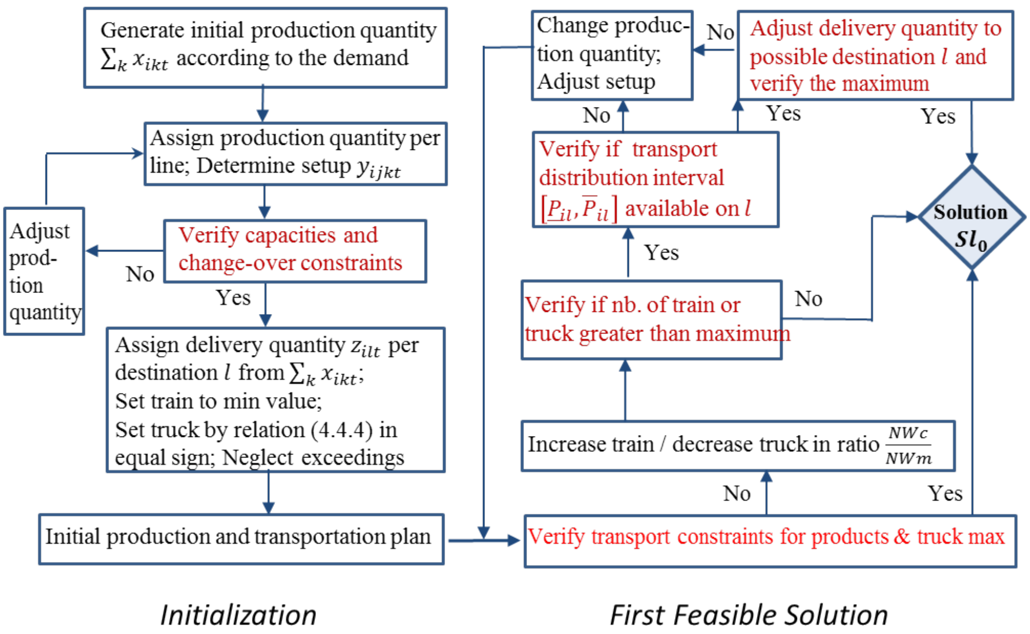

Figure 4.9: Construction for the first feasible solution - model ATC

4.4.2.2 Improvement: search for a near optimal solution

Based on the feasible solution obtained in the previous phase, the exploration of a near-optimal solution can be carried out in the same logic. Here the objective function values Z_1 and Z_2 play important roles, since the algorithm detects terms of big value with the largest coefficients in Z_1 to reduce the total cost, among the terms A, B, C and D for four main costs in our objective function.

The four cost terms A, B, C and D are presented in the following figures, illustrated in detail in Fig. 4.10 with cases A and B, and continued in Fig. 4.11 with C and D. A small algorithm bloc "Bloc P" is illustrated in Fig. 4.11. If the algorithm exploration comes up to "Bloc P" on the left of Fig. 4.10, or on the bottom of Fig. 4.11 ("Bloc P in Case A"), the algorithm enters directly the small algorithm Bloc P for further computation.

The algorithm is quite detailed in the following algorithms, but the real logic is simple. Each time when a decrease or increase of the cost term occurs, the concerning constraints linked by decision variables in this term will be immediately retreated. In order to keep the conservation of constraints, the algorithm may arrive to additional reduction or incrementation for other variables. For instance, inventory I_{it} and changeover y_{ijkt} are closely linked: if I_{it} is modified, the corresponding changeover y_{ijkt} must be checked, or even modified. The same thing happens to the numbers of train NW_{lt} and truck NC_{lt}. For those transportation cost terms, the mutual linkage is mainly determined by delivery distribution in their transport modes (train/truck). And, the problem-specific algorithm coding in VB.net has exploited the problem's data properties to avoid useless exploration so as to get directly to the next step.

