# Dynamic evaluation and simulation of variant-driven complexity costs in multi-echelon automotive supply chains

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**Abstract**

The proliferation of product variety driven by part variants imposes a great impact on the costs, performance and ecological burden of automotive supply chains. Costs are always the first aspect to be considered by manufacturers. This paper creates a multi-echelon automotive supply chain in the light of the process model and improves the KPI of low costs to evaluate the variant-driven complexity costs. Then, the evaluation models of different complexity costs are constructed. An automotive supply chain scenario model is constructed with the OTD-NET and the simulation results are analysed. The study of this paper will be helpful to automotive manufacturing in seeking to optimize the number and range of product variants.

*Keywords:* Automotive Supply Chain, Product Variety, Complexity Costs, OTD-NET

## 1 Introduction

Part variants are the main factors of product variety in automotive industry, as discussed by Lechner [1] and Klingebiel and Yi [2], so it is very important to evaluate their influence on automotive supply chains. The evaluation of supply chains can be carried out through economy, performance and ecology, as discussed by Klingebiel [3], in which the economy factor is always considered first since achieving profits is the primary objective for business. Therefore, reducing costs or increasing profits are crucial for evaluating or choosing a strategy.

Many researchers have focused on the impact of the proliferation of product variety on the costs or profits of automotive supply chains. As pointed out by Ramdas [4], simply increasing variety may not guarantee growth in long-term profits, and may even worsen a firm's competitiveness. Fisher et al. [5] and Schleich et al. [6] argued that a large product variety may increase overhead costs, resources costs, production costs and inventory costs. As variety increases, the plant may have to pay a higher cost in the form of fixed investments in variety handling systems, which is much higher than the variable cost of variety as discussed by Fisher and Ittner [7, 8] and Ittner and MacDuffie [9]. Jagersma [11] also concluded that complexity tends to increase the fixed costs of conducting business. As discussed elsewhere [1, 4, 11–20], other complexity costs that may be caused by an increase of product variety include retailers' costs, set-up costs, operational cost, overhead costs, raw material costs, equipment costs, management costs, space costs, etc. In general, Schoeller [21] claims that costs associated with excessive complexity become the main cost factors of supply chains, which can result in a considerable reduction of profit (as discussed by Berry and Cooper [22] and Kersten et al. [15]).

Therefore, it is necessary for automotive companies to discover the most suitable degree of product variety to control the increase of costs, as discussed by Benjaafar et al. [17], Scavarda et al. [23], Schleich et al. [6] and Thonemann and Bradley [11]. Scavarda et al. [23] also show that companies should evaluate how the costs can be influenced by variety in order to achieve this aim, and that variety in the automotive industry should be split between factory-fitted (variants) and dealer-fitted options. Nevertheless, Lechner [1] and Yi and Klingebiel [2] consider there is still a lack of research, especially on variants, as well as a lack of dynamic evaluation and simulation of this type of impact.

This paper aims to evaluate the impact of the growth of part variants on logistics costs in the automotive supply chain through the application of the OTD-NET simulator. The next section constructs a four-echelon automotive supply chain and examines the key performance indicators (KPIs) of logistics costs. We then build the models for evaluating different complexity costs induced by variant-driven variety, before the four-echelon supply chain is simulated and the results are analysed. The paper concludes and discusses future studies.

## 2 KPIs of logistics costs

The KPI system should be specified before the evaluation of complexity costs. This section constructs a four-echelon automotive supply chain as an area for study

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before generalizing about the KPIs in the light of the process chain model.

### 2.1 A FOUR-ECHELON AUTOMOTIVE SUPPLY CHAIN MODEL

The four-echelon automotive supply chain from suppliers to dealers that is studied and simulated in this paper is shown in Figure 1. Each supplier offers one part type, which may consist of several part variants, for the plant. The variety of finished cars is sold through a couple of dealers or importers who account for actual rates, respectively.

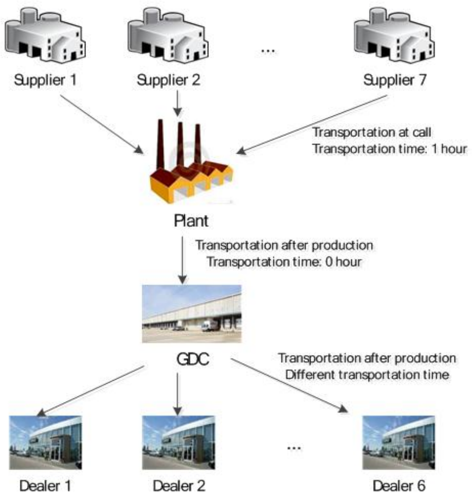


FIGURE 1 General structure of the four-echelon automotive supply chain model

In this supply chain, the suppliers are co-located with the plant in the same city in Germany. The transportation time from any supplier to the plant is one hour. As the product structure of the automotive industry is too complicated to simulate all the part variants, only seven part types are built in this scenario model to compose the finished product: “PC car”. These seven part types are body sheets, paint, engines, transmissions, seats, door and locks, wheels and tires. All suppliers are build-to-order (BTO) suppliers, except for body sheets and paint, which are build-to-stock (BTS). Only the BTS suppliers keep a minimum stock for each component in the plant’s warehouse, which is equal to the demands of three hours supply. There are four workshops in the plant: press, welding, paint and assembly. The labour time for all the workshops in the plant is 21 hours, from Monday to Friday, with three shifts, and the planned output of the plant is 50 per hour. The finished cars are driven to the global distribution centre (GDC) once they have rolled off the production line. The GDC is located in the plant area, so the transportation time from plant to GDC is considered to be zero. Four of the six dealers are in Germany and the others are in neighbouring countries. The transportation time for finished cars from GDC to each dealer varies from six to 24 hours, except for the ten minutes of one dealer lot that is co-located in the GDC. It is assumed that all customers belong to the same customer type, and want to receive their products as soon as possible and do not accept any deviations of the product. The dealers in different markets gather orders from the customers and send these orders to the plant every Monday. The GDC transport the finished cars once they have satisfied the minimum transport units.

