Collaborative Planning with Benefit Balancing in Dynamic Supply Loops

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Abstract: The paper presents a generic collaboration scheme for supply networks that is based on practical assumptions motivated by the automotive industry. Primarily, it is decentralized, allows autonomous decision making at the partners, and requires a relatively simple information exchange between immediate partners in a supply chain. Within this scheme called Dynamic Supply Loops (DSL), it is possible to balance the benefit of cooperation between the partners. Simulation results on a multi-echelon model show that the DSL approach outperforms traditional upstream planning and facilitates cooperation.

Keywords: Planning, Supply chain, Collaboration, Automotive

1. Introduction

This paper investigates a general and recurrent issue of supply chain management: the contrast between collaborative and local planning. Specifically, it deals with **collaborative planning** of autonomous decision makers, where alone the Original Equipment Manufacturer (OEM) has information about market demand, while all the partners keep their own constraints, objectives and decision mechanisms private. In this asymmetric situation, the goal is to coordinate planning activities of the partners along all tiers of a chain by having as few assumptions towards the local planning processes and communication protocols as possible.

The work presented here was strongly motivated by the above concerns in the field of the automotive industry where the general situation can be characterized by low and fluctuating demands for a growing variety of customized products. As customers become more and more ambitious, demand predictability decreases inversely with the growth of product variability. As a response, the European project AC/DC [9][14] defined a vision to provide a vehicle production and supply system capable of delivering customized vehicles within five days. This vision requires a radical reduction of the supply network lead time and also the definite increase of planning flexibility in the overall automotive production network. Hence, departing from strategy forecasts [30], AC/DC developed an approach called **customize-to-order** (CtO) which combines the advantages of the traditional build-to-order (BtO) and build-to-forecast (BtF) methods. While in the case of BtO, the production of parts or components is triggered and "pulled" by orders, in CtO customer-anonymous components are prefabricated according to forecasts and then customized either by flashing software and/or by parameterization at a late stage of production. One of the main research tracks of the project was to develop automotive components whose variety can be realized this way (e.g., smart actuators, modular sensors or an active rear axle). The other one that in the scope of this paper was aimed at developing new supply planning methods that can exploit the potential of CtO components, namely that they have smaller physical variety, consequently more stable forecasts and lower stock levels necessary for buffering eventual demand uncertainties and disruptions of production.

The planning method realizing these merits of CtO production is called **Dynamic Supply Loops** (DSL). When developing DSL, our main objectives were to improve the overall performance of the automotive supply chain in terms of service as well as inventory levels. Since under normal market conditions decisions in a supply chain are made in a decentralized way, DSL had to coordinate local planning decisions and provide means for turning cooperative attitude of partners into a competitive advantage. Hence, principles for **benefit balancing** have been developed to provide all supply network partners an incentive to act in a cooperative way. This approach that facilitates aligning individual interests with those of the other partners increases total profit of the whole supply chain, and, at the same time, offers advantage of this improvement for each individual partner.

The vision of AC/DC became especially relevant at the time of the financial downturn of late 2008 that had serious impacts on the automotive industry. This time, dramatically decreased market demand caused heavy fluctuations in sales and increased cost and service level pressure both on OEMs and suppliers. According to earlier practice, component supply as well as production systems and supply chains were optimized for operation at maximum utilization without explicitly supporting flexibility. Lack of flexibility and reactivity, as well as restricted communication and collaboration between the partners have led to severe planning inconsistencies, like material shortages that propagated along the chains and ramified to production line shutdowns, too. At crisis time local planning optimization without sufficient coordination often resulted both in over- and emergency production along the same chain, leading to high emergency logistic and contract penalty cost [9]. At the same time, cost pressure on the European automotive industry was growing. Automotive companies in newly industrialized countries have adapted to these new conditions and caught up quickly to the world's leading automotive standards. However, they produced, delivered and sold their cars at lower prices.

In the sequel Section 2 presents related works, while in Section 3 our collaborative planning problem is exposed, together with requirements towards a generic planning scheme. Section 4 outlines the DSL approach, and next Section 5 presents a benefit balancing method that can be realized within DSL. By embedding standard planning methods into this DSL scheme, computational test were also carried out on particular multi-echelon planning problem instances. The encouraging results summarized in Section 6 lead also to the conclusion in Section 7 that DSL is a viable approach to decentralized collaborative planning.

2. Background and related works

In industrial practice, where business is run by autonomous enterprises, the parties in a supply chain have very limited access to private data of the others and hardly participate in each others' planning processes. The consequence of this information asymmetry is that each party focuses on optimizing its own production and logistics by using information locally accessible. This leads to a **decomposed planning** scheme, where the overall planning problem of the supply chain is divided into as many sub-problems as the number of parties, and the sub-problems are solved one by one. Of course, so as to satisfy external demand, decentralized decisions have to be coordinated. Typically, local planning problems are solved in a sequence, where the solution of one problem sets target for the next one. The most common procedure widely applied also in the automotive industry is **upstream planning** [7][20], a hierarchical sequential decision scheme starting at the downstream party (e.g., OEM) who, after solving its own planning problem, generates demand to its suppliers. In a longer chain, this pattern is repeated upstream. Disparate objectives and the decentralization of decisions may easily lead to suboptimal overall system performance, a phenomenon known for long as double marginalization [27]. Information asymmetry and local autonomy cause together time and again inefficiencies like acute shortage situations or excess inventories. Recently, Albrecht analyzed and classified a number of drivers that lead to sub-optimality in decentralized planning [1]. Satisfying the target set by one partner may incur some extra costs at another one (e.g., when too large quantities, or too frequent deliveries are required), increasing thus the system-wide costs, too.