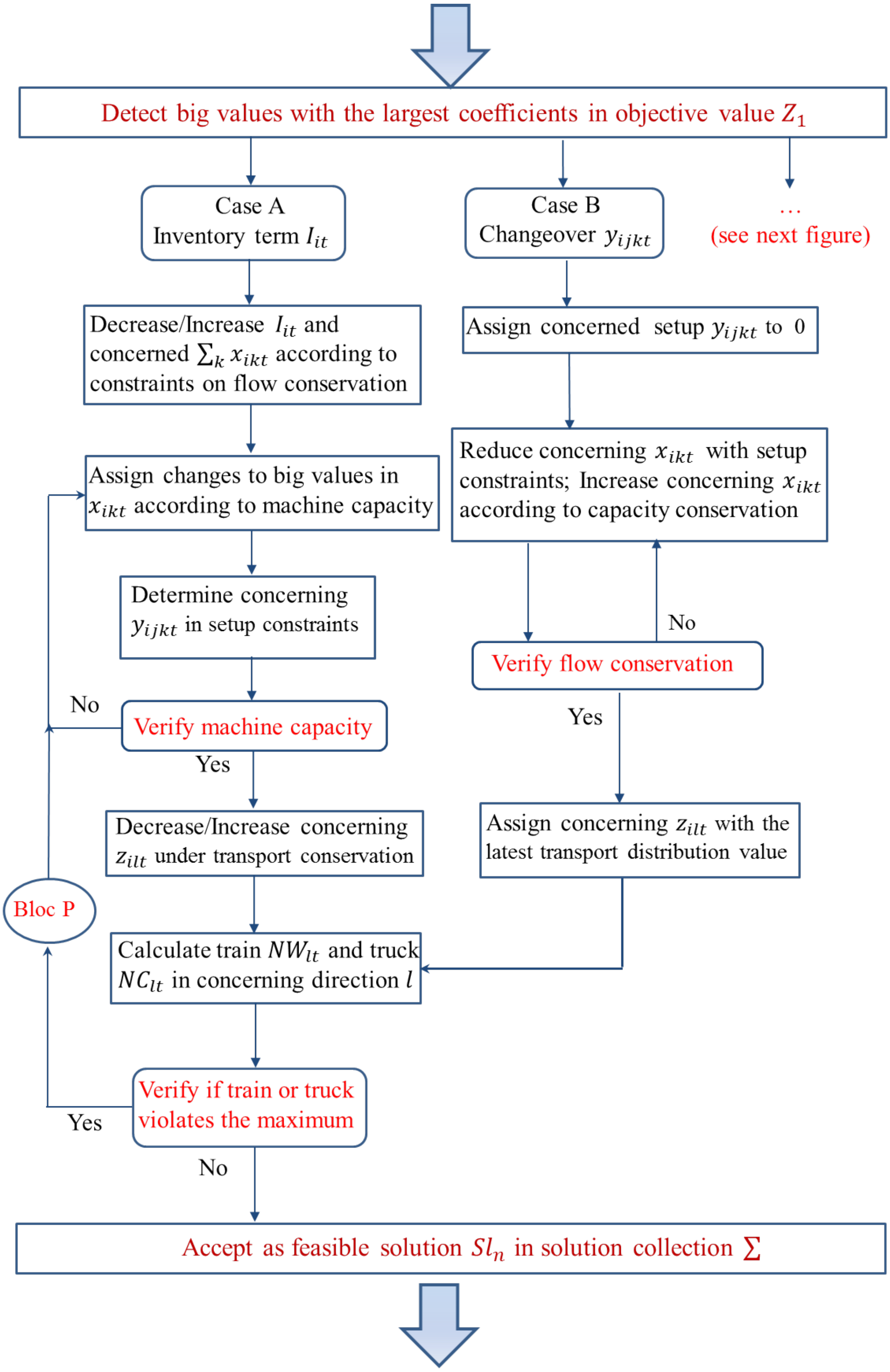

Figure 4.10: Improvement for next feasible solution for model ATC - part I

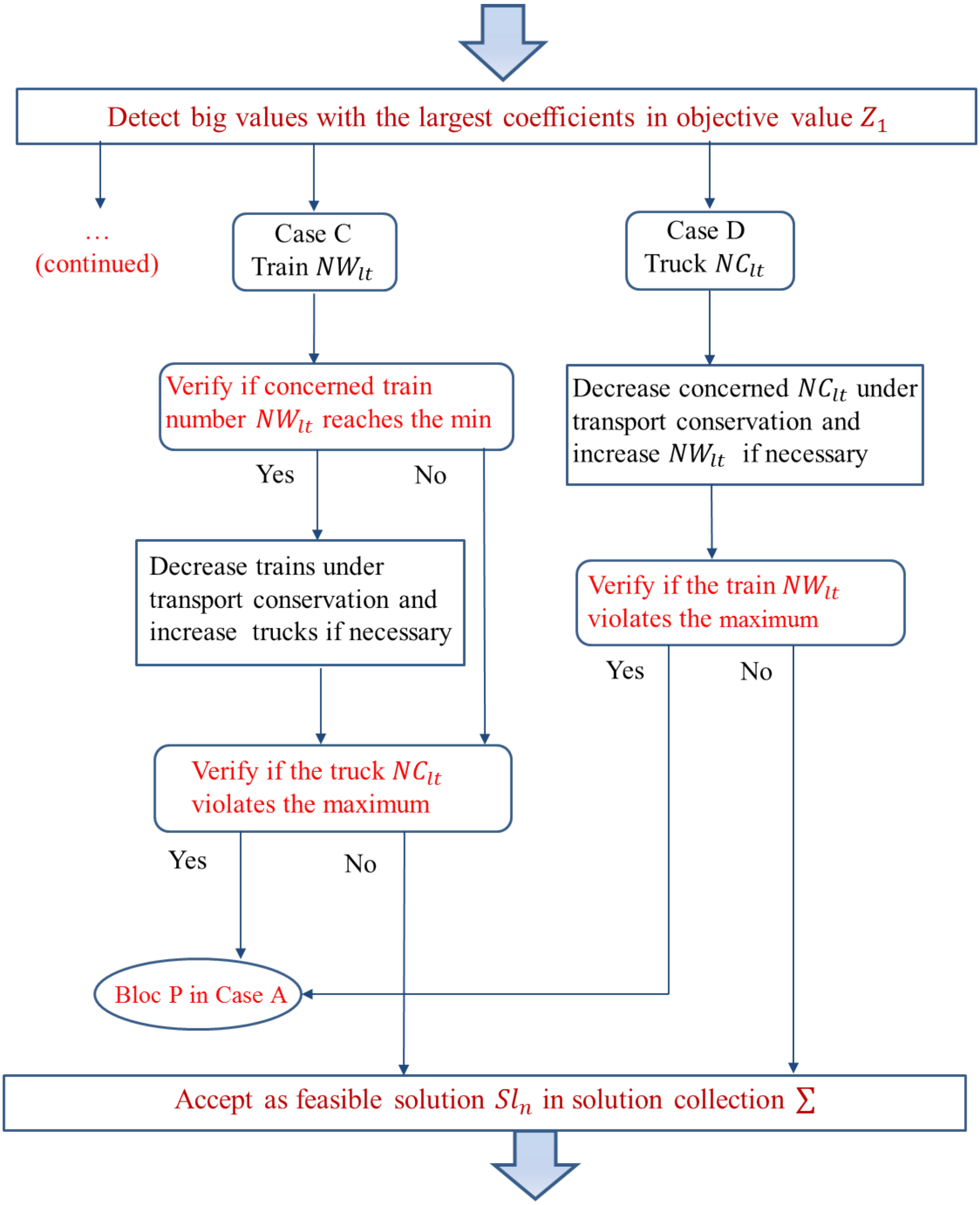

Figure 4.11: Improvement for next feasible solution for model ATC - part II

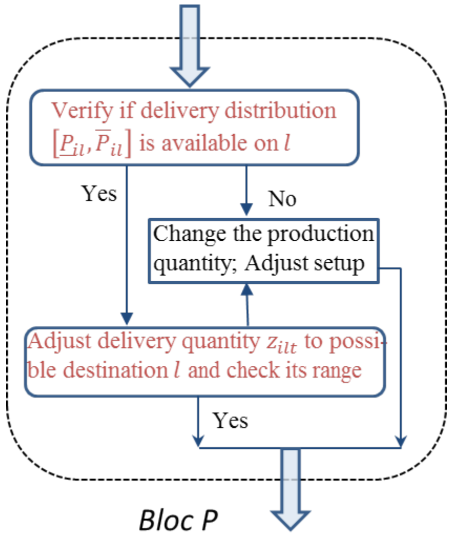

Figure 4.12: Improvement for next feasible solution for model ATC - Bloc P

4.4.2.3 Termination: accept a near-optimal solution and terminate the exploration

In this phase, the algorithm steps on to look for a better feasible solution as a near optimal one and terminate the exploration. Three control parameters $\{\delta_1, \delta_2, \delta_3\}$ are adopted to end the algorithm, which are percentages set by user to configure the required stopping criterions: δ_1 indicates the threshold for which the algorithm accepts $Z_1^{'}$ as better objective value without checking the objective value $Z_2^{'}$; δ_2 and δ_3 claim thresholds with which the algorithm accepts $Z_1^{'}$ as optimal objective value while the program is still in effective exploration.

The computation time and the quality of final solution vary by these $\{\delta_1, \delta_2, \delta_3\}$ parameters. For instance, in the solution collection $\sum$, Sl_0 is the first feasible solution at the end of the construction phase, and Sl_n is the nth feasible solution found in the improvement phase. For Sl_n, only if $\frac{Z_1^{Sl_{n-1}} - Z_1^{Sl_n}}{Z_1^{Sl_{n-4}} - Z_1^{Sl_{n-3}}} > \delta_2$ and $\frac{Z_1^{Sl_{n-1}} - Z_1^{Sl_n}}{Z_1^{Sl_{n-1}}} \leq \delta_3$, the solution Sl_n with objective value $Z_1^{Sl_n}$ can be immediately accepted as the near-optimal one. Furthermore, if no other solution improving the objective value is found during $N1$ consecutive iterations ($N1 = 100$ for example), the last one would be chosen as an approximate optimal solution. For on-going explorations if there exist always a better solution, and if the percentages δ_2 and δ_3 are validated as mentioned above, the current one would be accepted as final solution. Thus, we provide sufficient conditions to guarantee the algorithm's termination.

4.4.3 Computational Results

The computation is performed using a Dell Optiplex 780 computer with an Inter Core Duo 2.66 GHz Processor and 3.21 Go RAM under 32 bit WindowsXP environment. The proposed heuristic for the linear problem described in the previous sections was coded in language VB2005 (VB.net) with original data provided by the company in Excel files. When using Cplex of Ilog Cplex version 11.1 to solve the model to compare with our heuristics, we put weights on the two objectives Z_1 and Z_2 to merge into a single objective function. This case study makes use of the real input data from the Evian company. As described in section sec. 4.3, the results are presented in production plan and transportation plan. For reason of confidentiality, only an extract of results can be shown in table Tab. 4.5 and in table Tab. 4.6.

Tab. 4.5 gives out a production plan extracted from our output results, which specifies how many thousand bottles to produce in which production line in which period by SKU. For example, the SKU coding as 12424 in family EV50CT24 is proposed to produce 219,000 bottles in the fifth week. Tab. 4.6 gives out a train transportation plan, which specifies how many trains should be ordered in which direction in a period. For example, two complete trains must be reserved for warehouse Boulogne in the fourth week, and two and a half trains for Le Havre in the sixth week. For the direction to Le Havre, an entire train contracted with SNCF is composed by 28 wagons, that is, 2.5 trains = 70 wagons commanded.

On the one hand, since we do not have the detailed real production data by SKU provided by Evian, the comparison of the production plan with the real one is omitted. On the other hand, the transportation planning data is available for the first eight periods (week) in 2011 provided by Evian, shown in Tab. 4.7. So the transportation plan can be compared.

In this table, the column 2 and 3 denote the minimum and maximum values of train number, and if the corresponding transportation deployment by train does not violate this interval, the cell of train number is colored in green. If it exceeds the number, colored in purple, else if it is smaller than the minimum value, colored in red. The data from Evian reveals its clear deficiency on transportation plan, since there are a lot of shortages and surplus. Whereas, our output results in Tab. 4.6 have better arranged the train plan in the expected interval, and at the same time, the total truck numbers are smaller and more stable than those from Evian. The train number and truck number are not only the result of transportation planning but also the result of production planning. In this way, comparison between the two transportation tables confirms that our approach works well to provide good integrated production and transportation plans.

Production plan by SKU				Periods – model ATC								
Index	SKU	Family	Line	T1	T2	T3	T4	T5	T6	T7	T8	T9
6	8431	EV50CT24	Line A	0	0	0	0	0	0	0	0	0
7	8436	EV50CT24	Line A	0	0	0	0	0	0	0	0	0
11	8498	EV50CT24	Line A	0	0	0	0	0	0	0	0	0
22	8662	EV50CT24	Line A	0	0	0	2	0	0	7	0	1
33	9588	EV50CT24	Line A	0	0	0	0	0	0	0	0	0
34	9736	EV50CT24	Line A	0	0	0	0	0	0	0	0	0
49	12422	EV50CT24	Line A	0	0	0	0	0	0	0	0	0
50	12424	EV50CT24	Line A	378	217	46	795	219	407	67	39	238
51	12426	EV50CT24	Line A	0	0	0	0	0	0	0	0	0
52	12427	EV50CT24	Line A	0	0	0	0	0	0	0	0	0
53	12429	EV50CT24	Line A	78	44	152	723	21	332	170	267	57
54	12430	EV50CT24	Line A	0	0	0	0	0	0	0	0	0

Table 4.5: Output production plan for Evian problem - model ATC

Transportation	Periods - model ATC								
Train/Warehouse	T1	T2	T3	T4	T5	T6	T7	T8	T9
Amberieu	14	13	11	13	14	13	13.5	14	13
Anvers	2	2	2.5	2.5	3	3	3	3	3
Arles/Miramas	1	1.5	2	2	2	2	2	2	2
Boulogne	2	1.5	1.5	2	2	1	2	2	1.5
Bretigny	3.5	4.5	4	4.5	5	5	5	5	4.5
Coventry	3	3	3	3	3	3	3	3	3
Duisburg	0.5	0.5	0.5	1	1	1	0.5	0.5	1
Fos	2	1.5	1	1	2	2	1	1	1
Hockenheim	0.5	0.5	1	1	1	1	0.5	0.5	1
Le Havre	2	2	2	3	2.5	2.5	1	2	2
Rennes	0.5	0.5	0.5	0.5	0.5	0.5	0.5	0.5	0.5
Zeebrugges	8	6.5	5	7	7.5	5	7	4	5
Truck	87	90	93	83	79	96	78	83	77

Table 4.6: Output transportation plan for Evian problem - model ATC

Nevertheless, tests are carried out to compare the solution qualities and computation times with three algorithms: the proposed heuristic, the CPLEX program and the heuristic-CPLEX combined method.

The first algorithm is the suggested problem-specific heuristic, tested here with two sets of control thresholds $\delta = \{\delta_1, \delta_2, \delta_3\}$ in $\delta^1 = \{6\%, 90\%, 0.02\%\}$ and $\delta^2 = \{3\%, 95\%, 0.005\%\}$, which are presented in sec. 4.4.2.3.