The logistics process in the supply chain can be divided into three processes centring on the plant: inbound logistics; in-plant logistics; and distribution logistics. Inbound logistics refer to parts transported from suppliers to plant and parts stocked in the warehouse; in-plant logistics include producing processes in the plant and finished products stocked in the GDC; distribution logistics are those cars distributed from the GDC to dealer lots and cars stocked in dealer lots. Each logistics process consists of several processes, structures and resources according to the process chain model, which is proposed by Kuhn [24]. The process chain model visualizes and abstracts the material and information flows in each echelon of supply chains, so that the steps and their relationships can be grasped clearly (as studied by Kuhn and Hellingrath [25]). With an increase of variants, the structures should to be changed to deal with this, and additional processes and resources are required. The KPI of evaluation should reflect the costs resulting from these changes.

### 2.2 KPI OF EVALUATION OF COMPLEXITY COSTS

The general target of low costs for the supply chain can be described with respect to low process costs, low inventory costs and low resources costs, as discussed by Benjaarfar et al. [17], Lechner [1], Lechner [1], Thonemann and Bradley [11] and VDI [26]. Figure 2 summarizes the indicators with respect to these costs.

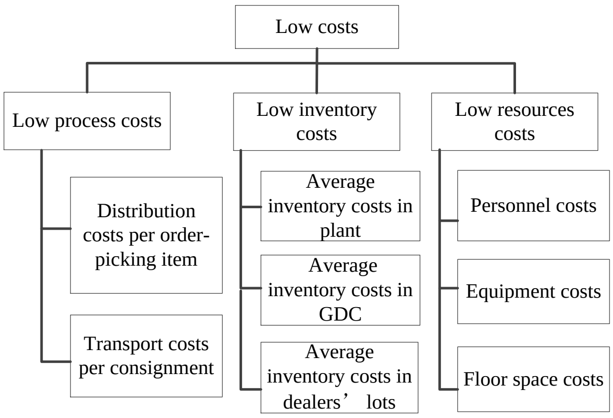


FIGURE 2 KPI of Low Costs to Evaluate the Variant-driven Product Variety

In order to improve the accountability of these indicators, they are analysed in combination with the logistics process discussed above. Table 1 shows the indicators with respect to logistics processes and functions.

The low process costs are measured by two indicators: distribution costs per order-picking item and transport costs per consignment. For the purpose of achieving coherence between the description of supply chains, the definition in OTD-NET and the KPI system, the distribution costs indicator is adopted to evaluate the process costs of delivery goods from GDC to dealer lots, while the transport costs indicator evaluates the process costs of transport parts from suppliers to plant.

The second sub-objective, which of low inventory costs, aims for a quick turnover of inventories in plant, GDC and dealer lots. The third sub-objective, low resource costs, can be evaluated from three indicators: personnel costs; equipment costs; and floor space costs. The personnel costs and equipment costs during the production logistics are both proportional to the process time of production, as demonstrated by Lechner [1]. The floor space costs are the costs of space in workshop, warehouse, etc.

It is obvious that variety is a “double-edged sword”, as shown by Karmarkar [27] and Shapiro [28]. An automotive supply chain should plan the suitable number of variety and variants for their products. Some approaches should evaluate the variant-driven complexity costs so that cost–benefit analysis of variant-drive product variety in the automotive supply network can be carried out. Here, the variant-driven complexity costs refer to the difference in logistics costs in the automotive supply network between a scenario with variants and a zero-based scenario. The next section introduces the evaluation approaches apart from the zero-based approach, and constructs the evaluation models based on such approaches.

TABLE 1 Function costs and process costs

| | | **Logistics/functional costs (*CTF*)** | | |
|---|---|---|---|---|
| | | Process costs (*CP*) | Inventory costs (*CI*) | Resources costs (*CR*) |
| Logistics processes costs (*CTP*) | Inbound logistics costs ($CI^B$) | Transport costs | Inventory costs of parts in plant | Personnel costs; equipment costs; floor space costs |
| | In-plant logistics costs ($CI^P$) | | Inventory costs of unfinished products; inventory costs in GDC | Personnel costs; Equipment costs; floor space costs |
| | Distribution logistics costs (*CD*) | Distribution costs | Inventory costs in dealers | Personnel costs; equipment costs; floor space costs |

## 3 Evaluation models

The simulation of the four-echelon supply chain and its results should be carried out based on the most suitable evaluation method. After introducing the zero-based and improved activity-based costing (ABC) approaches, the complexity costs evaluation models corresponding to the KPI are constructed in this section.

### 3.1 EVALUATION METHODS

A combination of three methods is introduced to evaluate the variant-driven variety complexity costs in automotive supply chains: variety-driven activity-based costing (VD-ABC), as studied by Lechner [1]; time-driven activity-based costing (TD-ABC), as studied by Kaplan and Anderson [29]; and the zero-based approach. The first two methods are both modifications of the ABC approach, while the latter is suitable for dynamic evaluation.

#### *3.1.1 Time-driven activity-based costing and variety driven activity-based costing*

Cooper and Kaplan [30] consider that the ABC approach identifies activities in an organization, and assigns the cost of resources for each activity to all products and services according to the actual consumption by each. This method can identify the indirect and direct costs of each activity, as it is helpful to know the profitability of each activity and then reduce or eliminate it in order to optimize overhead costs, as discussed by Goldbach [31]. However, Kaplan and Anderson [29] argue that the ABC approach is not suitable for large-scale organizations as it often fails to capture the complexity of actual operations, takes too long time to implement and is too expensive to build and maintain. In order to resolve these problems, the TD-ABC approach is developed by Kaplan and Anderson [29] by improving and revising ABC.