The inevitable sub-optimality of the decomposition approach motivated researchers to investigate **integrated** or **centralized** supply chain planning methods (see [12] for a recent overview). For instance, the first polynomial algorithm for solving the centralized problem with an arbitrary number of tiers has been proposed by Zangwill [31], using the concept of concave cost networks. (We will apply this method in a comparative analysis, see Section 6 later.) The potential gain by centralized versus decentralized decision making in supply chains has been investigated in [19], where the difference of the induced costs is defined as the price of anarchy. Hence, centralized models are of great theoretical relevance, but they may only be applied if the parties are strongly tied together, e.g., they are different divisions of the same enterprise or constitute a virtual enterprise [5]. In any case, the centralized approach presumes an agency that knows all the parameters and whose decisions are adopted by all partners. It minimizes the total cost on the supply chain level, while, in itself, it may increase or decrease the costs of the individual parties depending on the actual parameters. To guarantee that centralized planning is beneficial for all parties, its practical implementation often involves some settlement on the sharing of benefits, which may range from the reduced unit prices to complex pricing schemes. However, the application of centralized planning is unpractical in supply chains with more than two parties because of the increased computational complexity, the difficulties of sharing information, as well as of getting plans executed accurately even in face of uncertainties.

The key question of **coordinated planning** is whether it is possible to circumvent the deficiencies of the decomposition method when there is no opportunity for centralized planning? Can one improve the overall performance of the supply chain while maintaining the information asymmetry and local decision authority of the partners? Even though the literature provides quite a number of alternative definitions for coordinated planning, it is generally accepted that coordination complements the division of labour by re-adjusting some actions of the partners so as to achieve certain common, system-level goals [1][2][12][24]. That is why the term **collaborative planning** is used. In turn, coordination is rarely possible without information exchange, i.e., **communication**. The technical foundation of communication have been established for a long time, in general by the Electronic Data Interchange (EDI) standards, and, specifically, for the automotive industry by the ODETTE messaging standard and protocol [18]. The centralized SupplyOn platform has been developed by several European automotive part suppliers for facilitating information exchange between numerous planning tasks in the fields of engineering, sourcing, logistics and quality management [25]. A similar approach called myOpenFactory [22] proposes a centralized information sharing agency using standardized, industry-neutral data and process models. The AC/DC project developed also its fast, secure and easy-to-access Internet-based communication protocol, the so-called AC/DC messaging service that offers services for process automation supporting easy and inexpensive collaboration in the supply network [9]. Recently, we have developed and deployed a Logistics Platform that provides a complex service for exchanging information on the tactical and operational planning levels in a focal supply network operating in the consumer goods industry [28] [29].

However, information exchange alone is not sufficient: **cooperative** attitude of the partners is also needed so that eventually they align their individual interests with system-wide objectives [17]. Specifically, **cooperative** planning mechanisms are needed that (1) provide incentives for the partners to communicate relevant information about their actual status and future plans truthfully, and (2) facilitate the sharing of risks and profits to make partners interested in cooperation [12]. According to the strong notion of coordination, a supply chain is coordinated if and only if the partners' optimal local decisions are implemented and lead to optimal global performance. This problem can be captured in a game theoretic setting [4]: how to find a set of local supply chain actions (i.e., production and delivery) that result in a globally optimal solution, which is, at the same time, such an equilibrium from which no partner has an interest to deviate? The game theoretic perspective leads to theoretical contract models [3] or cooperative bargaining games [16] that coordinate a supply channel under rigorous simplifying assumptions (e.g., typically, one-period models are handled). Hence, a number of authors suggest a weaker concept: the supply chain is coordinated if the local, selfish production and delivery actions result in a better (at least as good) overall performance than the decomposed solution [1] [7] [24]. This definition allows for a wide spectrum of coordination mechanisms that have though some generic features in common:

- While keeping the privacy of sensitive cost factors, there is a need for sharing information on the intentions (specifically, plans) of the partners.
- So as to arrive at a coordinated solution acceptable for both parties, alternative plan scenarios have to be generated and evaluated mutually by all concerned parties.
- An incentive scheme is required that drives the partners towards coordinated solutions. This works only if the potential benefits of coordination are shared.

Though, when it comes to coordinate a real supply chain, the theoretical approaches are typically prone to fail due to some of the following reasons: they are rooted in unrealistic assumptions; the decision problems are computationally prohibitive; industry is reluctant to apply complex automated negotiation protocols; it is hard to transform an incentive scheme into a business model that is acceptable for each partner; and, last but not least, they preclude the application of well-proven planning methods available in *de facto* standard Enterprise Resource Planning (ERP) systems. Due to the above reasons, in the industrial practice collaborative planning is confined so far to information exchange.