The second one exploits the mixed integer optimizer of ILOG CPLEX, in which two objective functions are merged into a single one by a weighting system. CPLEX MIP solver uses the branch-and-bound technique to obtain an optimal solution. Since the train utilization is of the first priority, the objective Z_1 is roughly weighted 200 times than Z_2. Theoretically if we do not set any termination limits such as number of nodes, time, ...,

Evian Transportation Data			Periods							
Train/Warehouse	Min	Max	T1	T2	T3	T4	T5	T6	T7	T8
Amberieu	9	14	13.8	12.9	10.8	13.1	14.9	13.4	13.5	14.3
Anvers	2	3	1.7	2.2	2.8	2.4	3.0	5.2	1.7	3.6
Arles/Miramas	0	2	2.0	2.0	2.0	2.0	2.0	2.0	2.0	2.0
Boulogne	1	3	2.0	1.6	1.3	1.8	1.9	1.2	1.7	1.0
Bretigny	3	5	3.3	4.3	4.0	4.4	5.8	6.3	6.9	7.2
Coventry	3	3	2.9	2.3	1.9	2.5	2.7	1.7	2.5	1.4
Duisburg	0.5	1	0.4	0.5	0.6	0.8	0.8	0.9	0.6	0.4
Fos	1	3	1.8	1.4	1.3	1.0	1.9	1.7	0.8	1.3
Hockenheim	0.5	1	0.5	0.6	0.8	1.1	1.0	1.1	0.7	0.5
Le Havre	1	3	2.0	1.9	2.2	2.6	2.6	2.4	1.2	2.2
Rennes	0	1	0.5	0.5	0.5	0.5	0.5	0.5	0.5	0.5
Zeebrugges	0	8	8.1	6.6	5.4	7.1	7.5	4.7	6.9	4.1
Truck			120	116	125	97	92	101	84	93

Table 4.7: Transportation plan data provided by Evian

we could wait until the termination of the algorithm by finding final solution with guaranteed optimality. However, its optimality is sometimes relative to whatever tolerances and optimality criteria the user has set. For instance, CPLEX considers any user-supplied cutoff value (such as CutLo or CutUp) as well as the objective difference parameter (ObjDif) when it treats nodes during branch and cut; thus these settings affect termination indirectly.

The third algorithm is the heuristic-CPLEX combined method. It is more interesting, as we introduce initial feasible solution generated by the suggested heuristic as the starting feasible solution of CPLEX program (set MipStart=1 to load the solution then use other techniques to refine the solution). This is a combined approach; we theoretically expect it to be more efficient.

Sets	Heuristic				CPLEX		Heuristic + CPLEX		Gap (Heuristic vs CPLEX)	
	Termination δ^1		Termination δ^2						Termination δ^1	Termination δ^2
	Z_1	Time	Z_1	Time	Z_1	Time	Z_1	Time	Δ_1	Δ_2
SKU50	$2.243e^6$	13s	$2.241e^6$	15s	$2.241e^6$	31s	$2.241e^6$	22s	0.061%	0.011%
SKU100	$5.331e^6$	25s	$5.328e^6$	29s	$5,327e^6$	998s	$5.327e^6$	625s	0.073%	0.018%
SKU200	$8.767e^6$	70s	$8.763e^6$	87s	$8.761e^6$	4899s	$8.761e^6$	2868s	0.074%	0.022%
SKU420	$18.145e^6$	104s	$18.139e^6$	121s	$18.131e^6$	18207s	$18.131e^6$	9706s	0.083%	0.046%
SKU840	$34.679e^6$	167s	$34.277e^6$	189s	-----	------	-----	-----	-----	-----

Table 4.8: Comparison on objective value and run time for three algorithms in Model ATC

Tab. 4.8 shows the comparison on objective value and computation time respectively for the mentioned three algorithms. The first column marks the scenario datasets: for set SKU50, where input data involve only 50 SKUs on 3 production lines for 4 warehouse destinations in 12 weeks; 100 SKUs on 6 lines to 5 warehouses for SKU100 in 12 weeks; 200 SKUs on 7 lines to 8 warehouses for SKU200; 420 SKUs on 14 lines to 14 warehouses; 840 SKUs on 20 lines to 14 warehouses. Meanwhile, integer variables are always numerous. For heuristic column, the results are listed in termination criterion δ^1 and δ^2, mentioned in the paragraph above. For objective value column, Z_1 is the total cost in euros and for time column in CPU seconds.

From these results, we would conclude that the CPLEX optimizer provides the optimal solution, at a cost of consuming enormous amount of time due to the large number of integer variables, even in condition that a large number of integer variables are set to 0 according to some knowledge in modeling. For set SKU840, CPLEX cannot achieve the optimal solution in a reasonable amount of time and even for SKU420, it consumes a big amount of computation time. In contrary, the suggested heuristic shows a good performance to provide an approximate solution in very short time. A few minutes are enough to complete computing for set SKU420, while CPLEX encounters difficulties to look for the next feasible solution. It is also observed that the quick termination δ^1 really computes more speedily than δ^2, and provides similar results. We can change δ sets to get better solutions. The backorder cost is not counted in the objective function, but can be compensated by inventory penalty cost. In the proposed heuristic algorithm, backorder is rarely increased and only used to compensate small unequal amount; in the CPLEX method, it is a little hard to anticipate even if there is an inventory penalty evaluation to prevent from stock-out. Moreover, in the last column, the Gap represents the relative error of the heuristic solutions with respect to the optimal solutions provided by CPLEX. It can be observed that the Gap increases slightly as long as the problem size increases, however, the Gap observed are always insignificant when comparing the total cost against that of the optimal solution. For termination δ^1, relative errors are greater that those of the termination δ^2 with less computation time, but, still under 0.1%. For termination δ^2, relative errors can be observed as tiny gap (<0.05%). This shows that the proposed heuristic is well efficient to seek for solutions with good quality.

In the column "Heuristic + CPLEX" of Tab. 4.8, it is observed that the heuristic feasible solution followed by CPLEX program can reduces significantly the computation time, while providing a solution with similar quality to that obtained with the unique CPLEX optimizer. In fact, there is a slight difference in objective value for the scenario SKU200, due to different refining actions after loading the initial solution, which may lead to small differences on optimality. Nevertheless, its run time is still too long for a weekly planning solution. For a small size problem, the combined method is pretty good to substitute the traditional branch-and-bound algorithm. For a planning problem over 12 weeks updated each week with tremendous integer variables, it is worthless to look for a solution with guaranteed optimality in such a long horizon. In this way, the suggested problem-specific heuristic works more efficiently.

4.5 Model with variable transport cost (VTC) to solve Evian problem

In the previous model ATC, average quantity of pallets per wagon and per truck is adopted, to fill the wagon and the truck space in order to linearize the objective function. Even if the company approves this method, it is not accurate enough. After searching for a satisfactory solution, the algorithm releases a production plan and a transportation plan, but the number of pallets of bottles filled in train wagons or inside a truck is still unclear in detail. It is necessary to introduce additional modified variables substituting the average number of pallets by train wagon and by truck, and the proposed heuristic can be slightly modified to obtain results with much more precision.

4.5.1 Mathematical formulation

In addition to the preceding model ATC, the input data NWm representing the average number of pallets by train wagon and NWc the average number of pallets by truck, are eliminated. The fixed costs of utilization of train wagon and truck are completely separated from these pallet-average costs. As a result, transportation cost is explicitly divided into a fixed cost by train and by truck plus a variable cost relative to the number of pallets. Apart from the parameters for model ATC, volume data for each SKU pallet, train wagon and truck are the input data added into the new parameter list:

Parameters	
VT_l	Wagon volume in m^3
VC_l	Truck volume in m^3
V_i	Pallet volume in m^3 for each SKU i
α	maximum fill rate for a truck in volume (relative to the maximum loading allowance on auto-routes)
$CostTF_l$	fixed transportation cost per train to warehouse l
$CostTC_l$	fixed transportation cost per truck to warehouse l

Table 4.9: New parameters for integrated production and transportation problem in model VTC

Different from the previous model, the former decision variable z_{ilt} is splitted into two branches with index $c = 1, 2$ to provide more precision:

Decision Variables	
z_{ilct}	Production quantity of SKU i to be transported by train ($c=1$) or by truck ($c=2$) to destination l in period t

Table 4.10: New decision variables for integrated production and transportation problem in model VTC

With these modifications, the model with average transport cost (ATC) can be transformed to a model with Variable Transport Cost (VTC). Then the formulation of objective function in two levels of the model with variable transport cost (VTC) follows:

$$\begin{aligned} Min: Z_1 = &\sum_t \sum_l \left(\frac{CostT_l}{Q_i} \cdot \sum_{c=1} z_{ilct} + CostTF_l \cdot NW_{lt} \right) \\ &+ \sum_t \sum_l \left(\frac{CostC_l}{Q_i} \cdot \sum_{c=2} z_{iclt} + CostTC_l \cdot NC_{lt} \right) \\ &+ \sum_t \sum_i \sum_j \sum_k \left(y_{ijkt} \cdot CostChange_{ijk} \right) \\ &+ \sum_t \sum_i CostI_{it}(I_{it}) \end{aligned} \tag{4.5.1}$$

$$Min: Z_2 = \sum_t \sum_l NC_{lt} \tag{4.5.2}$$

subject to modified constraints, compared with the model in average transport cost:

$$I_{i(t-1)} + \sum_l \sum_c z_{ilct} - I_{it} = D_{it} \qquad \forall i, \forall t \tag{4.5.3}$$

$$\sum_i \left(\sum_c z_{ilct} / Q_i \cdot V_i \right) \leq NW_{lt} \cdot VT_l + NC_{lt} \cdot \alpha \cdot VC_l \qquad \forall l, \forall t \tag{4.5.4}$$

$$\sum_k x_{ikt} = \sum_l \sum_c z_{ilct} \qquad \forall i, \forall t \tag{4.5.5}$$

$$\begin{aligned} &\sum_c z_{ilct} \geq \underline{P}_{il} \cdot \sum_k x_{ikt} \\ &\sum_c z_{ilct} \leq \overline{P}_{il} \cdot \sum_k x_{ikt} \end{aligned} \qquad \forall i, \forall l, \forall t \qquad (4.5.6)$$

$$x_{ikt}, z_{ilct}, NC_{lt} \geq 0 \qquad \forall i, \forall j, \forall k, \forall c, \forall t \qquad (4.5.7)$$

subject to additional constraints for vehicle mode index $c = \{1,2\}$, compared with the model in average transport cost:

$$\sum_i (z_{il1t}/Q_i \cdot V_i) \leq NW_{lt} \cdot VT_l \qquad \forall l, \forall t \qquad (4.5.8)$$

$$\sum_i (z_{il2t}/Q_i \cdot V_i) \leq NC_{lt} \cdot \alpha \cdot VC_l \qquad \forall l, \forall t \qquad (4.5.9)$$

The other constraints remain the same with relations in the previous section in Eq. (4.4.5), Eq. (4.4.6), Eq. (4.4.8), Eq. (4.4.10) and Eq. (4.4.11).

