Towards coordination in robust supply networks

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Abstract: Supply chains nowadays frequently face risks caused by increased environmental volatility and performance inefficiency. In this paper an integrated supply chain planning approach is suggested that combines the three aspects of *optimisation*, *risk mitigation* and *decentralisation*. The goal of this paper is to outline the research directions for industrially relevant and applicable methods for integrating robust and coordinated supply chain planning.

Keywords: Supply chain, risk mitigation, robustness, coordination, inventory control

1. INTRODUCTION AND RELATED WORKS

Recently, supply chains have became more and more globalised and lean so that they can reduce their operating costs. However, this has also decreased their flexibility and increased their vulnerability. Several cases are known when unexpected disturbances at any distant point of their supply chains could paralyse even large multinational companies due to the lack of risk mitigation and uncoordinated decision making.

The RobustPlaNet project aims at developing an innovative business approach along with a supporting technology that will change the current rigid product-based business models into collaborative and robust production networks able to timely deliver products and services in very dynamic and unpredictable, global environments. This approach will allow distributed supply networks to efficiently operate with high service levels in global markets characterised by demand and variant uncertainty, and an environment exposed to disruptive events. In this paper we investigate the theoretical background, as well as the applicability and integrability of robust supply chain planning and coordination methods.

There are numerous risk factors in supply chain planning. One of the most frequently studied type is the *demand variation and obsolescence*. The demand for a product is not only fluctuating, but can even permanently cease, e.g., in case of the development of an improved substituting product. In order to avoid unnecessary excess inventories, the ramp-down phase of the products should be considered separately and planned with special care. An other problem is the *supply time uncertainty*: material shortages can occur also due to supplier fault, transportation problems, quality problems, to name a few. Furthermore, there is also *production uncertainty* due to machine breakdowns and personnel absence that can delay production. Finally, *disasters and other unforeseen events*—e.g., natural disasters, terrorist attacks, political instability—considerably influence the supply chain operations, but they are extremely hard to predict (Simchi-Levi, 2010).

Risks can be categorised into two types: *predictable* and *unpredictable* (Simchi-Levi, 2010). The predictable risks are quite frequent, thus they can be forecasted for example by statistical methods. Such predictable types are the demand fluctuation or the scrap production. On the other hand, unpredictable risks are rare (their probability is low), but if they happen, they have huge influence. Some recent extreme natural disasters—such as tsunami, flood, volcano eruption, blizzard—, sudden changes in the economic conditions or political environment fall in this category. An important metric of disruptions is the Time-To-Repair (TTR), i.e., the time required for the affected facility to return to full capacity.

Considering risks during the supply chain planning phase can be carried out in several ways. One can for example run several randomised *simulation*s in order to evaluate a plan in a stochastic environment. An other approach is to include the uncertainty into the planning model and apply a *stochastic programming* approach to solve it. Yet another possibility is the *scenario generation*, which does not require a stochastic model, but instead a number of alternative scenarios of possible disruptions in the system. Furthermore, *robust optimization* approaches aim at finding such solutions that also perform well if their uncertain parameters vary in predefined intervals.

In RobustPlaNet we define *robustness* as the ability of a system to provide the desired output even in presence of internal and external disturbances. Both uncertainties in the environment and partial failure of the system should be considered in order to call the system robust. A possible metric for supply chain robustness is the *Time-To-Survive* (TTS), which was proposed by Simchi-Levi et al. (2015). The TTS of a facility in a supply chain is the time that the customer service level can be maintained if the facility is disrupted, and the TTS of a supply chain is the minimal TTS of its facilities (the weakest link).

There are several planning decisions in supply chains that influence the robustness. For *supplier selection*, when the decision is made for the long term, single sourcing is very vulnerable. Instead, frequently dual (or even multiple) sourcing is applied—c.f., 2-flexibility from Simchi-Levi et al. (2015). The *place and level of the inventories* are also essential for the robust planning. For example, storing large amount of finished goods might provide safeguards against supply problems, but this is usually a quite expensive solution. Sometimes *production capacity* buffers and flexibility might be necessary in order to adapt to the increased demand and avoidance of bottlenecks, but this decreases the resource utilization. *Logistic decisions*—such as choosing the applied ordering policies, frequencies, order quantities and transportation modes—also affect the vulnerability towards disruptions. Further decisions can also indirectly influence robustness, such as the applied forecasting method or the product and part pricing.