3. Problem statement

3.1. Planning in automotive supply networks

Actually the supply chain in the automotive industry is organized as a hierarchical **upstream** planning system, proceeding top-down from the OEM to its suppliers [15]. Thereby the planning process encodes restrictive planning conditions where the OEM forces the $tier_1$ suppliers to fulfill its specific orders without compromises and delivering the needed information to generate a robust and reliable plan for a longer time period at $tier_1$. E.g., the OEM can optimize his costs unilaterally by forcing the $tier_1$ suppliers to deliver only just in time. In the supply chain, the same pattern is repeated between $tier_n$ and $tier_{n+1}$. Clearly, coordinating the supply chain via orders is not really possible, because optimal production quantities (and periods) depend also on factors—like setup and production costs, resource capacities—that are known to the upstream partner only. Further on, a $tier_{n+1}$ supplier serving several customers at a time may exploit economies of scale by aggregating distinct demands. By placing firm orders, the $tier_n$ party intrudes into the planning process of its supplier. Forced through the supply chain, this problem leads to several problems: loss of optimization potentials in local planning decisions because of restricted information policies, capacity overloads because of uncertainty according to future demand developments and the need of an enhanced event handling system to react fast to uncertain demand changes and occurring material shortages. These circumstances lead to an unstable and inflexible system wasting time and money for keeping it running, therefore increase the product price while reduce the accounts. All in all, the actual automotive supply chain is operated in local optima according to the specific situation of each partner.

3.2. Requirements towards collaborative planning methods

A new planning approach should be established that regards all the above problems in the automotive supply chain driving the overall system towards a better performance in terms of lead time, reactivity and overall system costs. The new planning concept should meet the following general requirements:

- It should guarantee local planning autonomy and the usage of existing local planning systems including multi-criteria decision making at each partner in the supply chain.

- Whenever sufficient information available, it should regard also non-local planning preconditions and information (like available capacities) about the upstream, $tier_{n+1}$ supply chain partner. Details of this problem have been analyzed in [6].
- The planning approach should allow competition between partners in the supply network as well as support cooperation between them. By using principles for benefit sharing and incentives for system participation, the system as a whole should be driven from local minimum points towards a performance that improves decomposed and even traditional upstream planning, i.e., coordinates the chain in the weak sense.
- It should support the coordination and collaboration of partners at all levels of the well-established planning hierarchy [10], i.e., at the levels of strategic, tactical as well as operational planning.
- While more information should be shared to find mutually beneficial solutions, information overflow and unstructured exchange should be avoided. Specifically, a simple protocol is needed for an efficient, bi-directional communication process, extending existing standards in automotive industry like ODETTE and enabling also smaller suppliers' information access and participation.

4. Planning in Dynamic Supply Loops

4.1. The overall Dynamic Supply Loop concept

The core concept of the DSL is a flexible readjustment of the supply network structure and decisions based on collaborative continuous planning processes in closed loops between $tier_n$ and $tier_{n+1}$ both on the strategic and the tactical planning levels. On the operational level, DSL controls event handling processes. All planning processes are based on a one-stage feedback loop to support process reliability and prevent long, cyclic adjustments of the planning decisions. The Dynamic Supply Loops target 100% reliability of delivery to the customer of end-product (i.e. reliability of delivery by the OEM).

The DSL are structured in three layers following the levels of the classical aggregation hierarchy of planning:

- The **strategic** loop generates the up to 5 years long frame plans for the whole supply network used as general planning agreements and valid as constraints for deriving tactical and operational plans. In particular, expected demands, needed capacities and locations on product platform level are determined here. The generation of initial frame plans has been described by Timm [26] using a hierarchical optimization model.
- **The tactical** loop offers planning methods for generating demand and corresponding production and supply plans on a horizon of up to 18 months. Planning in the tactical loop is discussed further in this paper.
- The **operational** loop handles short-term plans, implements pre-emptive event detection and provides real-time feedback from execution. It ensures fail-safe operation by adapting operational plans to changed conditions by making use of the flexibility of production resources on the shop floor.

Figure 1 shows how DSL breaks with the traditional upstream planning practice by establishing a one-step feedback planning loop between any immediate partners $tier_n$ and $tier_{n+1}$. Accordingly, $tier_n$ will propose several planning scenarios to its suppliers at $tier_{n+1}$ and ask them for the specific cost statements. The scenarios may include also informal knowledge about the plant locations, flexibility and delivery conditions of the suppliers. The idea is to propose only those scenarios which could be fulfilled by the supplier. $Tier_{n+1}$ will calculate scenario cost statements using its own planning facilities (e.g., an ERP system) and communicate those back to $tier_n$. This feedback will be used by $tier_n$ when making a final decision on the distribution of demand figures to the $tier_{n+1}$ supplier.

The resulting process is a strictly structured negotiation protocol which can be implemented easily and allows for fast reaction times. Because of using information on $tier_{n+1}$ during the scenario generation at $tier_n$, the accepted plans will be more focused to the actual situation at

$tier_{n+1}$, in opposite to the traditional upstream planning procedures in today's automotive supply chains. This additional information may refer to capacity capabilities, flexibility agreements, quality issues or specializations as well as the frame plan at $tier_{n+1}$.