According to Kaplan and Anderson [29], resource demands are estimated according to the cost per time unit, and only two kinds of parameters are required to be estimated for each group of resources – i.e. the cost per time unit of capacity and the unit times of activities. As opposed to the ABC approach, the TD-ABC approach can help supply chains catch the complexity of business far more simply and find which costs should be saved and which should be cut. It can accommodate the complexity of real operations by time equations, a new feature that enables the model to reflect how order and activity characteristics cause processing times to vary. Time equations greatly simplify the estimating process and produce a far more accurate cost model than traditional ABC techniques, as studied by Kaplan and Anderson [29]. In this section, TD-ABC is used to calculate the variant-driven personnel complexity costs, equipment complexity costs and part of the floor space complexity costs.

However, the TD-ABC approach also has its limitations. Some of the logistics costs cannot be expressed by time equations – for example, the inventory costs and corresponding floor space costs – because the process time of inventory is unrelated to the number of variants. That means it cannot track the influence of variants on the process time of inventory (see Lechner [1]). Consequently, Lechner [1] expand continually the TD-ABC approach to capture the capacities in parts, and square meter and name it VD-ABC so that it can allocate costs to the level of variants according to the actual input involved. Using the capacity cost rate to derive the costs of variant-driven variety, the VD-ABC can help to determine the number of variety subject to part variants. In this paper, VD-ABC is used to calculate the inventory complexity costs and the floor space complexity costs related to the inventory.

*3.1.2 Zero-based approach*

The idea of the zero-based approach originates from zero-based budgeting (ZBB), which is an approach to planning and decision-making that works in reverse to that of traditional budgeting. Sarant [32] demonstrates that the zero-based approach requires each budget request to be re-evaluated thoroughly so that each line item of the budget has to be approved, rather than only be changed. The definition of the zero-based approach is grounded in the federal training experience, as shown by Sarant [32], ie that: "A minimum level is actually the grass roots funding level necessary to keep a program alive." As discussed by Sarant [32], the minimal level here is the program or funding level below which it is not feasible to continue a program because no constructive contribution can be made toward fulfilling its objective.

The difficulty of cost management in achieving significant and sustainable cost reductions without threatening performance and competitiveness is discussed by Waterlander et al. [33]. They argue that zero-based cost management can re-examine the activities and associated costs necessary to achieve specific business outcomes so that it can avoid these potential problems. As proposed by Waterlander et al. [33], there are four steps for a successful zero-based approach: re-examining the vision; zero-basing the activities; assessing the outcomes; and embedding the change. The key of the zero-based approach is in justifying the retention or expansion of specific optional activities (and their full cost) for clearly articulated business benefits.

Lechner [1] extend the concept of the zero-based approach as the basic principle underlying variety-driven complexity in automotive inbound logistics. This paper applies the idea of zero-based approach to evaluate the variety complexity costs in whole automotive supply chains, to help them choose the right number of part variants since an affordability line can be used to filter the activities during the operation of the approach. The affordability line is a threshold cost initiated by cost managers to control costs through choosing the suitable number of product variety and part variants. An example of an affordability line is shown in Figure 3.

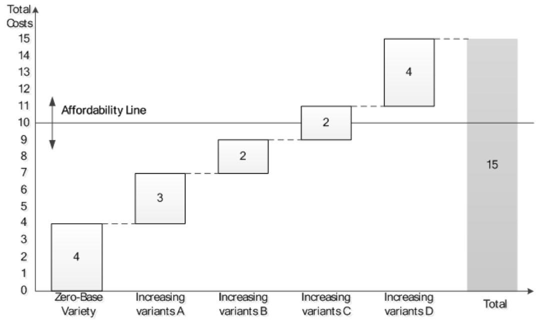


FIGURE 3 Complexity Costs Against a Cost Management Affordability Line

In this paper, a three-scenario model under the supply chain structure in Figure 1 is created, in the light of the zero-based approach, which represents separately that there are no variants, one variant and many variants in part types. The three scenarios are the zero-variant scenario, the one-variant scenario and the rich-variants scenario. The change of complexity costs from the one-variant scenario to the rich-variants scenario against the zero-variant scenario can help a supply chain master the influences of variant and make decisions on the number of variants and variety.

*3.1.3 Integrated evaluation steps*

Combining the zero-based approach with TD-ABC and VD-ABC, the total complexity costs can be calculated and analyzed. According to the classification of logistics costs in Table 1, the supply chain sets a respective affordability line for each type of costs, as well as for total costs, so that the suitable number of part variants can be decided comprehensively. Depending on the supply chain process and the classification of logistics costs, the integrated evaluation steps can be summed up as follows:

(1) Calculating every cost item in the three different scenarios: zero-variant, one-variant and rich-variants.

(2) Calculating logistics/functional costs, logistics processes costs and total logistics costs in the three scenarios.

(3) Calculating every complexity cost individually in the one-variant scenario and rich-variants scenario, this equals the costs difference between the costs in the latter two scenarios and the zero-variant scenario in (1).

(4) Calculating logistics/functional complexity costs, logistics processes complexity costs and total logistics complexity costs in the one-variant scenario and rich-variants scenario, which equals the cost difference between the latter two scenarios and the zero-variant scenario in (2).

(5) Evaluating the complexity costs or choosing the number of part variants according to the affordability lines.

The calculation methods of these costs are introduced in terms of the function in the following analysis since the same function costs in different processes can be calculated by the same method.