Numerous practical approaches have been proposed for supply chain risk mitigation focusing on the previously mentioned decision problems, see e.g., Tang (2006) or a recent literature review by Ho et al. (2015). Two of the most well-studied strategies are holding *protective inventory* and increasing *process flexibility*. Holding additional inventory is a straightforward way to hedge against disruptions: if the inventory is high enough to cover the demand for the duration of TTR of the disrupted facility, then it will not affect the service level, thus the supply chain can be considered robust. Note that the necessary protective inventory depends only on the TTR, thus the long lead-times of some suppliers do not increase the required inventory. Unfortunately, holding sufficient buffers can still be very expensive.

The process flexibility on the other hand, means introducing redundancy to the supply chain, e.g., when a plant or production line can build different types of products, thus the demand can be satisfied from different sources. Increasing flexibility can also be costly, and in addition, it also requires additional capacities: if there is no excess capacities in the system, the work cannot be redistributed in case of disturbances.

Simchi-Levi et al. (2015) suggests that protective inventory and process flexibility should be combined in order to provide sufficient robustness but also keep costs as low as possible. They point out that the probability of some supply chain risk are very difficult to estimate, furthermore, the resulted stochastic models are computationally rarely tractable. Therefore they suggest using a robust optimization approach by defining *uncertainty sets* for the uncertain parameters. They also suggest considering the *worst-case* possibility that helps identifying the vulnerabilities of a supply chain.

As we have just seen, robust supply chain planning is located at the intersection of optimisation and risk mitigation. Similarly, the supply chain coordination is at the intersection of (distributed) optimisation and autonomous systems. This idea is illustrated on Fig. 1. Considering robust planning and coordination together in supply chains is still a relatively unexplored research field (Lu et al., 2015). The goal of this paper is to outline the research directions for industrially relevant and applicable methods for integrating robust and coordinated supply chain planning. This paper focuses on the logistic optimization and disregards other related supplementary approaches of the project such as production optimization (Gyulai et al., 2014), lead-time reduction or required information and communication technology.

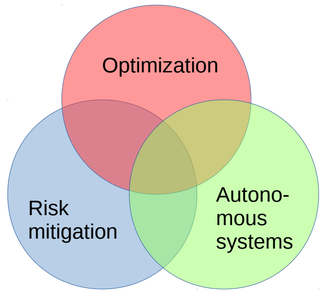

Fig. 1. Related research fields

2. INDUSTRIAL MOTIVATION

The setting of this case study is illustrated on Fig. 2. This supply chain produces electromechanical drives and its studied part consists of four stakeholders: the distribution centre (DC), the manufacturer, the inventory hub (IH) and a supplier of parts. The task of the DC is to provide the required electromechanical drives for the customers. In order to do this, it needs to make long-term (2-3 years) demand forecast aggregating across several customer areas and maintain appropriate finished good stock to satisfy the prompt demands. The manufacturer has to provide the required finished goods for the DC. Since the manufacturing process takes in average 50 days, the production is planned for the medium term, i.e., a few months ahead. For providing flexibility for production planning, some finished good buffer is held also at the manufacturer.

A required part for the manufacturing is supplied by a factory located in the Far East, which has a very long production time–approximately 8 months—, therefore their production has to be started quite in advance. In the studied case, the supplier is an external company operating in a Make-To-Order (MTO) manner, thus it is the responsibility of the manufacturer to give long-term orders based on demand forecasts. Note that such long lead-time suppliers are also typical in the European automotive industry (Zapp et al., 2012).

The transportation from the supplier to the IH also takes rather long time. The default transportation mode is by ship which takes 2.5 months, therefore the transportation also has to be planned in advance. In case of unexpected shortage however, a faster transportation alternative by plane can be chosen. By using air transportation the duration can be reduced to 3 weeks, but due to its high cost, only applied in emergency situations.