The supplier is getting more flexibility, now being able to reduce its costs and stocks because of better focused and more realistic demand plans from its buyer. Further on, it can evaluate various alternatives and express its preference in terms of prices. Though, when choosing the final scenario not only prices but other factors like lead times or inventory levels may matter, too.

<Figure 1 comes here.>

To offer incentives for taking part in the DSL, $tier_n$ and $tier_{n+1}$ should agree on some regulations for balancing the saved system costs as benefits of cooperation. E.g., the supplier at $tier_{n+1}$ offers its $tier_n$ partner a well operated vendor managed inventory without including the costs into the products, and $tier_n$ regards available inventory and capacity information on $tier_{n+1}$ when generating the planning scenarios [8]. Both have profit in this situation: the inventory level is on the needed level at sufficient costs and $tier_{n+1}$ is able to operate a robust production system relying on expected buyer call-offs from $tier_n$. On the long term, costs as well as stock levels can be reduced due to increased reliability and less nervousness of the whole planning system. Finally, the DSL scheme does not impose any particular planning and performance evaluation method on the partners.

4.2. Definition of the tactical level planning problem

The aim of the tactical planning is to convey between the strategic and the operational hierarchy levels: it transforms the long-term strategic visions and goals into a medium-term rough plan that should be later detailed and executed on the operational level. Due to the high level of uncertainty related to the medium-term environment, forecasting is a very important prerequisite of tactical planning. Forecasts can be related to different market conditions, such as demand, prices, raw material supply and transportation uncertainties (e.g., oil price, aviation security). We note that in a CtO production regime demand forecasts of components are more accurate than that of the end-products [9].

Based on the forecasts and the high-level goals, a medium-term plan (also called master plan) is created that often overlaps not only different functional areas—e.g., sales, distribution, production, procurement—but also different nodes of the supply network. That is one reason why supply chain coordination generally focuses on the tactical level, since the integrated planning in this case offers the largest possibility for collaboration and improvement of efficiency [1] [2].

The DSL concept does not favor a specific planning model, since different characteristics of the supply chains require different approaches. Instead, it assumes only that the planning problem can be solved in multiple ways—for instance by applying different algorithms or different parameters—, and the plans generated in this manner can be evaluated according to distinct criteria and by various supply chain partners.

To be more formal, let us generally define the tactical planning problem as the following: given a set of forecasts ($F_1,\ldots F_k$), the planner should derive a production plan (P_0), usually according to some optimality criteria. The forecasts can come as demands of different customers, from analysts of the customer service department, using statistical demand planning methods, or more frequently, from the combination of these. We also do not restrict the applied planning method, but we regard it as a black box that computes the production plan. From P_0 the supply plan (S_0) can be derived, which acts like a demand (forecast) for the suppliers of the next tier.

The DSL approach extends this framework by applying different planning methods (or parameter settings) in order to generate alternative scenarios for the production, and thus also for the supply. This idea of multiple scenarios is also supported by recent research in production flexibility that is aimed at exploiting a typical property of constrained optimization problems, namely that they have several solutions with dissimilar structure but similar quasi-optimal objective function value [23]. In such cases, it is often more beneficial to choose a quasi-optimal solution instead of the optimal one, considering also additional issues like robustness, or, as in our case, the suppliers' evaluations.

5. Coordination with benefit balancing

In traditional upstream planning the $tier_n$ enterprise optimizes its production without considering the consequences at the subsequent tiers. The DSL process changes this practice by involving the supplier into the decision making. But why would an enterprise choose collaborative planning instead of focusing exclusively on its own interests? The reason is the long-term sustainability: inefficient production anywhere in the process entails higher prices, which causes poor competitiveness of the whole supply chain. If for this reason the prices are kept artificially low, it becomes the source of financial, and eventually of supply problems.

In order to formally analyze the DSL approach, it is assumed that the supplier estimates the costs of the given scenarios and offers price discounts for its preferred plans. This can be interpreted as a combination of the **menu of contracts** and the **price discrimination** approaches of the classical microeconomic theory [13]. The price discrimination technique is applied when a seller declares different prices for the same product or service. One well-known example is when the price decreases as the purchased quantity grows, and so it inspires the customers to buy more. The menu of contracts is a tool of the contract theory for overcoming adverse selection, i.e., when the information asymmetry on a market results in an undesired outcome. According to this approach, the less informed party offers a menu of different contracts to the more informed one, which then can choose from the possibilities. If the menu is well constructed, then the chosen contract not only reveals the private information, but is also optimal for the one who offered the menu. This is a technique originated and most successfully used in insurance, where the risk-taking behavior of the clients is not known to the insurer in advance.