In view of Eq. (4.5.1) in this model, the objective Z_1 minimizes the sum of four types of cost for train plan, truck plan, production changeover plan and inventory penalty values. Transportation cost is clearly divided into fixed and variable cost per train and fixed and variable cost per truck. Corresponding to the stock penalty structure in Fig.4.7, costs in the fourth term $StockCost = \sum_t \sum_i CostI_i(I_{it})$ of Z_1 remain the same as a maximum group constraints (4.4.13) adding penalty cost to corresponding inventory.

The second objective marked as relation (4.5.2), remains the same and minimizes the utilized trucks. If other solutions with similar objective value are not found, (4.5.2) can be omitted referring to algorithm step 12) in section sec.4.4.2. Inventory flow conservation per SKU is shown in relation (4.5.3), where backorders are allowed instead of lost sales during T planning periods and so I_{it} can be negative. As I_{it} does not distinguish between physical stock in each warehouse and stock in transit (in transport to warehouses), the term $\sum_l \sum_c z_{ilct}$ just bring the two into consideration. Flow conservation by warehouses per SKU is expressed in volume conservation in (4.5.4), which sums up the total volume of SKU's pallets transported by trains and by trucks. This relation can be divided into two parts: train flow (4.5.8) with $c = 1$ and truck flow (4.5.9) with $c = 2$. For the truck flow, the truck utilization are not only limited by its volume capacity but also by loading weight on road, which refers to only one third of its volume fulfilled in the Evian case, that means we choose the parameter $\alpha = 1/3$ in Eq. (4.5.4) and Eq. (4.5.9). Moreover, Eq. (4.5.5) ensures the sum of production quantity x_{ikt} of SKU i on production line k is identical to the sum of $\sum_{c} z_{ilct}$ for SKU i to be transported to warehouse l in each period. To transport products to corresponding destinations, the company applies a percentage to allocate the delivery of SKU i to different possible direction l, within a fluctuated interval $\left[\underline{P}_{il}, \overline{P}_{il}\right]$ in Eq. (4.5.6). Other constraints remain the same to the first model with average transport cost.

Therefore, with this formulation we can calculate precisely the fill rates $Tfill_{lt}$ of train in $c = 1$ and $Cfill_{lt}$ of truck in $c = 2$:

$$Tfill_{lt} = \frac{\sum_{h} z_{ihct}/Q_i \cdot V_i}{NW_{lt} \cdot VT_l} \qquad \forall l, \forall t \tag{4.5.10}$$

$$Cfill_{lt} = \frac{\sum_{h} x_{ihct}/Q_i \cdot V_i}{NC_{lt} \cdot VC_l} \qquad \forall l, \forall t \tag{4.5.11}$$

4.5.2 Solution algorithm - heuristic

The capacitated mixed-integer model is formulated in the previous subsection. To avoid the great amount of computation time in finding an optimal solution with traditional branch-and-bound algorithms, still, a problem-specific heuristic algorithm is proposed.

This method is similar to that of model ATC (Average Transport Cost), based on "Construction-Improvement" logic and adopts the piecewise function of relation (4.4.16). The main heuristic is illustrated in the following figure. The basic difference away from the heuristic of model ATC, is that the delivery quantities transported by train and by truck must be assigned and adjusted according to the conservation constraints in volume, that means with particular respects to relation (4.5.8) and (4.5.9).

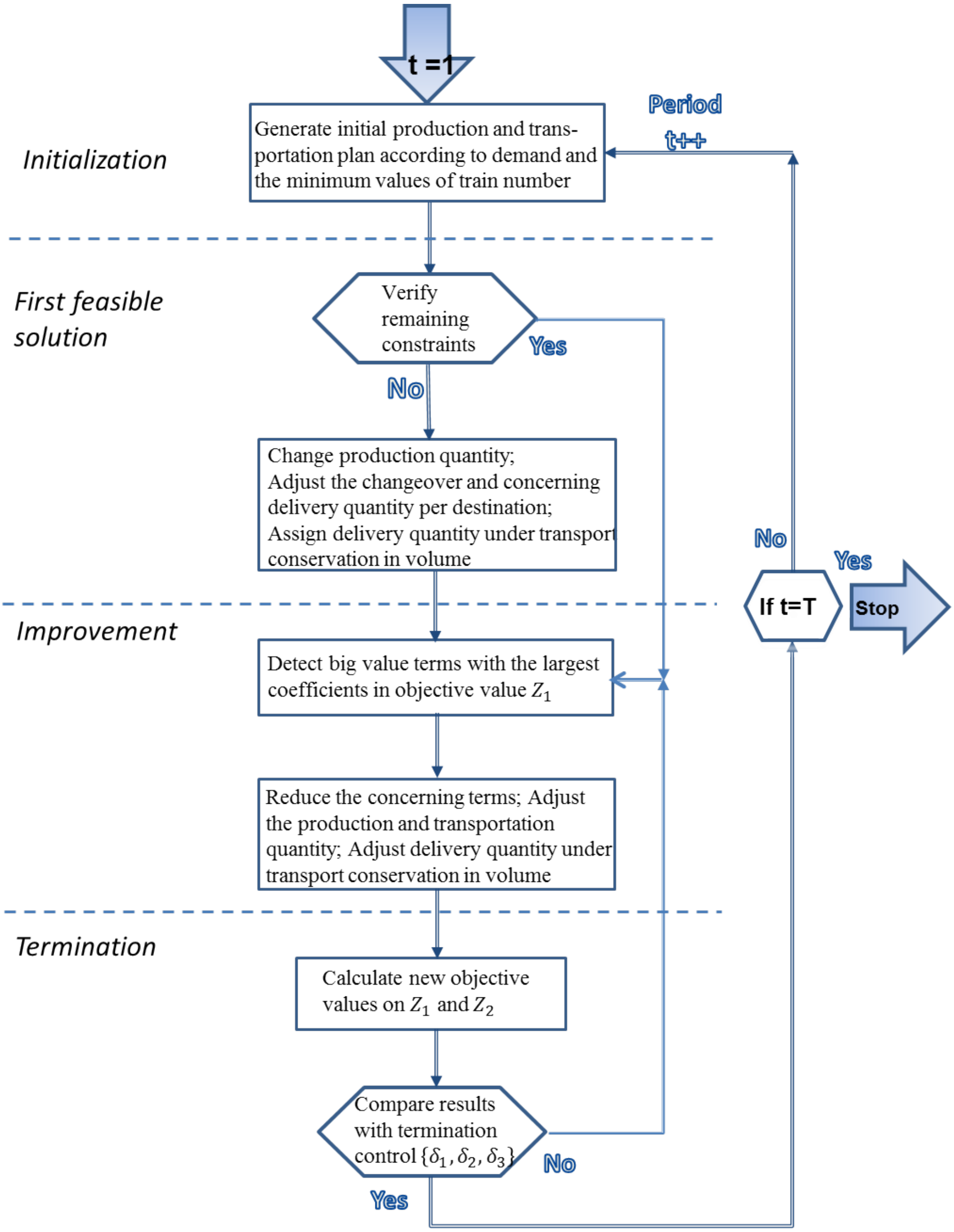

Figure 4.13: General algorithm of the heuristic to solve the integrated production and transportation problem VTC

4.5.2.1 Construction: first feasible solution

Similar to the methodology for the model with average transport cost, in order to obtain a feasible solution as the starting point, we first generate an initial plan which is not necessarily feasible. After that, the constraints which are not used to generate the initial plan, are examined one by one in order to adjust the production and transportation decisions to feasible ones. After the adjusting actions, constraints are reviewed to check whether all conditions are met; if not, go back to the adjusting phase; otherwise, a feasible solution is found and is stored in the solution collection $\sum$.

The key element of the algorithm does not change, for the sake of an initial production plan we set all trains to their min values. The differences with the ATC method, is that the product quantity transported by trains z_{il1t} and by trucks z_{il2t} must be figured out in the feasible solution, after the determination of overall production and transportation plans. Thus, this is slightly modified from the previous procedure and shown as follows:

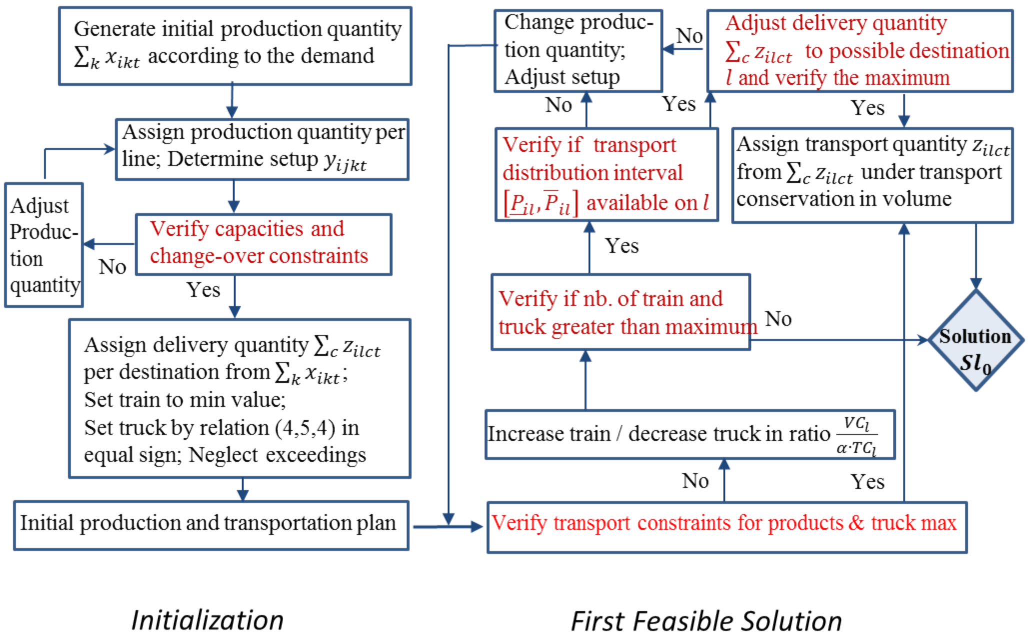

Figure 4.14: Construction for the first feasible solution - model VTC

4.5.2.2 Improvement: search for a near-optimal solution

Based on the feasible solution obtained in the initialization phase, the exploration of a near-optimal solution can be carried out in the same logic. The objective function values

Z_1 in Eq. (4.5.1) and Z_2 in Eq. (4.5.2) play important roles, since the algorithm detects variables of big value with the largest coefficients in objective value Z_1 to reduce the total cost among terms A, B, C, D, E and F for six main costs. The terms E and F are additional to the the model ATC.