### 3.2 EVALUATION OF PROCESS COMPLEXITY COSTS

Transport costs and distribution costs can both be regarded as transport costs that are related to transport modes, transport capacity and distance. For the transport of a certain product or part between two specific places, the transport cost $CT_{ij}$ can be expressed by the multiplication of the transport rate $r_{ij}$ and the number of products or parts $v_{ij}$ being transported:

$$CT_{ij} = r_{ij} \cdot v_{ij} \,. \tag{1}$$

In Equation (1), $i$ refers to the $i^{th}$ product/part, and $j$ refers to the $j^{th}$ route for the transport of the $i^{th}$ product/part. The total transport cost is equal to the sum of all the $CT_{ij}$:

$$CT_V = \sum CT_{ij} \,. \tag{2}$$

$V$ in Equation (2) is the total number of part variants. Therefore, the transport complexity cost is:

$$CCT_V = CT_V - CT_0 \,. \tag{3}$$

### 3.3 EVALUATION OF INVENTORY COMPLEXITY COSTS

The growth of total inventory costs in production/ inventory systems is associated with types of supplier–customer systems of supply chains as discussed by Wu [14], and is almost linear in the number of variety as discussed by Benjaarfar et al. [17]. One type of supplier–customer system is BTS with lower product variety but high volume, and another is BTO with high variety but low volume, as explored by Wu [14].

The increase of inventory is made up mainly of the stock type and safety stock. In respect to stock type, on the one hand, it is normal that more part variants induce more total volume in stock unless there is an absolute-zero inventory policy. On the other hand, the purchase price of parts becomes higher as the lot sizes decrease. Both these reasons promote the growth of inventory costs.

In respect to safety stock, the safety stock of part variants, work-in-progress (WIP) and finished products are raised to prevent the stock being out. Few safety stocks are needed in the zero-variant scenario because the demand and supply are stable and unchanged, whereas in the rich-variants scenario, due to there being more variants and lower average demands for each variant, the demand volatility is higher, and the plant and dealers have to keep safety stock for each part variant, even product variants. Of course, this implies greater inventory costs.

#### *3.3.1 Calculation of inventory costs*

There is a widely accepted formulation for the calculation of inventory costs, i.e. the multiplication of average stock, $I_{ik}$ and unit inventory carrying cost, $r_{ij} \cdot p_i$ :

$$CI_{ik} = I_{ik} \cdot r_{ik} \cdot p_i \,. \tag{4}$$

In Equation (4), $i$ still refers to the $i^{th}$ product/part, $k$ is the location of the warehouse of product/part $i$, $r_{ik}$ refers to the carrying cost rate of related product/part and $p_i$ is the purchase price of product/part $i$.

The average stock is related negatively to the turnover rate that is used to measure the quality of the inventory management in the warehouse. It provides information about the capital bound up in stocked products, as shown by VDI [26]. A successful BTO supply chain imposes great requirements on turnover rate in order to respond to customers in time.

#### *3.3.2 Evaluation of variant-driven inventory complexity costs*

The inventory equations with $v$ variants are shown in Equation (5), according to the VD-ABC proposed by Lechner [1]:

$$\begin{aligned}
I_0 &= \mu_0^0 + z\sigma_0^0 \\
I_1 &= \mu_0^1 + z\sigma_0^1 + \mu_1^1 + z\sigma_1^1 \\
&= I_0 + \left(\mu_0^1 + z\sigma_0^1 + \mu_1^1 + z\sigma_1^1\right) - \left(\mu_0^0 + z\sigma_0^0\right) \\
&\quad \ldots\ldots \\
I_V &= \mu_0^V + z\sigma_0^V + \mu_1^V + z\sigma_1^V + \cdots \mu_V^V + z\sigma_V^V = \\
&I_0 + \sum_{v=0}^{V}(\mu_1^V + z\sigma_1^V) - \left(\mu_0^0 + z\sigma_0^0\right).
\end{aligned} \tag{5}$$

The parameters in (5) are as follows:

$I_v$ – inventory in scenario with $v$ variants, $v=0, 1, 2, \ldots, V$;

$\mu_v^V$ – mean demand for variant v per unit of time in a scenario with V variants;

$\sigma_v^V$ – demand standard variation of variant v per unit of time in a scenario with V variants;

z – safety parameter chosen from statistics tables to ensure that the probability of this variants' stockout is above a certain service level.

The inventory cost is a proportion of the value of products in stock, as in Equation (4). The inventory costs with different numbers of variants are shown in Equation (6), as discussed by Lechner [1].

$$
\begin{aligned}
&CI_0 = I_0 \times p_0^0 \times r \\
&CI_1 = \left(\mu_0^0 + z\sigma_0^0\right) \times p_0^0 \times r + [\left(\mu_0^1 + z\sigma_0^1\right) \times p_0^1 \times r + \\
&\left(\mu_1^1 + z\sigma_1^1\right) \times p_1^1 \times r - \left(\mu_0^0 + z\sigma_0^0\right) \times p_0^0 \times r] = \\
&CI_0 + [\left(\mu_0^1 + z\sigma_0^1\right) \times p_0^1 \times r + \\
&\left(\mu_1^1 + z\sigma_1^1\right) \times p_1^1 \times r - CI_0] \\
&\qquad\ldots\ldots \\
&CI_V = CI_0 + [r \times \sum_{v=0}^{V} \left(\mu_v^V + z\sigma_v^V\right) \times p_v^V - CI_0]
\end{aligned} \quad . \tag{6}
$$

$CI_v$ – inventory cost in scenario with v variants, v=0, 1, 2, …, V;

r – interest rate of holding the stock;

$p_v^V$ – purchase price of variant $v$, $v=0, 1, 2, \ldots, V$.