Hence, the **tactical planning loop** works in the following steps:

1. Instead of generating only one optimized plan (S_0), the $tier_n$ enterprise generates several alternative scenarios ($S_0,\ldots,S_m$). Let c_i^n denote the cost in $tier_n$ of executing the *i*th scenario, where S_0 is the default upstream plan, i.e., c_0^n is the lowest cost for the buyer.
2. The $tier_{n+1}$ enterprise does not know the buyer's costs for the scenarios, but only its own estimated costs: c_i^{n+1}. Then it calculates how much benefit can be realized in $tier_{n+1}$ executing S_i instead of S_0: $b_i^{n+1} = c_0^{n+1} - c_i^{n+1}$. If b_i^{n+1} is positive, the supplier prefers the *i*th alternative compared to S_0, and therefore is willing to share its benefit in order to inspire the buyer deviating from the default upstream scenario. The ratio of the benefit sharing is up to the supplier, considering both its own interest and the sufficient inspiration to $tier_n$.
3. Let t_i^{n+1} denote the compensation offered as price discount for choosing S_i scenario, then the compensated total cost for $tier_n$ is $c_i^n - t_i^{n+1}$.
4. In the end, the buyer selects the scenario which incurs the lowest total cost.

It is easy to see that the total cost of the two tiers—not explicitly known by either of the partners—can only decrease by applying DSL instead of upstream planning. The loop is **coordinated**, if the $tier_n$ chooses the scenario which results in the lowest total cost. Since guaranteeing this requires unrealistic assumptions, i.e., complete information, a workable objective is to improve the performance compared to upstream planning (see also [1] [24]).

The above process can be illustrated by the example in Table 1. Accordingly, the buyer prefers S_0, the supplier S_4, while S_1 is the optimal scenario. In this case, offering half of the benefit results in a coordinated solution (S_1), and price reductions from 13 to 12 in $tier_n$, and from 30 to 28 in $tier_{n+1}$. The example also shows that coordination—or even improvement—does not necessarily happen: if $tier_n$ offers only scenarios S_0 and S_2-S_5, the result will not be the optimal one (in this case S_4), but the same as in the upstream case.

<Table 1 comes here.>

Although DSL cannot worsen performance in a two-echelon chain compared to upstream planning, this is not guaranteed in longer chains. Therefore, the behavior of DSL in multi-echelon cases is studied next.

6. Computational study

6.1. The experimental setup

This section illustrates the behavior of the DSL planning concept based on some numerical experiments. Since the realistic planning algorithms are very complex (see [26]), here the simpler **multi-echelon dynamic uncapacitated lot-sizing problem** had been analyzed. In this problem the end-product demand is given on a finite horizon that should be fulfilled by a chain of manufacturers. At each echelon, all demand is satisfied without backordering. Production incurs a fixed setup cost as well as inventory holding costs. The total cost in the whole supply chain can be minimized by applying Zangwill's centralized model and algorithm [31]. This model assumes that every cost parameters are known by a central decision maker, whose aim is to minimize the incurring cost at the chain level, disregarding its distribution between the echelons. Zangwill developed an efficient dynamic programming algorithm that determines the optimal order quantities, at each echelon.

For generating alternative DSL scenarios, the following standard single-echelon lot-sizing methods had been applied (see [11]).

- Wagner-Whitin. An exact algorithm for solving the single-echelon uncapacitated lot-sizing problem that guarantees achieving the minimal total cost.
- Lot-for-Lot (LFL). The simplest heuristic that results in an ordering quantity equal to the demand in each period. This rule results in zero holding and maximal setup costs, therefore it is usually applied when the setups are negligible.
- Economic Order Quantity (EOQ). This rule assumes constant demand by regarding the average demand on the horizon and applies the EOQ square root formula to obtain the optimal order quantity. This results in a fixed quantity that is ordered whenever shortage would occur otherwise.
- Periodic Order Quantity (POQ). This policy also uses the EOQ square root formula, but instead of determining the quantity, it is used to appoint the ordering periods. When the ordering times are given, the order quantities are equal to the sum of the demand until the next ordering.
- Silver-Meal. This heuristic tries to balance the setup and holding costs by contracting quantities starting from the beginning of the horizon, until the decrease in setup is greater than the increase of the holding cost. After determining a quantity, the algorithm continues until the end of the horizon is reached.

The above methods are also available in most commercial ERP systems [21]. For upstream planning, the Wagner-Whitin method was used at each tier, which provided the optimal solution for the single-echelon problem. The simulations were made with four different methods:

- Zangwill's algorithm provides a theoretical lower bound on the achievable cost.
- Upstream planning provides the as-is default solution.
- DSL approach with fair benefit sharing, i.e., when the suppliers offer half of their benefits to the downstream partner as compensation.
- Coordinated DSL is also a theoretical solution, where $tier_n$ chooses the scenario which minimizes the total cost of $tier_n$ and $tier_{n+1}$. I.e., $tier_{n+1}$ offers all of its potential benefits to the downstream partner.

Compelling questions are as follows: Is it worth applying DSL instead of upstream planning? How far is the decentralized DSL solution from the theoretical optimum? These are real issues also in longer chains where bilateral collaboration of DSL cannot guarantee overall improvement.

6.2. Summary of simulation results

For the simulation studies, we have regarded four parameters of the problem:

- the length of the horizon,
- the length of the supply chain,
- the average demand, as well as
- the growth of the average time between orders (ΔT) upstream in the chain.