Cost terms A, B, C, D, E and F are presented in detail in the logic bloc, illustrated in Fig.4.15 with cases A, B and C, continued in Fig.4.16 with D, E and F. And there is a small Bloc P' illustrated in Fig.4.17. If the algorithm comes up to "Bloc P"' on the left of Fig.4.10, or on the bottom of Fig.4.11 ("Bloc P' in Case A"), the algorithm enters directly the small algorithm Bloc P' for further computation.

From the detailed algorithms in the following, we see the logic of this algorithm has a similarity to the previous one of model with average transport cost. Because of the introduction of new parameters and variables to this model, differences between the new heuristic for model VTC and the old one for model ATC, lie principally in the assignment of transportation quantity z_{ilct} by train and by truck of their total one $\sum_c z_{ilct}$. Thus, the linkage between the detailed delivery quantity by train z_{il1t} and by truck z_{il2t} play an important role.

The case E and case F in Fig.4.16 treat this linkage problem, which is absent in the model ATC. Subsequent operations are simple, in case A, B, C and D, the on-going algorithm must specify the delivery quantities before and after the transport rearrangement. Some differences also lie in the treatment of transport conservation in volume of train and truck, linked by relation (4.5.4), (4.5.8) and (4.5.9), and treated in the algorithm. At the same time, the problem's data characteristics are exploited to speed up the algorithm.

