Method for Optimizing Supply Chain Flexibility in the Production of Electrified Powertrains

Jens Niemann, Daniel Breschan
Production of electrified powertrains
BMW AG
Munich, Germany
jens.niemann@bmw.de
daniel.breschan@bmw.de

Andreas Schlegel, Matthias Putz
Production Management
Fraunhofer IWU
Chemnitz, Germany
andreas.schlegel@iwu.fraunhofer.de
matthias.putz@iwu.fraunhofer.de

Abstract — **Electromobility is one of the main solutions for tackling current challenges such as climate change or the scarcity of fossil resources [1]. Currently, there are large uncertainties regarding future production volumes of electric vehicles with forecast for 2025 varying between4 % and 38 % [2]-[4]. This demand volatility combined with rising importance of supply chain partners requires a fast adaptability of production volumes within the supply chain leading to a higher need of supply chain flexibility [1]. In this paper we present a method to optimize the contractual volumes between two supply chain partners coordinated by a quantity flexibility contract with fixed flexibility. Specifically, we examine whether a quantity flexibility contract fulfils its coordinating role in settings of changeable production systems. We validate our method with an example from the production of electrified automotive powertrains. The results show that we can further improve both costs and supply chain flexibility but that the coordinating role of the quantity flexibility contract is limited.**

Keywords-component; Supply Chain Management, Capacity Planning, Production, Production Planning, Electric Vehicles,

I. INTRODUCTION

In 1912 numerous companies produced a total of 34.000 electric vehicles worldwide [1]. Yet, technological innovations for combustion engines and low fuel prices eventually reduced the market share of electric vehicles to a niche product [1]. Nowadays, a new generation of electric vehicles is on the rise, due to high emission standards, rising fuel costs, environmentalism and political influence). Paralleling these dynamics, factors like customer behavior, infrastructure and technological improvements cause high volatility in forecasted market volumes for electric vehicles [1]. Current forecasts predict a production share between 4 % and 38 % in 2025 (compare Figure 1) [2]–[4]. As a result of the changing market environment we can observe a change in the supply chain concerning relevant supply chain partner, their influence and supply chain structure. Ordered volumes of suppliers with a high share of added value for conventional cars will be transferred to suppliers of electronic components. Consequently, OEMs face the challenge to integrate non industry suppliers into existing supply chains while maintaining current industry standards (e.g. quality and flexibility) [1]. Supply contracts take over a coordinating role between the OEM and his supplier. Presently, the automotive industry primarily uses quantity flexibility contracts that fulfil a certain volume flexibility corridor. Yet, given high demand fluctuations, the corridor is often undercut and/or exceeded in many years, which can lead to increased costs or even supply bottlenecks. In order to avoid higher supply costs while increasing flexibility and supply security, new concepts and methods must be developed that meet the volatility requirements in the production of electrified powertrains. In this paper, we introduce a new method in which we optimize contract volumes of a quantity flexibility contract based on possible scenarios and the buyer's changeable production system. Further we evaluate, if this contract type can coordinate a supply chain, which contains a changeable production system. Our paper is structured as follows: in the next chapter we define all relevant terms and give an overview of supply contracts. In the third section we explain our method and we further validate it using an example from the production of electrified powertrains. Lastly, a conclusion and an outlook close our work.

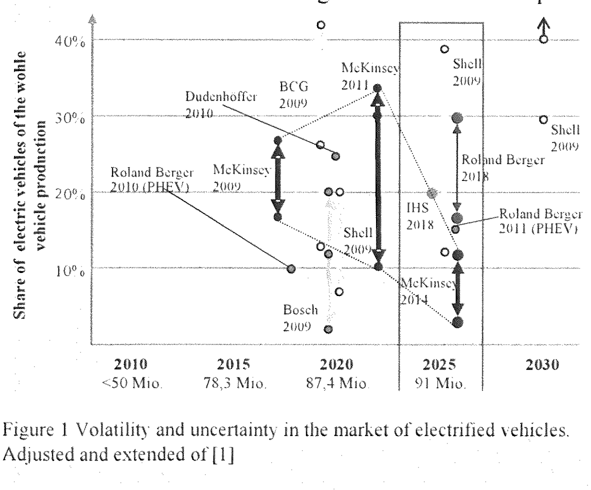

Figure 1 Volatility and uncertainty in the market of electrified vehicles. Adjusted and extended of [1]