Since the inventory space at the manufacturing site is limited, the storage of the parts between the supplier and the manufacturer takes place at an IH. The IH is located close to the manufacturing site managed by an external service provider collaborating with the manufacturer. Besides the storage of the parts, the IH is responsible for choosing the transportation mode from the supplier and providing the

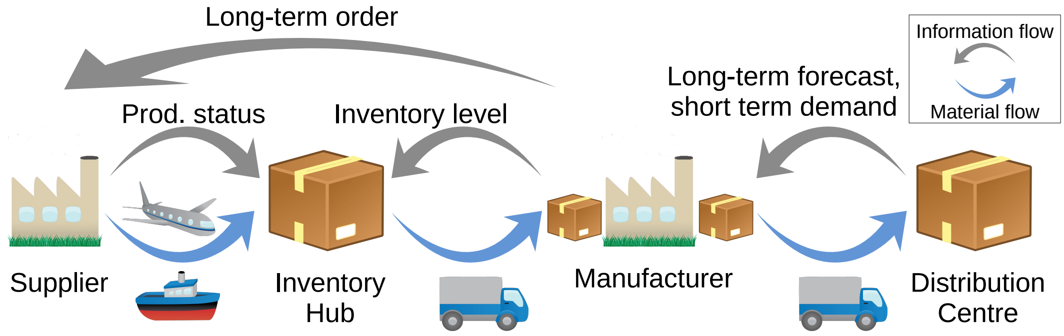

Fig. 2. Supply chain of the case study

required parts for the manufacturer, who only maintains a small inventory of parts.

The primary key performance indicators (KPIs) for the supply chain are *delivery time* (for low-runner customised products), *quality* and *customer satisfaction* (on-time delivery for high-runner standardised products). Note that these KPIs measure the performance of the whole supply chain and disregard the viewpoint of the different stakeholders described above. Therefore further KPIs should be used—such as cost, inventory level, number of reconfigurations/setups, required investments, resource utilization—in order to measure the performance and efficiency of the whole chain as well as its members. Since the survey conducted in the project pointed out that the logistic (inventory and transportation) costs are very high compared to the manufacturing expenses, the goal of this study is to provide an approach for optimizing these costs while maintaining robustness and the required service level towards the end-customers.

3. PROBLEM FORMULATION

In this section we formulate a model for the above described logistic optimization problem. For the long-term we assume static demand, but the approach remains similar in the dynamic case, too. We consider a serial supply chain with n stages, where the nodes represent inventories and the links between them are either production or transportation operations. Inventory can be held at each node with different h_i unit holding costs. The market demand is stochastic with mean μ and expected value σ, but the L_i lead-times between the nodes are deterministic. We also consider that the production and transportation incurs K_i fixed costs. The studied supply chain in this formulation is illustrated on Fig. 3.

Since there are fixed costs involved, we cannot use the *base-stock model* as in Egri (2012). Instead, we assume the first stage considers continuous stochastic demand, therefore applies the standard (s, Q) policy with the Economic Order Quantity (EOQ) model (Harris, 1913). Accordingly, it determines the s_1 level of reorder point, and as the inventory position drops to s_1, orders Q_1 products—which covers the demand approximately for $T_1 = \mu/Q_1$ time.

According to the model of Muckstadt and Roundy (1993), the other stages (stage i) take the order quantity from the previous stage (Q_{i-1}), and use dynamic lot sizing method together with safety stocks. This results in reorder point s_i and order quantity Q_i—which equals to $\theta_i Q_{i-1}$ for some $\theta_i \in \{1, 2, 3, \dots\}$—which covers the demand for T_i time. Fig. 4 illustrates the expected inventory positions for the first two stages, i.e., the inventory level plus the ordered items.

3.1 Computing the reorder point

The reorder point should be determined in such a way that it would cover the demand until the order arrives, i.e., the demand during the lead-time. According to Simchi-Levi et al. (2000), the reorder point is the average demand during the lead-time plus a safety stock to handle the uncertainty in the demand. Assuming *normal distribution*, this yields $s_i = \mu L_i + F^{-1}(\alpha)\sigma\sqrt{L_i}$, where F is the cumulative standard normal distribution and α is the required *service level*.

3.2 Computing the order quantities

Traditionally, supply chain decisions are made in a hierarchical manner: the first stage decides its optimal Q_1 order quantity, then makes its orders. After that the second stage makes its decisions, and so on, upwards the supply chain. We call this *decomposed planning*. While this approach is very simple and easy to implement, the problem with it is that a decision introduces constraints to the upstream planning, which may cause additional costs, and eventually inefficiency in the overall supply chain (Egri et al., 2011).