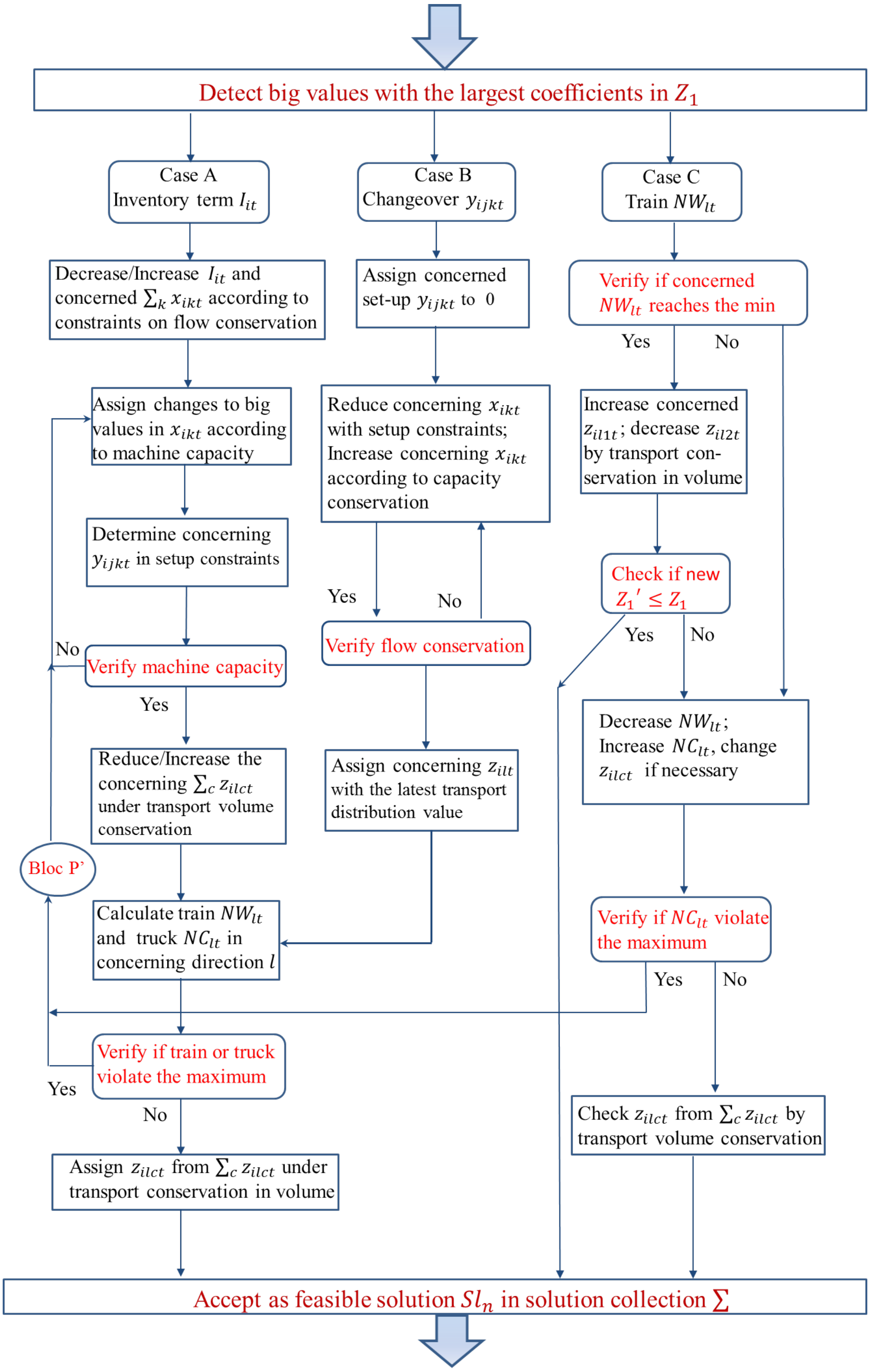

Figure 4.15: Improvement for the next feasible solution for model VTC - part I

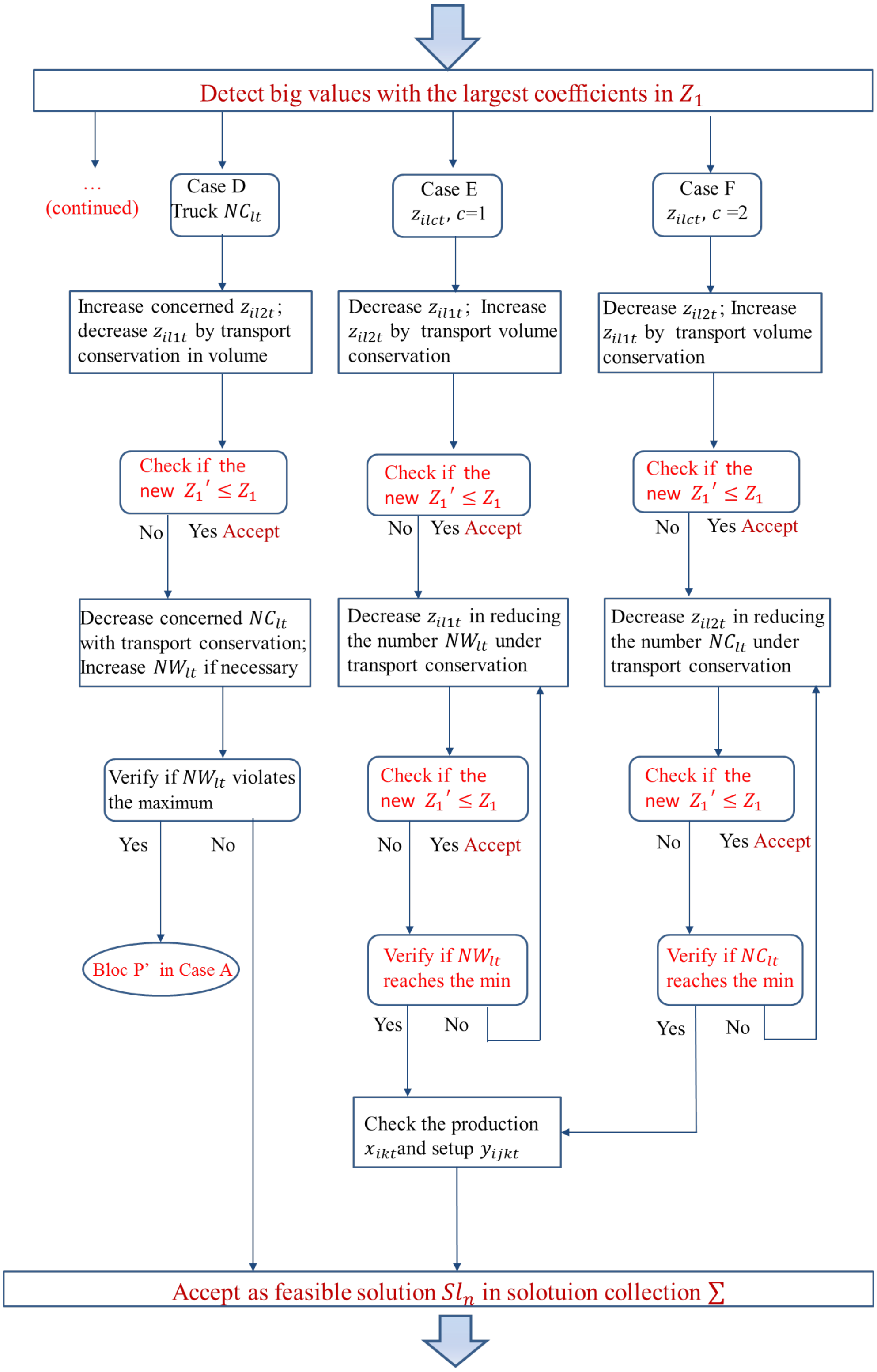

Figure 4.16: Improvement for the next feasible solution for model VTC - part II

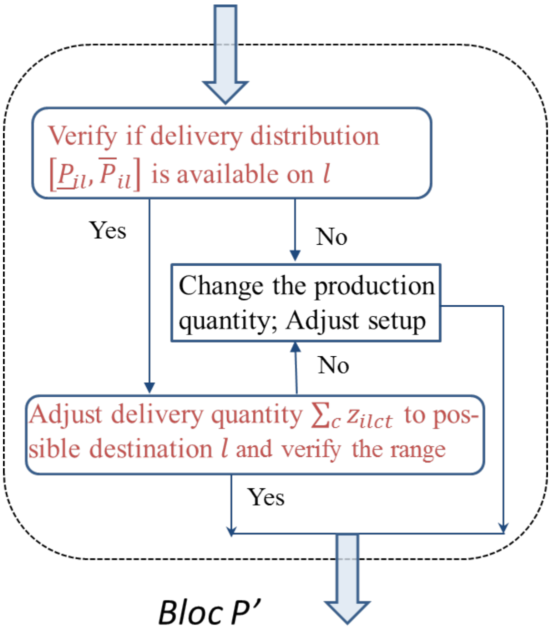

Figure 4.17: Improvement for next feasible solution for model VTC - Bloc P'

4.5.2.3 Termination: accept a near-optimal solution and terminate the exploration

All these blocs assure the algorithm to move on between adjacent feasible solutions, and the exploration of new feasible solution must be terminated using the termination parameters $N1$ and $\{\delta_1, \delta_2, \delta_3\}$ in the same steps in sec.4.4.2.3, in order to provide a near-optimal solution. As a result, different $\{\delta_1, \delta_2, \delta_3\}$ sets may lead to divers speed of convergence and different quality of final solutions. The judgement phase of termination remains the same to the previous bloc for model ATC, so it is omitted to be presented here.

4.5.3 Computational Results

Same to the test in sec.4.4, the computation is performed using a Dell Optiplex 780 computer with an Inter Core Duo 2.66 GHz Processor and 3.21 Go RAM under 32 bit WindowsXP environment. The proposed heuristic algorithm for the linear problem is coded in language VB2005 (VB.net) with original data provided by the company in Excel files. The Cplex used is Ilog Cplex 11.1 version.

To launch the computation, the truck 44T with $44m^3$ is adopted by us as default truck and the wagon with 34 Euro pallets (size 800x1200 m) of volume $120m^3$ as default wagon type in the train. As described in section sec.4.3, the industrial results are presented in production plan and transportation plan in forms of Tab.4.5 and Tab.4.6.

Transportation data is available for the considered periods in 2011 provided by Evian, thus, we propose to compare the transportation plans in Tab.4.11 and Tab.4.6. These are extract tables of our output transportation plan, with 13 transport destinations listed in the left column and 9 periods for other columns. Train numbers are presented in 9 periods for 13 destinations for model VTC. On the bottom of Tab.4.11, the total used trucks are specified in each period. Truck results of current model VTC is colored in blue, those of model ATC (the previous model) colored in black and those of Evian in red.

Transportation	Periods - model VTC								
Train/Warehouse	T1	T2	T3	T4	T5	T6	T7	T8	T9
Amberieu	13.5	13	11	13	14	13.5	13.5	14	13
Anvers	2	2.5	3	2.5	3	3	2.5	3	3
Arles/Miramas	2	1.5	2	2	2	2	2	2	2
Boulogne	2	1.5	1.5	2	2	1	2	2	1.5
Bretigny	4	4.5	4.5	5	5	5	5	5	4. 5
Coventry	3	3	3	3	3	3	3	3	3
Duisburg	0.5	0.5	1	1	1	1	0.5	0.5	1
Fos	2	1.5	1	1	2	2	1	1	1
Hockenheim	0.5	0.5	1	1	1	1	0.5	0.5	1
Le Havre	2	2	2	3	2.5	2.5	1	2	2
Rennes	0.5	0.5	0.5	0.5	0.5	0.5	0.5	0.5	0.5
Zeebrugges	8	6.5	5	7	7.5	5	7	5	5
Truck VTC	95	83	86	92	75	87	73	80	82
Truck ATC	87	90	93	83	79	96	78	83	77
Truck Evian	120	116	125	97	92	101	84	93	90

Table 4.11: Output transportation plan for Evian problem - comparisonwith model VTC

Significant differences are exposed between output transportation plans of model ATC and model VTC. For instance, 13.5 trains go the direction to Amberieu and 2 trains are heading for Arles/Miramas in period T1, while those numbers of model ATC are respectively 14 and 1. At the same time, only 87 trucks are deployed by model ATC, and 95 trucks used and sent by model VTC, which is relatively higher. In other periods, most truck numbers of model VTC are smaller than those of model ATC. Since the model VTC give more precision on transportation planning with fixed charge and variable cost for both trains and trucks, the current planning are to provide precised results to achieve better near-optimal objective value in model VTC. However, the transport differences between VTC and Evian are quite clear, our results send a lot fewer trucks and do not show drastic increase and decrease. Output transportation plan shows that model VTC have better arranged the train plan with respects to the min-max interval in periods, which is result of the proposed heuristic. In this way, the comparison between transportation plans confirms that our approach works efficiently to provide good integrated production and transportation plans.

Still, tests are carried out to compare solution qualities and computation times with three algorithms. The suggested problem-specific heuristic presented in this previous sub-section is the first one, with two sets of control thresholds $\delta = \{\delta_1, \delta_2, \delta_3\}$ in $\delta^1 = \{6\%, 90\%, 0.02\%\}$ and $\delta^2 = \{3\%, 95\%, 0.005\%\}$. The second algorithm uses the mixed integer optimizer in ILOG CPLEX, where two level objectives are merged into a single objective function by weighting the objective Z_1 200 times than Z_2, using the traditional branch-and-bound technique to obtain an optimal solution if we could wait until termination.

The third algorithm is the heuristic-CPLEX combined method, introducing the initial feasible solution generated by the suggested heuristic as the starting point of CPLEX program and afterwards, searching for the optimal solution in the traditional branch-and-bound way.

Sets	Heuristic				CPLEX		Heuristic + CPLEX		Gap (Heuristic vs CPLEX)	
	Termination δ^1		Termination δ^2						Termination δ^1	Termination δ^2
	Z_1	Time	Z_1	Time	Z_1	Time	Z_1	Time	Δ_1	Δ_2
SKU50	$2.831e^6$	19s	$2.829e^6$	22s	$2.828e^6$	41s	$2.828e^6$	32s	0.074%	0.025%
SKU100	$6.711e^6$	36s	$6.707e^6$	41s	$6.704e^6$	2951s	$6.704e^6$	1811s	0.096%	0.034%
SKU200	$9.967e^6$	81s	$9.960e^6$	93s	$9.955e^6$	10213s	$9.955e^6$	4307s	0.108%	0.049%
SKU420	$21.354e^6$	132s	$21.347e^6$	159s	-----	------	-----	-----	-----	-----

Table 4.12: Comparison on objective value and run time with three algorithms in Model VTC

Tab. 4.12 shows the comparison on objective value and computation time for the three algorithms. The first column marks the scenario datasets: for set SKU50, where the input scenario consists of only 50 SKUs on 3 production lines for 4 warehouse destinations in 12 weeks; 100 SKUs on 6 lines to 5 warehouses for SKU100 in 12 weeks; 200 SKUs on 7 lines to 8 warehouses for SKU200; 420 SKUs on 14 lines to 14 warehouses. For heuristic column, the results are listed in termination criterion $\delta^1 = \{6\%, 90\%, 0.02\%\}$ and $\delta^2 = \{3\%, 95\%, 0.005\%\}$, presented in the sec. 4.4.2.3. For objective value column, Z_1 is the total cost in euro and for time column in CPU seconds.

We would conclude that the CPLEX optimizer provides always the best solution by looking for an optimal solution, and at the same time, it consumes enormous amount of computational time because of a large amount of integer variables. We observe this time, for the set SKU420, CPLEX cannot achieve the optimal solution in a reasonable amount of time, while in the results for model ATC, set SKU420 is still passable. The introduction of new variables and new constraints increase the complexity of the problem, and the CPLEX optimizer manifest worse performance in time-consuming. In contrary, the suggested heuristic is observed to provide a good approximate solution in 132 seconds, that means just a few minutes are enough to complete computing for set SKU420, while CPLEX optimizer encounters difficulties to look for the next feasible solution. Thus, the proposed heuristic has significantly sped up the solution exploration. It is also noticeable that the results with termination control δ^1compute more speedily than δ^2, while δ^2 could provide better solution.

Besides, the total cost value Z_1 in model VTC is generally bigger in each set than that of model ATC, due to transport cost data in more precision. The Gap in the last column indicates the relative error of the heuristic solutions against the optimal solutions from CPLEX program, while the termination δ^1 shows bigger errors than δ^2. For the two termination groups, all the Gap values are greater that those in the model ATC, mainly due to increased complexity from new variables and new constraints. We can see clearly in the table, the Gap increases as the problem size increases. However, the Gap values observed are not remarkable: for termination δ^1, they are increased but still kept around 0.1% for the SKU200; for termination δ^2, kept tiny below 0.05%. The performance of the proposed heuristic to seek solutions with good quality is well preserved.