II. LITERATURE REVIEW

A. Definitions of flexibility and changeability

Current literature often defines the terms flexibility and changeability differently. Thus we define volume and supply chain flexibility as well as changeability. Volume flexibility is also referred to as capacity flexibility [5]. They describe the ability to operate a production system economically with different capacity utilizations and changing production volumes. [6] Second, the adaptability of a buyer-supplier relationship to volatile demand scenarios or deviating delivery conditions defines supply chain flexibility [7]. Stevenson and Spring extend this definition to include the aspect of consistent quality [8]. Alternative definitions according to Kumar, Fantazy, Kumar and Boyle additionally integrate the restructuring of the supply chain [9] and the inclusion of new supply chain partners [10]. Contrarily, Gosling, Purvis and Naim understand supply chain flexibility as the flexibility that results from all involved companies [11]. In this paper we follow Stevenson and Spring's definition.

According to Seebacher, changeability begins to take impact when the flexibility corridor is exceeded and is generally referred to as the potential for change. Möller expands it in his definition and calls it "the ability of a production system to adapt quickly to changes in the environment by changing its structure" [12]. The assessment of the changeability of a production system based on simulations [13] or on ERP data [14] are topics discussed in further papers.

B. Supply Contracts

Supply contracts can be seen as the elementary component of our research work. They determine prices, delivery conditions and quantities between the supply chain partners and are thus jointly responsible for the coordination of the supply chain and the available supply chain flexibility [15]. Research in the area of supply contracts has developed rapidly in the past years, so that a lot of new contract types have evolved. In the following we will present an overview of currently known supply contracts. Due to its simplicity the ***wholesale-price contract*** belongs to the most widely used contracts. It is characterized by its quantity independent pricing [15]. The ***quantity discount contract***, on the other hand, sets a unit price that is decreasing with each additional unit [16]. The ***buy-back contract*** obliges the supplier to compensate the buyer for unsold quantities [15]. This contract type is used in many industries, especially in those adopting new technologies frequently [17]. In contrast, the ***rebate contract*** rewards the buyer for every sold unit. In fact, the rebate contract is widely spread in the hardware, software and automotive industry [15]. The ***revenue sharing contract*** commits the buyer to return a prenegotiated portion of its realized profits to the seller and is, for example, frequently employed in the rental industry e [15]. First described by Tsay and Lovejoy in 1999 the ***quantity flexibility contract*** has a flexibility corridor that is defined by a negotiable maximum percentage of the contractual volume and a minimum purchase commitment of the buyer. Within this flexibility corridor the supplier is obliged to cover all requests [18]. With the ***option contract*** the retailer orders a quantity of units and has the right to modify his order if necessary. The supplier in return receives the compensation for the modification of the order by the precalculated option premium [19],[20]. Lastly, the ***trade credit contract***, where suppliers offer incentives to the buyer such as cash discounts to encourage him to pay trade credits earlier, is not taken into further consideration since it is not focusing on supply chain flexibility [21]. Among the contract types mentioned above there exist several derivatives and additionally many other contract types that we do not focus on in this paper. The choice which supply contract should be used depends on the existing supply chain and challenges. These include the supply chain topology, contract length, decision variables (e.g. price, capacity), agent characteristics, supply chain environment and the information structure [17].