This latter characterizes the ordering frequency, i.e., if ΔT=1 then an order is made in every period, while larger ΔT denotes less frequent orders. We modeled various chains with increasing ΔT upstream in the chain with a single parameter, the growth of ΔT, that expresses the difference of ΔT between subsequent links of the chain. When the ΔT growth is zero, ΔT is 1 in each echelon. When the growth is 2, the ΔT values are 1, 3, 5, 7, etc. At $tier_0$ (OEM) the production is considered to be continuous (ΔT=1), while upstream the ΔT usually increases. This reflects that next to the market a pull principle is applied (CtO), while the other end of the chain is rather operated in a push manner (build-to-stock) [9] The investigation of the role of ΔT is especially relevant in automotive supply chains, where suppliers more and more upstream in the chain operate typically with increasing times between orders (c.f., final assembly, electronic and hydraulic components manufacturing and semiconductor industry).

The inventory cost in $tier_i$ is taken as a uniformly distributed random variable between $0.3/i$ and $0.5/i$. This way both randomness and decreasing tendency characterize the inventory costs, since storing end-products is typically more expensive than holding parts and raw materials.

The setup costs can then be determined from the inventory costs and the ΔTs using the EOQ formula $q = \sqrt{2ds/h}$ and the fact that $\Delta T=q/d$, where d is the average demand, s is the setup cost, h is the inventory holding cost, and q denotes the optimal order quantity. Thus the setup becomes $s=hd\Delta T^2/2$.

We have considered 5 different horizons (from 10 to 50 periods), 7 chain lengths (from 2 to 8 echelons), 21 ΔT growth values (from 0 to 2) and 10 different average demands (from 100 to 1000) to provide a wide spectrum of experiments. All 7350 combinations of the parameters were used as basis for 100 randomly generated problem instances, which were solved with the centralized Zangwill algorithm, the upstream planning, the “fair” DSL, and the coordinated DSL methods. The figures presented below illustrate how the latter three methods performed in comparison to the Zangwill algorithm that generated the theoretical optimum. The performance indicator of the methods is their relative cost surplus compared to the optimal solution, in percentages.

<Figure 2 comes here>

Figure 2 shows that as the chain is longer and longer, the planning approaches are also more and more inefficient. One should note that in a two-echelon case the costs of the upstream and coordinated DSL are tight upper and lower bounds for the DSL approach. However, the gap is also slightly increasing between the upstream and the DSL approaches. This is remarkable, because while in the two-echelon case the upstream solution is an upper bound on the performance of the DSL, it is not guaranteed in longer chains: an improvement at the beginning of a chain may worsen the performance later. In principle, for chains longer than two partners, DSL may result in larger costs than upstream planning, as we have seen on scattered examples during the simulation runs. Though, in spite of this theoretical possibility, the experiments show improving average performance of the DSL compared to the upstream planning as the chain is getting longer.

<Figure 3 comes here>

In Figure 3 the effect of the increasing ΔT can be observed. When the ΔT is growing throughout the chain (all except the first bars in each row), the planning methods are far from optimal. However, the DSL approaches tend to improve when the ΔT increasingly grows. This is also a noteworthy phenomenon, because in several supply chains the ΔT grows significantly, i.e., in the automotive industry the OEMs should react to demand in a few days, while at the other end of the chain, the semiconductor suppliers have a couple of months lead-time due to technological reasons.

<Figure 4 comes here>

Examining the cases with the different average demands revealed that this parameter does not affect the results significantly; the inefficiency remains almost constant for each method.

<Figure 5 comes here>

As far as the length of the planning horizon is concerned, the results are somewhat surprising, namely, as the horizon increases the performance of the DSL converges to the upstream solution that barely changes. This suggests that the DSL can be most successfully applied on shorter planning horizons.

All in all, simulations confirmed that applying DSL does not decrease in average the performance of planning in comparison to the traditional upstream planning method, while under certain circumstances its application results in significant cost reductions. Considering the total costs accumulated in the whole chain, the fully coordinated version of DSL performed definitely better. At the same time, it is necessary to study extensively the potential planning models, cost structures and ΔTs before implementing any particular protocol of the DSL collaboration scheme.

7. Conclusions

Although the need for collaborative planning in supply chains is generally recognized, there is still a gap between theoretic proposals and practical requirements. The suggested principles of the Dynamic Supply Loop can be treated as a viable compromise for more optimized inter-company planning: it offers a platform for other partners' options, while keeping communication and decision complexity at bay through a relatively simple information exchange and decision protocol confined to immediate partners in a chain. DSL is open to embed standard planning techniques and novel incentive schemes alike. Simulation results on a multi-echelon model showed that DSL outperforms traditional upstream planning and facilitates channel coordination. Although it has been developed to support collaboration in an automotive supply chain, DSL has no special assumptions or features that would hinder its transfer to other industrial sectors.

8. Acknowledgement

This work has been supported by the EU AC/DC IST No. 031520, the OTKA No. T73376 and the OMFB No. 01638/2009 grants.