In the last column of Tab. 4.12, the combined method with heuristic feasible solution and CPLEX MIP program turns out with less consuming time when providing a solution with similar quality to that obtained with the unique CPLEX optimizer. This result is similar to that described in section sec. 4.4 of model ATC. The results of the model VTC prove as well that the combined method works pretty quicker than the unique traditional branch-and-bound method. Thus, for a relatively small size problem with less integer variables, the combined method may be a good alternative compared to the traditional branch-and-bound CPLEX program. For a synchronized planning problem over 12 weeks updated each week with tremendous integer variables in industrial case, it is unpractical to look for a guaranteed optimal solution in waiting for such long time. In this way, the proposed problem-specific heuristic works efficiently, and the results issued in a few minutes are well within the range of tractability.

4.6 Conclusion

Flexibility considerations lie in every step of the supply chain, where the production and transportation activities count for large costs. Literature on production planning problems, transportation planning problems and integrated production and transportation planning problems in supply chain are reviewed and discussed in the first half part of this chapter.

At the second half of the chapter, we take a glance at a real life production and transportation system, and attempt to exploit its given flexibility tolerances in an optimized way. The company has many restrictions on its production and transportation planning, such as no storage space and limited available train numbers, whereas some other allowable flexibility intervals are imposed to its planning system, like flexible distribution percentages to this or that warehouses. All these requirements lead to a conclusion that its production planning and transportation operations need to be integrated and optimized in a synchronizing way. In fact, three heterogeneous modes of transportation appear in this study: (i) railway train, (ii) truck, (iii) multi-modal transport with train plus truck. Moreover, since each train is composed of different numbers of wagon, and a wagon contains different numbers of pallet, the transportation mode is more heterogeneous than a great part of studies in the literature.

The industrial problem is then formulated as a mixed integer programming problem considering an Average Transportation Cost (ATC) for unit products by train and by trucks to simplify the model, and then solved by a problem-specific heuristic procedure. Compared with the traditional CPLEX program, the heuristic combined CPLEX method can provide an optimal solution in consuming less computation time, and the proposed heuristic can give a good near-optimal solution in a considerably less time. The gap between our solutions against those by CPLEX program are pretty insignificant, for some termination criterion, the gap away from the optimal solution remains quite tiny (<0.05%).

Furthermore, in order to obtain more details, we slightly modify the first model with Average Transport Cost (ATC) per pallet by train and by truck, and then the triple subscripted decision variables in the model ATC become quadruple, called model with Variable Transport Cost (VTC). Products coded with different references can be easily transported together in a same train wagon or a truck. A same logic problem-specific heuristic coding in VB.Net is proposed to solve the problem, and compared again with the CPLEX solution and the combined heuristic-CPLEX solution. The results prove that the combined method runs more quickly than the unique traditional branch-and-bound method and gives an optimal solution if the number of variables is reasonable. Therefore, the combined method may be a good alternative compared with the traditional branch-and-bound method if the decision variables quantity are not too immense. Whereas in our case, for an integrated production and transportation planning problem over 12 weeks updated with tremendous integer variables, it is unpractical to wait such long time for a guaranteed optimal solution. In this way, the proposed problem-specific heuristic works efficiently to give a good near-optimal solution within a reasonable amount of computation time.

5 Conclusions and future research directions

Conclusions

Supply chain strategies have evolved considerably in recent decades. Under the increasing competition in the global market, a good adoption and integration of flexibility decisions can reduce considerably the supply chain operating costs and lead to better potential competitiveness.

The first objective of the work is to provide a better understanding of supply chain flexibility. For the time being, there is no taxonomy of supply chain flexibility universally accepted in the literature and in industries. We first describe different conceptual aspects of flexibility existing in the literature and causative uncertainties. Interconnections and overlappings among flexibility dimensions are revealed and exhibited, as well as the presentation of flexibility terms which are more frequently supported in the literature or of great importance. The flexibility concepts from the supplier, manufacturer, distributor and also all the three are integrated as a whole. In this way, a new framework of supply chain flexibility is outlined and proposed, with several flexibility terms called *major flexibilities* and *other flexibilities*. This new flexibility framework is based on 8 core dimensions: machine, labor, routing, product-mix, volume, supplier, delivery and transshipment flexibility. This framework provides a clear definition and classification, and leads to a complete understanding of the supply chain flexibility. Moreover, we clarify the levers that serve as an action to influence corresponding flexibilities to enrich this framework, which is of great practical sense for companies to set about on how to implement the flexibility in the industry. This chapter 2 has contributed for the defining phase of supply chain flexibility.

In the following part of work, we review the existing evaluation methodologies of supply chain flexibility, and are aware that quantitative studies are still not extensive. Method of Rogalski [Rog11] incorporating explicitly the volume flexibility, product-mix flexibility and expansion flexibility, is carefully presented because each of them can be expressed separately without interfering too much into the analytical model for details. Other measures and methods as Penalty of Change, Design of Systems for Manufacture, Mechanical

Analogy, Simulation of Petri nets and Toolbox Approach are reviewed. To settle an practical assessment on hand, we implement Mechanical Analogy method in supply chain to evaluate the flexibility performance for stores of Louis Vuitton in Japan. This method was rough and never used in supply chain, and our study extends its application scope to whole supply chain and provide good understandable results. We then conclude that, the flexibility performance of one store is generally lower and not as stable as the bigger stores during a year, whereas the products in bigger volume manifest a general better flexibility throughout the year. These results coincide with the real situation of the company, and can help the company identify the flexibility behavior of its stores and products. As a result, a practical evaluation procedure is established to carry out this method in supply chain, where the notion of period-classification and object-classification are emphasized before implementing the analogy method.

We also review the literature on traditional production planning problems, traditional transportation planning problems and then the integrated production and transportation problems. To go further, we go inside an integrated planning problem, especially with a set of given flexibilities. In the Evian situation, no storage space is placed on site, which implies a strong interference between activities of production and transportation. The existence of heterogeneous vehicles is emphasized and presented by train and by truck, and we underline the detailed choice that each train can be fractionated to different numbers of wagon, and a wagon contain different numbers of different pallets. As a result, the transportation mode in this model is more heterogeneous than a great part of studies in the literature.

To solve this problem efficiently, we formulate two mixed integer programs, the first model with an average transportation cost, the other with fixed and variable transportation cost. The solutions are both obtained by three algorithms: the proposed problem-specific heuristics, the traditional branch-and-bound in CPLEX program, and the heuristics-CPLEX combined method. Results prove that the near-optimal solution of our heuristics is close to the optimal one by CPLEX, and runs within a considerably less amount of computation time. Even the CPLEX combined method works quicker than the unique traditional branch-and-bound one. In this way, the proposed problem-specific heuristic is proved to be efficient in solving the Evian problem, and the results issued in a few minutes compared with the optimal solution are well within satisfiable quality. Furthermore, the CPLEX combined method is proved to be really a good approach to look for an optimal solution in considerably less amount of time, if the quantity of decision variables is not too large.

In conclusion, our thesis has well worked to contribute to fill in traditional gaps between academic research and industrial needs mainly on three flexibility fields: i) defining the supply chain flexibility; ii) assessing the supply chain flexibility; and iii) use and management on supply chain flexibility.

Future research directions

For the time to date, quantitative researches on supply chain flexibility are increasingly blooming but still limited. More quantitative methods need to be explored, with the knowledge that a general applicable methodology for different business sectors is difficult to construct. Particularly, methodologies that develop and evaluate a specific subdivided flexibility - the precise dimension of flexibility - are relatively few but extensively interesting for industries. Therefore, it would be quite a good direction to raise further studies.

In the mechanical analogy method, several attributes remain hidden behind the analogical system and can be further investigated. Firstly, a mechanical system of a single degree of freedom has always an elastic spring, a damper and a mass. It is simple to derive a mathematical relation on analogical mass of a supply chain, but difficult to acquire a detailed presentation of the corresponding spring and damper. Therefore, a further direction for this method is to develop this relation to describe a meaningful and representable stiffness and damper of the studied supply chain, which is important to understand the three analogical system attributes. And if impossible to go on in this way, one can adopt the simulation approach to observe: with different input and output data, what has exactly happened in the interior of the company? In this manner, although it is hard to obtain a precise formulation of stiffness and damper of supply chain, an approximate relation to understand the supply chain's mechanical properties would be possible.

Another research point is, if the degree of freedom of a supply chain or a sub-echelon of a supply chain can be identified, the exact mechanical analogy can be made, in analogy to a vibration system with more than one degree of freedom. For a vibrator system with more than one mass, spring or damper in successive way or in parallel, the corresponding supply chain may manifest similar behavior. The limit lies in the fact that, this kind of mechanical system is difficult to be studied, because the analogical response is complicated to be formulated with much more deres of freedom, but remains a really interesting research direction.

For the integrated production and transportation planning problems, flexibility tolerances are always severe questions. More integrated planning models with given flexibility intervals can be developed, and some particular measures presented in chapter 3 could be incorporated in the model.

Nevertheless, the existing integrated production and transportation planning studies have little explored heterogeneous transportation modes. For instance, there are three heterogeneous modes of transportation in our study in sec. 4.3: (i) railway train, (ii) truck, (iii) multi-modal transport with train plus truck. As an example, this could be further developed with more complex delivery modes in the following : (i) railway train with integrated production and transportation option, (ii) truck with non integrated production and transportation planning options, (iii) multi-modal transportation with partial integration, etc. Thus, heterogeneous transportation usage can be further explored.

Most existing studies on integrated production and transportation planning consider deterministic models where product demand is known in advance. However, many kinds of products in real world does not figure in this field. For example, for products having a large variety with short life cycle, the customer demand is of high uncertainty and difficult to anticipate. Furthermore, most existing production-transportation problems involve linear transportation costs, which may be unrealistic in industry. Therefore, more further studies with nonlinear cost and stochastic demand are expected.