The simple version of $CI_v$ as in Equation (7) can be obtained from Equation (6):

$$CI_V = r \times \sum_{v=0}^{V} \left(\mu_v^V + z\sigma_v^V\right) \times p_v^V . \tag{7}$$

The variant-driven inventory complexity costs with $V$ part variants $CCI_v$ can be calculated from Equation (8), as discussed by Lechner [1], on the premise that the inventory policy will not change with the increase in variants.

$$CCI_V = CI_V - CI_0 . \tag{8}$$

The variant-driven inventory complexity costs may occur in the materials inventory during inbound logistics, in the WIP inventory at the original equipment manufacturer (OEM) and in the finished automotive inventory in distribution centres.

## 3.4 EVALUATION OF RESOURCES COMPLEXITY COSTS

There are not only greater requirements for inventory and transport, but also changes of the process of production and logistics in the total automotive supply chain system due to the proliferation of variant-driven variety. Some additional processes are added to the existing production process in order to mitigate the mistakes or reworks when the variants increase to a certain level; and a more complicated production process may cause a reduced level of automation in return. Both these impacts prolong the whole production process. Meanwhile, in order to solve the problem that floor space beside an assembly line is not sufficient to deal with too many variants, some additional processes have to be added before assembly outside the assembly shop. The increase of processes brings demands for additional personnel, space and equipment resources. The costs of personnel, floor space and equipment are all related to the process time, and so can be evaluated by TD-ABC. The summation of the three kinds of costs with $V$ part variants is regarded as the resources costs, $CR_v$. Accordingly, the resources complexity costs are $CCR_v$.

### *3.4.1 Production process time*

Since there are some relation formulae between process time and resources costs, process time and incremental process time should be calculated first. The process time equation with different numbers of variants in this project can be shown as Equation (9), according to TD-ABC as discussed by Lechner [1].

$$
\begin{aligned}
&TP_0 = t_0 x_0^0 \\
&TP_1 = t_0 x_0^1 + t_1 x_1^1 = t_0 x_0^0 + \left(t_0 x_0^1 + t_1 x_1^1 - t_0 x_0^0\right) \\
&\qquad\ldots\ldots \\
&TP_V = t_0 x_0^V + t_1 x_1^V + \cdots t_V x_V^V \\
&\quad = t_0 x_0^0 + \sum_{v=0}^{V} t_V x_V^V - t_0 x_0^0
\end{aligned} \tag{9}
$$

$t_0$ – process time in the zero-variant scenario;

$t_v$ – incremental process time of incremental activity $v$, $v=1, 2, \ldots, V$;

$TP_v$ – time for process in a logistics system with $v$ variants;

$x_v^V$ – parts number of variant $v$ in products with $V$ variants.

This equation makes sure that the process time is allotted to individual variants. The fixed-step cost characteristics can also be shown by this equation. These occur if there is no margin for existing capacities, and new processes have to be added to expand the capacities.

Set $\triangle TP_v$ is the incremental process time between the scenario with $V$ variants and the zero-variant scenario, as in Equation (10):

$$\Delta TP_V = TP_V - TP_0 \tag{10}$$

### *3.4.2 Evaluation of personnel and equipment complexity costs*

The personnel complexity costs $CCP_V$ and equipment complexity costs $CCE_V$ can be calculated through multiplying the process time by correspondent cost rates according to TD-ABC, as proposed by Kaplan and Anderson [29]. The equipment here includes both equipment and auxiliaries.

$$CCP_V = \Delta TP_V \cdot CRP \,, \tag{11}$$

$$CCE_V = \Delta TP_V \cdot CRE \,. \tag{12}$$

*CRP* – cost rate of the capacity supply of personnel;
*CRE* – cost rate of capacity supply of equipment.

The key point here is to count completely the increasing process time in every segment. These times may include transport and delivery, loading and unloading, sequencing, unpacking and repacking, etc.

*3.4.3 Evaluation of floor space complexity costs*

There are two kinds of requirements for more floor space with an increase of part variants in automotive supply chains. The first, $CCF_{p,V}$, is caused by the increase of processes for supporting the production process. The second, $CCF_{s,V}$, derives from keeping the incremental stocks of part variants and finished products. These will be examined in turn.

First, for floor space complexity costs for additional processes, Lechner [1] analyzes the interaction between total time consumed and floor space in different working processes. She certifies that the improvement in processes, i.e. from standard delivery to delivery with internal preparation to just in sequence (JIS) delivery, can change the requirements for floor space beside the assembly line through extending the whole process time.

There should be floor space for the implementation of new increased processes. These floor spaces, which may be located in the internal warehouse, beside the assembly line or in the external warehouse, are closely related to the containers and equipment used during such processes. Hence, the container areas can be used to estimate the floor space needed by new processes:

$$\begin{array}{l} F_{p,1} = r\left(c_1^V \times f_1^V\right)\left(w_1^V \times l_1^V\right) \\ \quad\quad\quad \ldots\ldots \\ F_{p,V} = r\sum_{v=1}^{V}\left[\left(c_v^V \times f_v^V\right)\left(w_v^V \times l_v^V\right)\right] \end{array} . \tag{13}$$

$F_{p,v}$ – area of floor space induced by additional processes with $v$ variants, compared with the zero-variant scenario, $v=0, 1, 2, \ldots, V$;

$w_v^V$ – width of the containers for variant $v$;

$l_v^V$ – length of the containers for variant $v$;

$r$ – magnification coefficient of floor space when considering the demands of activity space for equipment and workers;

$c_v^V$ – number of containers for variant $v$;

$f_v^V$ – binary variable to express whether an incremental process is required or not with $v$ variants. If it is required, $f_v^V = 1$; otherwise, $f_v^V = 0$.