Considering existing supply contracts with respect to the challenges of the automotive industry, we focus on the quantity flexibility contract (QFC). In the following, we present a selection of current research work in the field of QFC in order to derive the requirement of our research work. Research on the QFC is primarily dedicated to the coordinating role of the contract in a supply chain. The contract is viewed either from the supplier's or the buyer's perspective with different contract parameters. Zhu and Hu, for example, consider the optimal order and production quantities from the buyer's perspective in a multi-period study [22]. Lian and Deshmukh calculate the optimal replenishment strategy, but assumes that there are discounts for early ordering [23]. Wang and Pan complement this research by investigating whether a QFC can still assume a coordinating function in the supply chain for an unreliable supplier [24]. Soo Kim, Il Park and Young Shin , on the other hand, do not just look at one supplier, but starts from several QFCs and suppliers for the same product and calculates the optimal distribution of orders per supplier [25]. Alternative research approaches are offered by Kesen, Kanchanapiboon and Das, their research being prior to the final supplier contracting and simulating different QFCs to find the lowest supply cost [26]. Kim also takes a different approach, which establishes a connection between the offered flexibility and the customer service from the supplier's perspective and calculates the optimal relationship between both parameters [27]. In the literature we do not find any research work that determines the optimal contract volume from the buyer's perspective. Starting from a buyer's changeable production system, the goal of is to increase supply chain flexibility and to ensure a reliable supply.

III. METHOD

In the paper, we develop a 4-step method for optimizing contractual volumes of quantity flexibility contracts in order to achieve both, low costs and maximum flexibility from the buyers perspective.

A. Generation of volume scenarios

In our research, we discovered that companies allocate contractual volumes for supply contracts on the basis of their own volume forecasts. This, however, neglects external opinions and independent studies, resulting in biased results. For this reason, we supplement internal volume scenarios with external volume scenarios.

To form volume scenarios for our method, we look at the external and internal volume scenarios of the planned contract length per year. Each year we test all our volume scenarios for a normal distribution, using the Anderson Darling Test. If there is a normal distribution, we recommend to consider all volume scenarios between the 1st and 3rd quartile, since these scenarios include all scenarios with a high probability. By weighting the volume scenarios, we can further increase or reduce the internal company assessment.

B. Analysis of the OEM's production system

We suggest a bottom-up approach for the analysis of the production system, starting with the analysis of the production type. Hereby, it is to specify whether it is e.g. an assembly line or a highly automated production line.

Next, we focus on the products to be manufactured on the considered line. This involves for example analyzing the products technologically and viewing their cycle times. Additionally, since different variants of a product are often produced on identical lines it is also recommendable to analyze to what extend the products differ and how they influence each other under production aspects. We use these information to calculate all possible product mixes. Information about this enables us to assess the considered product's proportion of total machine capacity. Besides the annual capacity, we have to investigate the production rate per hour, as these may also have to be covered by the supplier. For the calculation of machine capacity, we consider the shift model and flexibility measures. We assume a 1, 2 or 3 shift model for our method. Further flexibility measures could possibly be additional shifts or break passages. In addition to flexibility, we investigate changeability, which is gaining popularity in volatile environments. We have to figure out, if there are any changeability measures that are planned or already defined. All existing and scheduled changeability measures in the capacity calculation need to be included to get a precise view of the buyer's production capacity per year.

Crucial for the successful application of our method is the correct calculation of planned capacity per time interval. We calculate it using the planned shift model, machine capacity and capacity proportion for the considered component per time interval.

C. Calculations of different contract volumes

Our method's goal is finding an optimal contract volume. The quantity flexibility contract includes a flexibility corridor around the contract volume. All ordered volumes within thiscorridor are sourced at the fixed unit price p. Otherwise we assume an increase in the unit price.

Therefore, we calculate the unit costs in our optimization as a function of varying unit prices, which (1) depend on the regarded volume scenario. The penalty costs, which occur outside of the corridor can be individual. In our method we assume that cases volume reductions ($s < b_{low}\, n$), the result of the division of the contract volume n by the scenario volume s will be multiplied by the unit price. If the quantity exceeds the corridor ($s > b_{high}\, n$), we assume that the supplier will invest to expand its production system. The necessary investment sum I will be allocated to the unit price. If the costs are calculated differently, equation (1) needs to be adjusted. We maximize the flexibility of the quantity flexibility contract in relation to the buyer's changeable production system (2) to increase the supply chain flexibility and synchronize the flexibility within the supply chain. Additionally, we integrate the company's opinion whether the volumes will increase or decrease (3). As volumes increase, we focus on maximizing scenario coverage in the μ to the 3rd quartile range. It means that all scenarios in this range should be purchased at the fixed unit price. In the case of decreasing volumes, we concentrate on the 1st quartile to the mean value μ range. We introduce the following objective functions that we aim to optimize:

$$f_{\text{Cost}}(n,s) = \begin{cases} p \cdot \dfrac{n}{s} & , \quad s < b_{\text{low}}\, n \\ p & , \quad b_{\text{low}}\, n \le s \le b_{\text{high}}\, n \\ p + \dfrac{I}{s} & , \quad s > b_{\text{high}}\, n \end{cases} \tag{1}$$

$$f_{\text{Flexibility}}(n) = b_{\text{high}}\, n - c_{customer} \tag{2}$$

$$f_{\text{Scenario Coverage}}(n) = b_{\text{high}}\, n - \mu \tag{3}$$

n = contract volume

s = scenario volume

p = contract price per unit

I = Investment

c_{buyer} = capacity of the buyer's productionsystem

b_{low} = lower bound of the flexibility corridor

b_{high} = upper bound of the flexibility corridor

μ = average value of the scenarios

We scale every formula and use weighting factors to adapt the multi-criteria optimization to the company's goals. The costs are minimized, whereas we maximize flexibility and the scenario coverage. To be able to calculate the equations, we transfer the maximization into minimization problems. To find the objective functions optimum we summarize (1), (2) and (3) to a combined function with three weighting factors. Speaking of weighting factors, these can range from maximum flexibility (flex. factor = 1, cost factor = 0) to minimum costs (flex. factor = 0, cost factor = 1), any possible combination in between is acceptable. In addition, the cost function allows to define whether the contract volume should be exceeded or preferably undercut. We can achieve it by additionally weighting the cost function. We recommend either weighting the cost functions equally or increasing the costs for exceeding the corridor. We consider the latter to be advisable in order to be able to guarantee the supply of components. We use a nonlinear solver to find the optimal values for n. Depending on the choice of the weighting factors, the contract volumes are either cost-optimal or flexible.

D. Economic and flexibility-based evaluation

In the final step we assess the new contract volumes with regard to flexibility and costs. Hereby, flexibility terms of both the new contract volumes as well as the old contract volumes are compared to the capacity of the production system. Regarding costs, we recommend a comparison between total costs of the old contract volumes and the new ones. Depending on the used weighting factors, the quantity flexibility contract can have several contract volumes, either tending to be cost or flexibility optimal. It is the company to decide whether costs or flexibility should be prioritized higher. Irrespective of the decision, flexibility is increased in each of the cases investigated.

IV. VALIDATING EXAMPLE

We have taken a two-tier topology with two nodes example of the production of electric powertrains to validate our method. The buyer is an automotive OEM and we consider the production of an electric drive with the supplier being in charge of delivering a component of the power electronics. In our case the quantity flexibility contract has a contractual flexibility (b_{high} and b_{hlow}) of 20 % per year and a price per unit p of € 149. If the desired volume quantity exceeds the maximum fixed quantity an additional investment in the production system is required. This investment sum I amounts to 12 million €.

We begin with the generation of volume scenarios. In our validating example, we consider a period from 2019 to 2024 by looking at 3 external scenarios. We have further supplemented the external volume scenarios with 2 internal scenarios in order to obtain a comprehensive picture of the environment. The Anderson Darling Test confirmed a normal distribution each year. After generating the volume scenarios, we focus on the analysis of the OEM's production system. We investigated a production line, which produces a total of 4 electric drives. The component of the supplier is, however, only relevant for one of these products. Analyzing this specific electric drive, we find that the component is the most frequently manufactured product on the line requiring approx. 35 % of the capacity. The production system of the OEM is scalable and consists of two lines, each comprising four capacity expansion steps. The expansion of one step results in a doubling of capacity. For the considered period of time there already exists a timetable for the expansion of production. The production is designed for a 3-shift operation and additional measures (e.g. extra shifts) allow increasing capacity by up to 23 % (compare Table 1).