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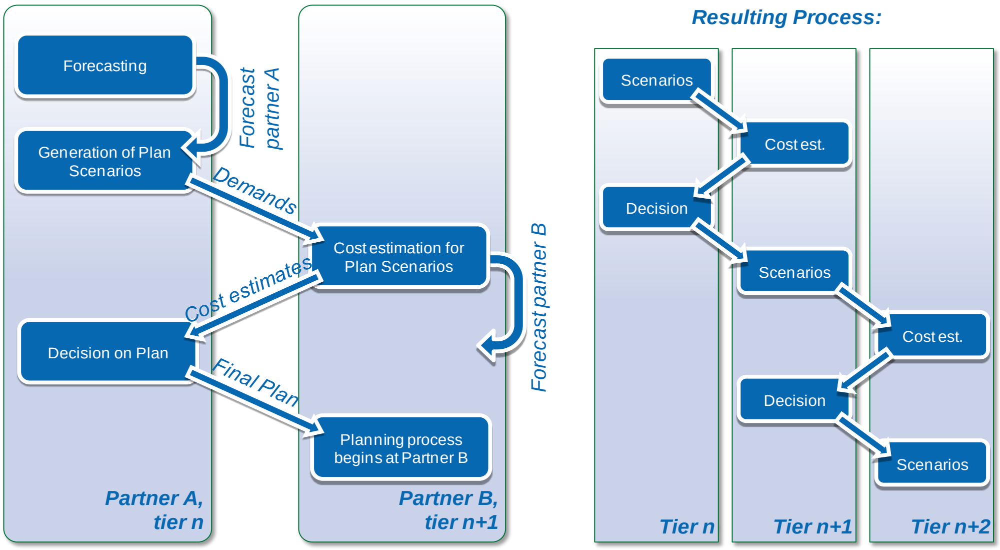