Then, the first kind of floor space complexity costs can be calculated in Equation (14), as shown by Lechner [1]:

$$CCF_{p,V} = F_{p,V} \cdot CRF_p \,. \tag{14}$$

$CRF_{p,V}$ – floor space cost rate for the additional process area.

Second, for floor space complexity costs for increased stocks, it is difficult to estimate these costs because there are several possible solutions for a company to obtain the floor space, such as through renting, construction or third-party logistics (TPL) management. It should be assumed that all factories rent warehousing to satisfy their demands for floor space in this project. The floor space complexity costs can be calculated through multiplying the lease costs and space demands. As for floor space, it can be estimated by stock level, container/pallet size, warehouse height and the effective area utilization factor:

$$F_{s,V} = \sum_{v=0}^{V} \frac{I_{v,\max}}{f_V L_v} \cdot \left(w_v \cdot l_v\right) . \tag{15}$$

$F_{s,V}$ – floor space demands for stocking area of $V$ variants, $v=0, 1, 2, \ldots, V$;

$f_V$– effective area utilization factor of warehouse, which refers to the ratio of storage area to warehouse area;

$I_{v,\max}$ – maximum stock of variant $v$ in warehouse;

$L_v$ – stack layers of container/pallet of variant $v$ in warehouse.

$L_v$=[$H$ / $h_v$]. [$H$ / $h_v$] is the maximum integer that is less than or equal to $H$ / $h_v$. $H$ refers to the height of warehouse. The parameters, $w_v$, $l_v$ and $h_v$ are the width, length and height of the container/pallet of variant $v$, respectively.

The floor space costs $CF_{s,V}$ and the complexity costs of floor space $CCF_{s,V}$ can be achieved through Equation (16) and (17):

$$CF_{s,V} = CRF_s \cdot F_{s,V} \,, \tag{16}$$

$$CCF_{s,V} = CF_{s,V} - CF_{s,0} \,. \tag{17}$$

$CRF_s$ – monthly floor space cost rate for the incremental area.

Just as with the inventory complexity costs, the floor space complexity costs may also occur in the materials inventory during inbound logistics, WIP inventory in OEM and the finished automotive inventory in distribution centres.

### 3.5 TOTAL COMPLEXITY COSTS

Obviously, the total logistics costs *CV* and complexity costs *CCV* are, above all, the sums of the corresponding costs, which are shown in Equations (18) and (19):

$$CV = CT_V + CI_V + CR_V = CT_V + CI_V + \left(CP_V + CE_V + CF_{p,V} + CF_{s,V}\right), \quad (18)$$

$$CCV = CCT_V + CCI_V + CCR_V = CCT_V + CCI_V + \left(CCP_V + CCE_V + CCF_{p,V} + CCF_{s,V}\right), \quad (19)$$

where $CP_V$ and $CE_V$ are the personnel costs and equipment costs with *V* variants individually.

## 4 Simulation with OTD-NET and analysis of the results

In this section, the four-echelon automotive supply chain model in Figure 1 is created firstly by the OTD-NET. Three different scenarios are then simulated separately, and the complexity costs are calculated and analyzed in order to evaluate the impacts of variants on the supply chain.

### 4.1 SCENARIO-BASED PROCESS MODEL

The discrete event simulation tool OTD-NET was developed by the Fraunhofer Institute for Material Flow and Logistics (IML). OTD-NET has been applied successfully in many logistics projects (e.g. Intelligent Logistics for Innovative Product Technologies, ILIPT, for VW commercial vehicles) and in the dissertations of Cirullies [34] and Klingebiel [35]. It is especially suited for use in the field where information flow is tightly coupled with material flow, as shown by Cirullies [34] and Klingebiel [35]. The initial aim of OTD-NET was to serve the automotive industry, and it has now gained experience in application and improvement in this industry over many years. It was able to simulate the diversity and complexity in the automotive supply chain necessary for this paper. Therefore, we chose OTD-NET as the simulation tool to obtain our evaluation results. The modelling structure of the scenario supply chain is shown in Figure 4.

As an object-oriented simulation tool, OTD-NET contains the classes “supplier”, “plant” and “dealer”. Hence, these supply chain nodes can be created directly in the simulation model, as demonstrated in Figure 4. However, there are no classes such as “warehouse” and “distribution center” in OTD-NET. It provides other innovative concepts: “buffer” (including “inbuffer”, “outbuffer” and “goods receipt buffer”), “routing” and “distribution channel”. “Buffer” (expressed by the green chevron-shaped symbol in Figure 4) and “distribution channel” (expressed by the blue chevron-shaped symbol) are both used to emphasize that goods should be always in the flow process but not in stagnancy before they reach the ultimate customers, as found by Wagenitz [36] and Li [37]. The warehouses are represented by “inbuffer” and “outbuffer”, respectively, according to their functions and positions in this project. “Inbuffer”, in which the containers of inbound logistics are provided, must be created when modeling an inbound logistics system. Wagenitz [36] proposes that “outbuffer" is defined as the starting point of the inbound logistics between the second- and first-tier suppliers, or between the supplier and the plant. The GDC is also represented by “buffer” in this project.

“Distribution channel” is one of the most important classes used to model the distribution, as discussed by Wagenitz [38]. Wagenitz [36] and Li [37] argue that a “distribution channel” can represent an actual route channel from starting point to end point located in different positions (e.g. from suppliers to plant, from plant to dealers), or the route in a logistics node such as in a warehouse or distribution center. It describes the transport time and transport capacities between the locations as discussed by Wagenitz [36]. However, Wagenitz [36] also claims that if there are several alternative routes between logistics nodes in two echelons, a class “routing table” (expressed with a diamond-shaped symbol in Figure 4) and its attribute “routing” (expressed with grey chevron-shaped symbol) will be used to choose an alternative distribution channel (e.g. air cargo instead of seaborne transport). Each “route” has a corresponding “distribution channel”.