Instead of the decomposed planning, we apply a *multi-echelon model* for considering the average cost of the whole supply chain:

$$C(T_1, \dots, T_n) = \sum_{i=1}^{n} \left(\frac{K_i}{T_i} + \frac{h_i \mu (T_i - T_{i-1})}{2} \right), \qquad (1)$$

where $T_0 = 0$. When $i = 1$, this yields the cost used in the EOQ model; while for $i > 1$, the terms reflect to the inventory shape in the right side of Fig. 4.

Then we have the following optimization problem:

$$\min C(T_1, \dots, T_n) \qquad (2)$$

s.t.

$$T_i = \theta_i T_{i-1} \quad i \in \{2, \dots, n\} \qquad (3)$$

$$T_i \geq 0 \quad i \in \{1, \dots, n\} \qquad (4)$$

$$T_0 = 0 \qquad (5)$$

$$\theta_i \in \{1, 2, 3, \dots\} \quad i \in \{1, \dots, n\} \qquad (6)$$

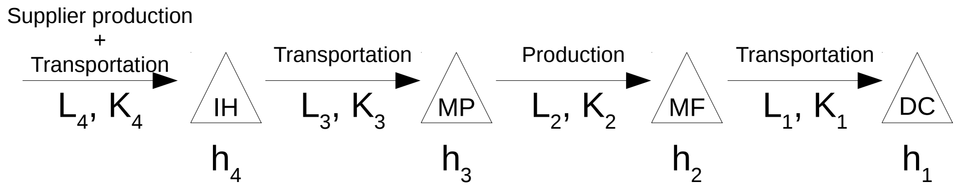

Fig. 3. Example supply chain model for the case studied (IH: inventory hub, MP: manufacturer's part inventory, MF: manufacturer's finished goods inventory, DC: distribution centre)

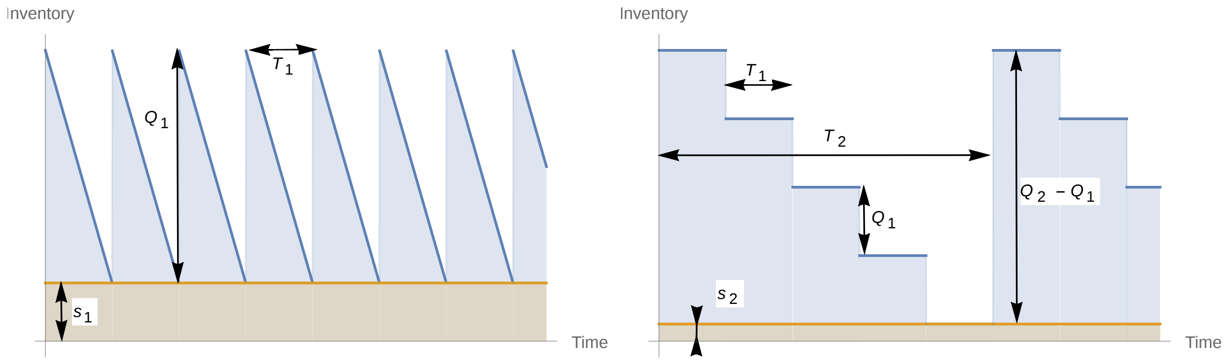

Fig. 4. Expected inventory positions of stages 1 and 2

This is a non-convex *mixed integer nonlinear programming* (MINLP) problem, whose exact solution is hard to compute, therefore usually an approximation algorithm is used (Muckstadt and Roundy, 1993). After having the quasi-optimal T_i values, the order quantities can be straightforwardly computed with $Q_i = \mu T_i$. Note that in case of dynamic demand forecast, the algorithm of Zangwill (1969) can be applied for solving the multi-echelon lot-sizing problem.

3.3 Determining the transportation mode

As we have seen, the transportation between the supplier and the IH has two possibilities: by water or by air. Choosing the latter drastically reduces the lead-time, which results in lower reorder point, but in higher fixed cost. These two alternatives result in two instances of the optimization problem formulated above, which can be solved separately and compared according the different KPIs.