Figure 1 Planning protocol of the Dynamic Supply Loops

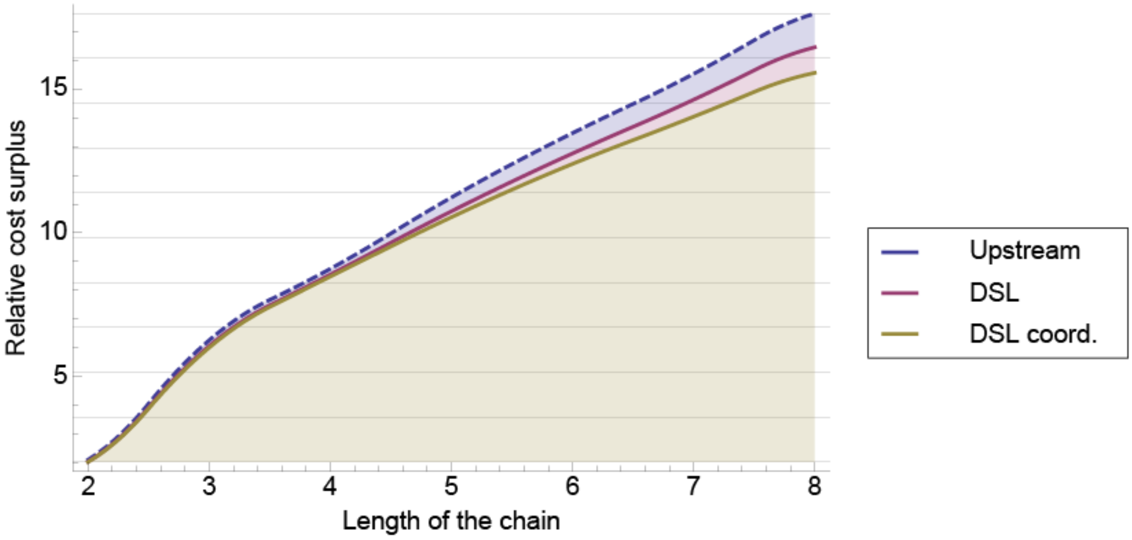

Figure 2 Performance of planning methods for increasing chain lengths

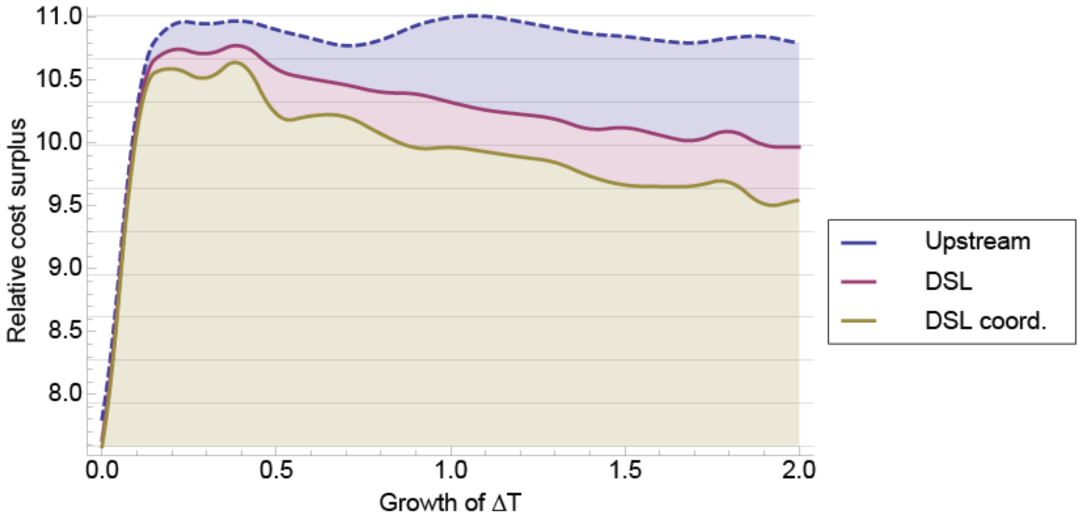

Figure 3 Performance of planning methods for increasing *ΔT*s growths

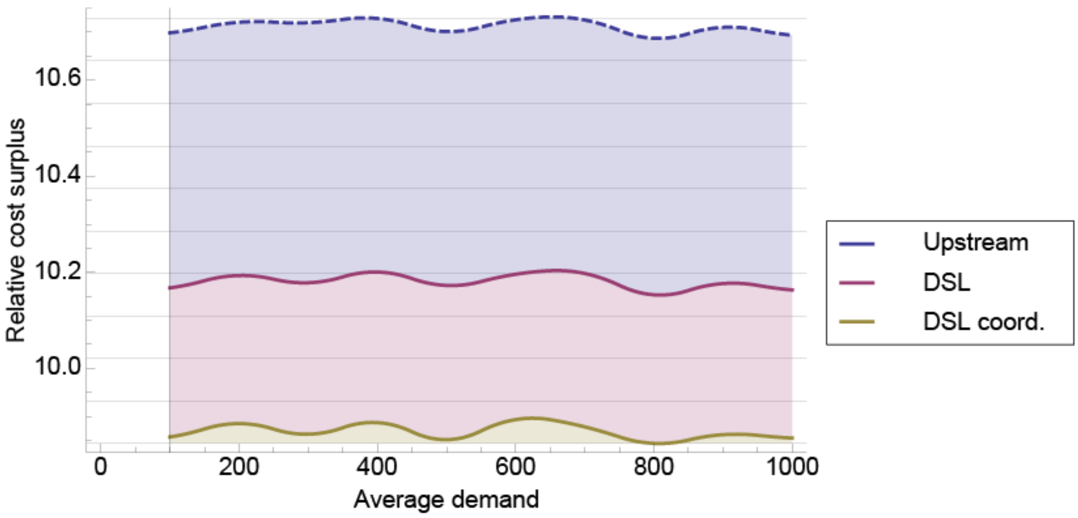

Figure 4 Performance of planning methods against average demand

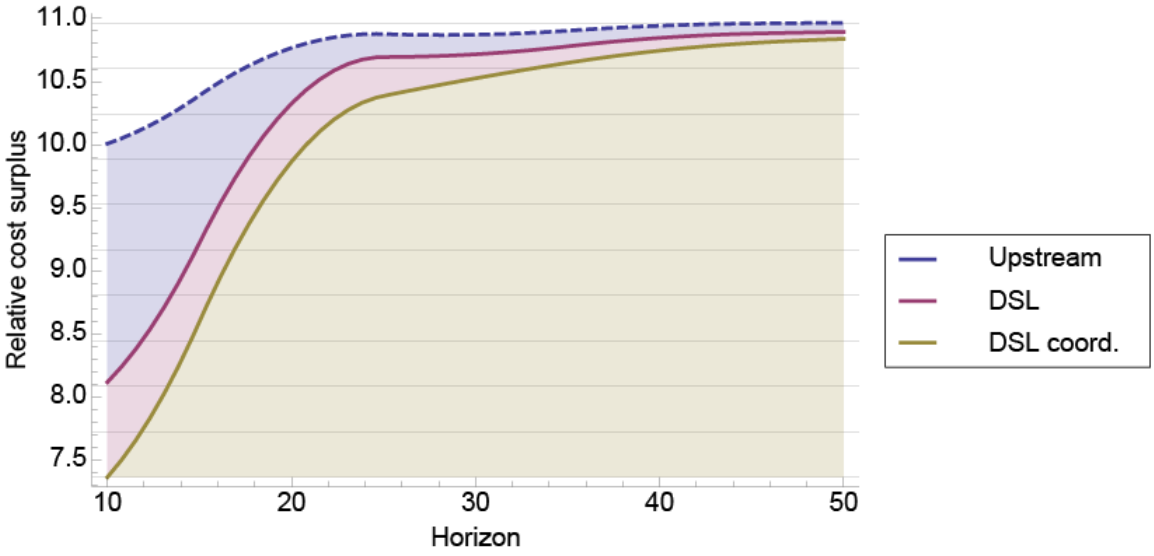

Figure 5 Performance of planning methods for various horizons

Tables

Scenario	S_0	S_1	S_2	S_3	S_4	S_5
Tier_n cost (c_i^n)	**13**	14	15	16	17	18
Tier_{n+1} cost (c_i^{n+1})	30	26	28	28	**24**	32
Total cost ($c_i^n + c_i^{n+1}$)	43	**40**	43	44	41	50
Benefit ($b_i^{n+1} = c_0^{n+1} - c_i^{n+1}$)	0	4	2	2	6	-2
Compensation ($t_i^{n+1} = 50\% \times b_i^{n+1}$)	0	2	1	1	3	0
Tier_n compensated ($c_i^n - t_i^{n+1}$)	13	**12**	14	15	14	18
Tier_{n+1} compensated ($c_i^{n+1} + t_i^{n+1}$)	30	28	29	29	27	32

Table 1 Example of benefit sharing