From Figure 4, it can be shown that the group body in white comes into being after production in the welding shop. Therefore, two layers of suppliers are built here. The combination of press shop and welding shop is regarded as a BTO supplier (i.e. body shop) and the body sheets supplier is the BTS supplier of the body shop. In order to simplify the model, the paint shop and assembly shop are combined into one plant: “paint and assembly plant” in the model.

### 4.2 EVALUATION OF COMPLEXITY COSTS OF VARIANT-DRIVEN VARIETY

In the three scenarios of zero-variant, one-variant and rich-variants, in the zero-variant scenario there is only one kind of base part in each part type, which means only one kind of base product is produced. This product has a 100% actual rate in the market, and the actual rates of all the parts are also 100%. In the one-variant scenario, one part variant is added in the part type group paint. The actual rates of the two kinds of paint are 0.6 and 0.4. Therefore, two kinds of automotive are produced in this scenario. In the rich-variants scenario, there are a couple of part variants in each part type. In detail, there are 11 kinds of paint, six kinds of engine, four kinds of transmission, seven kinds of seat, two kinds of door and locks, three kinds of wheels and tires, and three kinds of body in white as the unfinished products in the body shop. All these part variants have different actual rates. Therefore, the total number of product variants is equal to the arithmetic product of all the number of part variants, that is 3*11*6*4*7*2*3=33,264 if all the part variants in one part type can match with all the part variants in other part types.

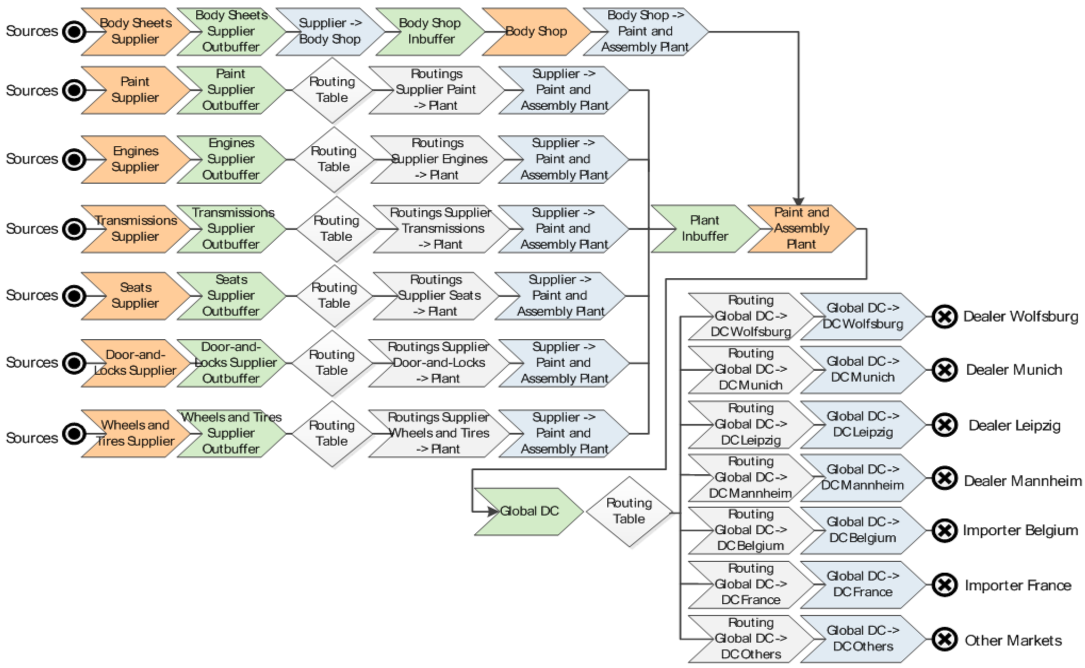


FIGURE 4 OTD-NET modelling structure of the scenario supply chain

The production cycle time of a car is 2,340 minutes in the zero-variant and one-variant scenarios, but it goes up to 2,640 minutes in the rich-variants scenario. Assume the market demands for a car in one year shown in Table 2. By running the simulator, all the complexity costs can be calculated with the evaluation models in the previous section.

TABLE 2 Total market demand for PC car

| **Month** | 1 | 2 | 3 | 4 | 5 | 6 |
|---|---|---|---|---|---|---|
| **Demand** | 18000 | 13500 | 13500 | 15000 | 18000 | 15000 |
| **Month** | 7 | 8 | 9 | 10 | 11 | 12 |
| **Demand** | 15000 | 12000 | 10500 | 9000 | 12000 | 13500 |

The total production of the three scenarios is 164435, 164495 and 163539, respectively. In the rich-variants scenario, because of the longer processing time and more complicated logistics operation, the production is less than that of the other two scenarios. Table 3 shows all the logistics costs of three scenarios discussed in the previous section, while Table 4 shows all the complexity costs of the last two scenarios. In these tables, scenario 1, scenario 2 and scenario 3 refer to the zero-variant scenario, one-variant scenario and rich-variants scenario, respectively.