In practice, the difference between the costs of water and air transportation is so huge, that the IH chooses water shipment whenever possible. Therefore the longer and cheaper transportation mode is considered in the above optimization. However, the quicker transportation mode can be used as a protection tool against shortages: whenever the IH observes that increased demand shall cause stockout, it can change the transportation of the already ordered and produced parts in order to speed up supply.

3.4 Designing for robustness

In the previous subsections we have introduced a planning framework which can be applied for supporting medium- and short-term supply chain decisions assuming a given chain. We have considered uncertain demand and determined the necessary safety stocks to hedge against the demand fluctuation. The model described in the previous subsections therefore helps to estimate the medium-term costs assuming different supply chain configurations, hence it also supports the strategic level decision making.

Since the possibilities of process flexibility in our use case are limited, we focus here on determining the required protective inventories for providing robustness. For each edge i in the supply chain model we have to determine TTR_i, i.e., the time within edge i can be recovered after a disruption. Similarly to the reorder point, the protective inventory at the end of edge i can be computed with the following formula: $\mu TTR_i + F^{-1}(\alpha)\sigma\sqrt{TTR_i}$, which is used as a safety buffer until edge i is recovered.

Note that the protective inventory at the IH should consider only the TTR of the supplier, since in case of a shipment failure, there is an alternative transportation mode. Without the possibility of the air transportation, the maximum TTR of the supplier and the shipment should have been taken into account instead.

4. COORDINATION

As we have previously seen, the main objective for the supply chain relates to the customer satisfaction. In this aspect, similar results can be provided by completely different plans. For example, the service level can be guaranteed by high end-product inventories, or by investing into new, high speed production equipment, or by ensuring fast replenishment by using air transportation. Even though all of these might provide the required service level, and their costs might be similar, these costs are distributed differently between the stakeholders.

Coordination considers the supply chain planning as a distributed decision making problem. Generally, a coordination mechanism aims at aligning the objectives of the different stakeholders with the global supply chain objective. Therefore we now overview the decisions and costs of the stakeholders of our case study. (Since the supplier is an external company not involved in the project, we enumerate only the other participants.)

Table 1. The decentralised setting

	Decision	**Cost**
IH	transportation mode transportation schedule	inventory transportation
Manuf.	long-term orders production plan min/max part inventory transportation to DC	production transportation to DC inventory
DC	forecasts short-term orders	inventory forecasting

It can be seen that the decisions not only affect the decision makers, but the other stakeholders, too. For example, if the manufacturer orders too much products, that causes high inventory levels (and costs) at the IH; on the other hand, if the ordered quantity is not enough to cover the demand, the IH might have to use the expensive air transportation in order to speed up the supply. The aim of coordination mechanisms is to guarantee that the autonomous decision makers follow the globally optimal supply plan and to fairly redistribute the occurred costs among the collaborating stakeholders. Sometimes achieving the exact optimal solution is not realistic, thus in a weaker sense, coordination should result in Pareto-improvement compared to some baseline plan, such as the decomposed solution (see Section 3.2). The applied tools for achieving coordination usually include novel business models, special contracts (e.g., buyback) and sharing the benefit of the cooperation with specialized payment schemes (Gao, 2015).

4.1 Decision support for coordination

In this project we aim at the analysis of the distributed optimization in order to support negotiation among the stakeholders. For this reason, we suggest generating different supply chain scenarios and compute the resulted costs, inventory levels, resource utilizations and other local KPIs for each stages. This helps quantifying how much compensation is needed for the stakeholders to change their behaviour. For example, with appropriate quantity discounts a buyer can be inspired to increase the order quantities, i.e., the discount helps to partially redistribute the benefit—caused by the increased order quantity—from the supplier to the buyer.

In addition, one can also take the total cost of these different plans. Specifically, if we compare the optimal solution of the (non-cooperative) decomposed decision model and the (cooperative) multi-echelon decision model described above, we can get the so-called Price of Anarchy (PoA) that measures how much benefit can be gained from cooperation (Nisan et al., 2007).

Similarly, one can compare non-robust plans and plans with different levels of robustness. This measures the *price of robustness* and that who pays this price according to the given plan.

Eventually, the fair redistribution of the benefit can be based on the contribution to the supply chain, which can be measured applying the Shapley value concept of the cooperative game theory. Calculating the Shapley value however usually involves solving a series of mathematical programming problems, thus might be practically inappropriate when the number of the participants is large.