Additionally, for the integrated production and transportation planning problems solved by the traditional branch-and-bound CPLEX program and the heuristics-CPLEX combined method, the latter provides optimal solutions within a pretty quicker computation time. It is the method to obtain a first feasible solution by our proposed efficient heuristics, and then use this feasible solution as the starting point of CPLEX program. This method demonstrates a pretty better performance in computation time, and worth to be implemented to reduce the running time in solving other complex problems if the data scale is not too tremendous.

Annex I - Transportation planning problem

A simple form of *multi-plant, multi-commodity, multi-DC, multi-customer* and *two-echelon* transportation problem at tactical level could be formulated as follows:

Decision Variables	
x_{ijkm}	quantity of commodity i to be shipped from plant j through distribution center k to customer market zone m
y_{km}	binary variable will be 1 if DC k serves the customer zone m, otherwise 0
z_k	binary variable will be 1 if DC k is acquired and opened, otherwise 0

Parameters	
D_{im}	demand of commodity i in customer market zone m
S_{ij}	supply of commodity i at plant j
$\underline{V}_k, \overline{V}_k$	allowed minimum and maximum annual throughput for a DC k
cd_k	fixed annual possession and operation cost for DC k
cv_k	variable cost per unit for DC k
ct_{ijkm}	transportation cost per unit for shipping commodity i from plant j through DC k to customer market zone m
t_{ikm}	average time to make a delivery for commodity i to zone m after receiving an order at DC k
T_i	maximum allowed delay of commodity i

The objective function is formulated:

$$Min : Z = \sum_i \sum_j \sum_k \sum_m ct_{ijkm} \cdot x_{ijkm} + \sum_k \left(cd_k \cdot z_k + cv_k \cdot \sum_i \sum_m y_{km} \cdot D_{im} \right) \tag{.0.1}$$

subject to

$$\sum_j x_{ijkm} = y_{km} \cdot D_{im} \qquad \forall i, \forall k, \forall m \tag{.0.2}$$

$$\sum_k \sum_m x_{ijkm} \leq S_{ij} \qquad \forall i, \forall j \tag{.0.3}$$

$$\underline{V}_k . z_k \leq \sum_i \sum_m y_{km} \cdot D_{im} \leq \overline{V}_k \cdot z_k \qquad \forall k \tag{.0.4}$$

$$\left(\sum_k \sum_m t_{ikm} \cdot y_{km} \cdot D_{im} \right) \leq T_i \cdot \sum_m D_{im} \qquad \forall i \tag{.0.5}$$

$$y_{km} = \{0,1\}, z_k = \{0,1\} \qquad \forall k, \forall m \tag{.0.6}$$

$$x_{ijkm} \geq 0 \qquad \forall i, \forall j, \forall k, \forall m \tag{.0.7}$$

In this formulation, the amount $\sum_i \sum_m y_{km} \cdot D_{im}$ interprets the total annual throughput of the distribution center k. Constraints (.0.2) specify the flow conversation for customer market demand and also x_{ijkm} must be 0 for all i, j if $y_{km} = 0$. Constraints (.0.3) insure the supply quantity of commodity i. Constraints (.0.4) stipulate the correct logical relationship between binary variable y_{km} and z_k and make sure the total annual throughput lies in the right interval. Constraints (.0.5) keep the order lead time less or equal than the maximum delay to customers.

From this formulation, a market zone m can be served simultaneously by several distribution centers. If it is not the case, we can still add a relation (.0.8) to restrict a certain market zone $m = l$ to be served by a single DC:

$$\sum_k y_{kl} = 1 \qquad \forall l \tag{.0.8}$$

The cost term ct_{ijkm} can be also modified into a cost function containing a fixed charge and a variable part. In the case that some commodities must be shipped and delivered directly from plants to customers, terms of corresponding cost ct_{ijkm} could be defined independent of intermediate DC, and the corresponding combinations for commodity i and market zone m could be omitted in the term $\sum_i \sum_m y_{km} D_{im}$. If a certain market zone is supposed to receive all commodities directly from its plant, a fictitious distribution center k_0 could be added, together with the associated z_{k_0}, $y_{k_0 m}$ and $ct_{ijk_0 m}$ in the model.

Annex II - Integrated Production and transportation problems class (A)

This model is a simple integrated production-transportation, facility location-allocation problem *[PF2]* in problems class (A) described in sec.4.2.3.1.

For a typical production-transportation, facility location-allocation problem across multiple stages of the supply chain, decision variables and parameters in different echelons must be taken into account. Consider a simple multi-supplier, multi-plant, multi-level, multi-commodity, single-period and homogeneous vehicle problem, on condition that a warehouse serves only one customer zone, we list all the decision variables and parameters as follows:

Decision Variables	
x_{lk}	production quantity of product l produced at plant k
q_{ijkl}	quantity of product l shipped from plant k via warehouses j to customer zone i
m_{skr}	quantity of raw material r shipped from supplier s via warehouses to plant k
p_k	binary variable {0,1} indicating whether the plant k is open or not
y_{ij}	binary variable {0,1} indicating whether the warehouse j serves customer zone i or not
z_j	binary variable {0,1} indicating whether the warehouse j is open or not

Input data	
ow_j	annual fixed cost for operating a warehouse at site j
op_k	annual fixed cost for operating a plant k
vw_j	unit cost of throughput for a warehouse at site j
vp_{lk}	unit production cost for product l at plant k
ts_{skr}	unit transportation and purchasing cost from supplier s to plant k for raw material r

Input data (continued)

tw_{ijkl}	unit transportation cost for product l from plant k via warehouse j to customer zone i
d_{il}	demand for product l at customer zone i
W_j	annual throughput at warehouse j
C_k	capacity of plant k
CS_{sr}	supply capacity of supper s for raw material r
u_{rl}	utilization rate of raw material r per unit of finished product l
Cu_l	capacity utilization rate per unit of finished product l
P	maximum opened facilities
W	maximum opened warehouses

The problem can be then formulated as a cost-based minimization model:

$$[PF2] \qquad Min : Z = \sum_j ow_j z_j + \sum_i \sum_j \sum_l vw_j d_{il} y_{ij} + \sum_k op_k p_k + \sum_l \sum_k vp_{lk} x_{lk} + \sum_s \sum_k \sum_r ts_{skr} m_{skr} + \sum_i \sum_j \sum_k \sum_l tw_{ijkl} q_{ijkl} \tag{.0.9}$$

subject to

$$\sum_j y_{ij} = 1 \qquad \forall i \tag{.0.10}$$

$$\sum_i \sum_l d_{il} y_{ij} \leq W_j z_j \qquad \forall j \tag{.0.11}$$

$$\sum_j z_j \leq W \tag{.0.12}$$

$$\sum_k q_{ijkl} = d_{il} y_{ij} \qquad \forall i, \forall j, \forall l \tag{.0.13}$$

$$\sum_{k} m_{skr} \leq CS_{sr} \qquad \forall s, \forall r \qquad (.0.14)$$

$$\sum_{l} u_{rl} x_{lk} \leq \sum_{s} m_{skr} \qquad \forall k, \forall r \qquad (.0.15)$$

$$\sum_{l} Cu_{l} x_{lk} \leq C_{k} p_{k} \qquad \forall k \qquad (.0.16)$$

$$\sum_{i} \sum_{j} q_{ijkl} \leq x_{lk} \qquad \forall l, \forall k \qquad (.0.17)$$

$$\sum_{k} p_{k} \leq P \qquad (.0.18)$$

$$z_{i}, p_{k}, y_{ij} = \{0, 1\} \qquad \forall i, \forall j, \forall k \qquad (.0.19)$$

$$m_{skr}, x_{lk}, q_{ijkl} \geq 0 \qquad \forall i, \forall j, \forall k, \forall s, \forall r \qquad (.0.20)$$

The objective function (.0.9) minimizes the total cost, including the fixed cost of opening and operating plants and warehouses, the variable cost of production and distribution, transportation cost to transfer raw materials from suppliers to plants and to transfer finished products from plants to retailers through warehouses. Constraint (.0.10) shows the simple assignment of a warehouse to a customer zone and the warehouse throughput is imposed by (.0.11). Constraints (.0.12) and (.0.18) limit the total number of opening warehouses and plants. Constraint (.0.13) ensure that each demand is satisfied without backlogging. Raw material restriction and requirement for production are expressed in (.0.14) and (.0.15). Production in the plants is subject to capacity constraint (.0.16). For each product, the total quantity shipped from one plant to all customer zones through warehouses cannot exceed the production quantity of that product in this plant in (.0.17).

Finally, constraint (.0.19) and constraint (.0.20) impose the integrality restriction and non-negativity condition on the decision variables.

The problem formulation [*PF2*] can be easily extended to multi-period model with inventory flow conservations backlogged or not, between any two adjacent periods. Warehouse assignment in constraint (.0.10) can be modified for the sake of serving more customer outlets. In order to take heterogeneous vehicles into account, the unit transportation and purchasing cost, noted as ts_{skr}, with indices from supplier s to plant k for raw material r, can be splitted into multiple costs ts_{skrv} with different vehicles $v = 1, 2, ..., V$, if the costs are vehicle-independent. Meanwhile, the unit transportation cost designated by tw_{ijkl}, for product l from plant k via warehouse j to customer zone i, can be transformed in the same way: tw_{ijklv} for independent vehicle modes $v = 1, 2, ..., V$. On condition that the vehicle utilization cost is dependent one to another, ts_{skr} and tw_{ijkl} are forced to be functions of the existing vehicle modes $ts_{skr} = ts_{skr}(v_1, v_2, ..., v_V)$ and $tw_{ijkl} = tw_{ijkl}(v_1, v_2, ..., v_V)$. And, the vehicle velocity, volume and loading limits could be also studied for a more detailed problem construction.

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