TABLE I. PLANNED CAPACITY OF THE OEM'S PRODUCTION SYSTEM

OEM Capacity (C_{buyer}) [t. Units]	**Year 1**	**Year 2**	**Year 3**	**Year 4**	**Year 5**
Production Capacity	31	62	135	187	249

The supplier assembles the component on one dedicated production line. We use formulas (1) to (3) to optimize the quantity flexibility contract. For the flexibility optimized calculation we weight the costs 0.2, the flexibility with 0.7 and the scenario coverage with 0.1. For the cost optimization we choose to weight flexibility with 0.2, costs with 0.7 and the scenario coverage with 0.1 (compare Table 2). We used equal weighting factors for the cost function.

TABLE II. OVERVIEW OF THE VARIOUS CONTRACT VOLUMES

Contract Volumes *[t. Units]*	**Year 1**	**Year 2**	**Year 3**	**Year 4**	**Year 5**
Status Quo	9	37	94	149	213
Cost oriented	9.6	36	106	154	194
Flex. oriented	10	38	118	168	215

In Table 2 we see that a flexibility focused weighting results in contract volumes tend to be higher and hence closer to the OEMs production system maximum capacity. Contrarily, with a greater weighting of costs, contractual volumes assume lower values that are closer to the median of the volume scenarios.

In the final step we carry out the economic and flexibility based evaluation of the results that we achieved when applying the newly optimized contract volumes. In order to obtain comparable results we evaluate the cost reduction and flexibility increase across all possible scenarios in the considered corridor weighted with their respective occurrence probability. What we see is that in both cases, flexibility and cost oriented weighting, we achieve an increase in flexibility up to 8 %. With cost oriented weighting, savings can be up to € 9 million. An overview of three examples can be seen in Table 3.

Negative values of the flexibility show that the OEM's production system is still more flexible than the supplier. This can be explained by the OEM's changeable and scalable production system, which can cover a higher volume corridor. The quantity flexibility contract, on the other hand, is limited to a fixed flexibility corridor, which is smaller.

TABLE III. EVALUATION AND COMPARISON OF THE ORIGINAL AND OPTIMIZED CONTRACTS

Cost [mio. €] *Flexibility [o-%]*		Status Quo	Flex. optimized	Cost optimized
Scenario 1st quartile	Cost	155	170	154
	Flex.	-19	-15	-19
Scenario median	Cost	117	116	116
	Flex	-30	-24	-29
Scenario 3rd quartile	Cost	174	157	170
	Flex.	-37	-31	-37

V. CONCLUSION AND OUTLOOK

Currently strong volatility in the electromobility market requires OEM's to integrate flexibility not only in the automotive production but also in the supply chain. Our research enables buyer's to design contract volumes in supply contracts differently and thereby enhance supply chain flexibility. In this paper, we developed a method to optimize contractual volumes of quantity flexibility contracts. The quantity flexibility contract is primarily used in the automotive industry because it enables a high degree of supply chain flexibility. Our results show that the properties of the buyer's changeable production system are insufficiently included in contractual volumes. With our developed method, we optimize contractual volumes based on different demand scenarios and an analysis of the buyer's productions system. In our validating example, we examined a two-tier topology with two nodes. Our method enabled us to increase volume flexibility and to reduce supply chain costs. Furthermore, the method offers various possibilities to integrate entrepreneurial ideas through weighting factors and thus the possibility to replicate the purchasing strategy of the company.

Developing of our method we have identified strong optimization potential. However, we also found that the quantity flexibility contract reaches its limits in coordinating the supply chain, especially with regard to changeable production systems. In a changeable, in terms of scalable, production system the achieved volume range cannot be covered. In our future research, we will focus on researching a concept for a changeable supply chain. This includes the development of a new supply contract as well as the extension of our presented method to the supplier's production system and to further supply contracts.

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Authors' background (This form is only for submitted manuscript for review)

Your Name	Title*	Affiliation	Research Field	Personal website
Niemann, Jens	Phd Candidate	BMW Group	Supply Chain Management, Capacity Planning	https://www.researchgate.net/profile/Jens_Niemann2
Breschan, Daniel	Student	BMW Group	Supply Chain Management	
Andreas Schlegel, Dr.	Senior Lecture	Fraunhofer IWU	Modelling and Simulation, Industrial Engineering, Environmental Engineering	https://www.researchgate.net/profile/Andreas_Schlegel6/info https://www.iwu.fraunhofer.de/en/research/business_units/production-systems.html
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