4.2 Coordination by mechanism design

In case of incomplete information—e.g., when some information (such as the private cost parameters) are not known by all the stakeholders—mechanism design can help in the coordination. For example, the Vickrey-Clarke-Groves (VCG) mechanism has been designed to inspire the individual participants to share their private information truthfully, and applies a similar concept of marginal contribution as the Shapley value. In Egri (2012) VCG mechanisms were used to coordinate inventory decisions in a supply chain where the inventory holding costs and the lead-times were private information of the corresponding decision makers—but there was assumed to be no fixed costs.

Although VCG mechanisms result in globally optimal plans even with autonomous decision makers and private information, they have some properties that make them difficult to apply in the practice of supply chain coordination:

- Usually an independent entity is required to collect all information and do the planning.
- An external budget is needed for the mechanism.
- When the optimization is done by an approximation algorithm—as it was suggested above for the multi-echelon inventory planning—the VCG does not provide the appropriate incentive to cooperate.

When the private information are statistical distributions of random variables which can be later evaluated with their realized values—for example in case of demand forecasts—then *information elicitation mechanisms* can be applied which avoid the above mentioned drawbacks of VCG. For example, Egri (2015) presents such a model, which in supply networks leads to the widespread practical ideas of *vendor managed inventory* (VMI) and *risk pooling.*

Another approach is to apply an iterative mechanism, which may not result in globally optimal solution, but can improve efficiency compared to a baseline solution, e.g., the decomposed planning solution. Such model was presented in Egri et al. (2011), where adjacent stages in the chain applied a feedback mechanism called *dynamic supply loop with benefit balancing* in order to provide a possibility of collaboratively improving supply chain planning considering standard ERP lot-sizing policies. A similar coordination model was compared to different other solutions—namely the decomposed (non-cooperative), the integrated (cooperative) and the bilevel—in Kovács et al. (2013). While the previously mentioned models provide only one feedback loop and relatively simple planning problems, there are also multi-step iterative mechanisms for *collaborative planning* tasks (Albrecht, 2010).

5. CASE STUDY

In this section we illustrate the above described analysis considering one of the industrial partners in the project

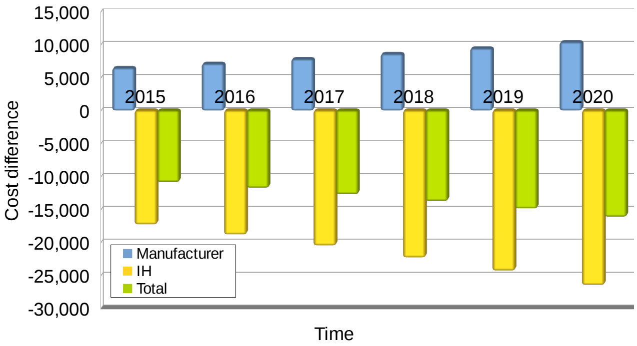

Fig. 5. Comparison of alternative supply chain configurations

and one of its suppliers from the Far East. We have performed numerical analysis comparing two scenarios: (i) continue purchasing from this supplier or (ii) switch to a European supplier providing higher component prices. Fig. 5 shows the estimated difference in the *purchasing cost*—which is paid by the manufacturer—and the *logistic costs*—which is paid by the IH for a specific component. It can be seen that the savings in the logistic cost surpass the effect of the increased purchasing cost, therefore it is beneficial to change despite being disadvantageous to the manufacturer. In order to motivate the manufacturer, the IH should offer a compensation by sharing its benefit determined by the numerical study.

A further possible scenario could be to apply a dual sourcing and therefore increasing process flexibility. This would necessitate additional qualitative risk analysis besides considering costs, i.e., whether the potential risks of purchasing from the Far East surpass the benefit of having an alternative supplier or not.

6. CONCLUSIONS

In this paper we have outlined a research agenda for integrating robust planning and coordination in supply chains. We have presented a case study of an industrial supply chain, concentrating on the long lead-time supplier which is one of the most serious sources of difficulties. We have focused on inventory optimization taking specifically robustness into account and also illustrated possible coordination approaches that consider the supply chain stakeholders as autonomous decision makers. As for future work, we will develop a multiagent simulation tool for decision support integrated into the RobustPlaNet cockpit.

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