TABLE 3 Total variant-driven variety costs

| | *CT* | *CI* | *CR* | | | | *CV* |
|---|---|---|---|---|---|---|---|
| | | | *CP* | *CE* | $CF_p$ | $CF_s$ | |
| Scenario 1 | 40472706 | 12151358 | 134672265 | 38477790 | 0 | 363038 | 226137157 |
| Scenario 2 | 40483628 | 12030035 | 134721405 | 38491830 | 0 | 359790 | 226086688 |
| Scenario 3 | 40275500 | 22259627 | 151110036 | 43174296 | 1866.24 | 570701 | 257392026 |

TABLE 4 Total variant-driven variety complexity costs

| | *CCT* | *CCI* | *CCR* | | | | *CCV* |
|---|---|---|---|---|---|---|---|
| | | | *CCP* | *CCE* | $CCF_p$ | $CCF_s$ | |
| Scenario 2 | 10922 | -121323 | 49140 | 14040 | 0 | -3248 | -50468,51 |
| Scenario 3 | -197206 | 10108269 | 16388631 | 4682466 | 1866,24 | 207663 | 31191689 |

The simulation results of all the complexity costs can be summarized as follows, according to the calculation results.

(1) Process complexity costs. The number of parts and finished cars transported in the three scenarios is almost unchanged because the productions are similar. Therefore, the process costs are approximately the same. The process costs change very slightly, meaning the impact of variants on process costs is very small.

The impacts of increasing variants on transport costs are so insignificant as to be negligible if the total market demands or outputs remain unchanged. The total demands for parts and products will not change either under such a situation, so the transport burden on parts and products is the same. What will be altered are the transport frequency and transport volume of each part variant at each time.

(2) Inventory complexity costs. The stocks of body in white and unfinished cars are not considered because normally they are kept on the production lines and do not produce demands for additional resources. Only the inventory complexity costs of parts and finished cars are analyzed in this paper. The number of part variants of body sheets is the same in the three scenarios, so the inventories are all the same. All the other numbers of part variants in scenario 2 is equal to that in scenario 1, except for paint. That is why the average inventories in scenario 2 are comparatively close to that in scenario 1. In scenario 3, as compared to the other two scenarios, the number of every part variant increases greatly, apart from body sheets, which leads to a sharp rise in the inventory. Completely different process costs and impact of variants on inventory costs are manifest. The inventory costs of parts change slowly when there are few variants, while they increase quickly with greater variety due to the multiplicative effect of more part variants.

The characteristics of the BTO supply chain maintain the stock of cars at a low level. Moreover, all the variants of the finished automobiles ordered by one dealer are distributed through one distribution channel, which are distinctive to the transportation of parts: each part variant is transported through a special distribution channel. The gaps of stocks of finished cars among the three scenarios are not as huge as those of parts. Therefore, there is not so great an impact of variant-driven variety on inventory costs of finished cars as on part inventory costs. In particular, when there are only few variants, the inventory costs of automobiles change very little (and sometimes decrease slightly).

(3) Resources complexity costs. Personnel and equipment complexity costs are both related directly to the total process time. Although the values of the two kinds of costs above are completely different, their variation tendencies are the same. That is, an increase in variants has the same impact on personnel costs and on equipment costs. In the model constructed in this project, an additional process, sequencing, occurs in scenario 3 compared with scenarios 1 and 2. That means the requirements for floor space on processing in scenario 2 are the same in scenario 1. All the other five-part types, except for body sheets and paint, should be sequenced before being fed to the assembly line. Therefore, floor space complexity costs for additional processes only occur in scenario 3. As for floor space complexity costs for increased stocks, they are decided by the maximum stock of parts and finished cars. The variation of floor space costs for storing parts conforms to the change of maximum stocks. Similar to the change of inventory, the maximum stocks in scenario 2 are very close to those in scenario 1, while the maximum stocks in scenario 3 increase significantly. Obviously, that phenomenon is the result of the huge increment of variants from scenario 2 to scenario 3. However, the impacts of variants on maximum stocks of cars are not as substantial as on part stocks.

Furthermore, because of the decrease of production volume and the difference of transportation volume, several complexity costs in Table 4 are negative. Nevertheless, it can be shown from Table 4 that the total costs increase greatly. Table 5 shows the growth rate of each complexity cost. According to Tables 4 and 5, the total logistics costs in scenario 3 increases by about 13.8% from that of scenario 1. Figure 5 shows the costs in Table 3 using a bar chart. It is obvious from Figure 5 that resources costs account for the majority of total logistics costs compared with the other two kinds of costs, while it can also be seen that inventory complexity costs in scenario 3 account for about 83.186% of the inventory costs in scenario 1 – i.e. the growth rate of inventory costs is 83.186% between scenario 1 and scenario 3. Inventory costs change slowly when there are few variants, while they ascend quickly with the propagation of variety because of the multiplicative effect of more part variants. In addition, the impact of parts on inventory costs is greater than that of finished cars.

TABLE 5 Growth rates of logistics costs compared with scenario 1

| | *CCT* | *CCI* | *CCR* | *CCV* |
|---|---|---|---|---|
| Scenario 2 | 0.027% | -0.998% | 0.035% | -0.022% |
| Scenario 3 | -0.487% | 83.186% | 12.265% | 13.793% |

To sum up, the proliferation of variant-driven variety had a huge influence on the increase of logistics costs, especially on inventory costs and resources costs. Hence, managers should pay more attention to the management of inventory costs and resources costs during an increase in the number of variants.

## 5 Conclusion

With the objective of helping automotive manufacturers optimize the number of part variants and product variety in respect of saving costs, this project studies the methods for evaluating the complexity costs caused by the proliferation of part variants on automotive supply chain. First, a four-echelon automotive supply chain model from suppliers to dealers is constructed with a process chain model, and the KPI system of evaluating complexity costs is achieved. Second, combining the TD-ABC, VD-ABC and zero-based approaches, the evaluation models of all complexity costs in regard to KPI are constructed. These complexity costs are process complexity costs, inventory complexity costs and resources complexity costs. Lastly, the four-echelon supply chain model is created with an OTD-NET simulator and three scenarios with different number of variants are simulated. The results of these three scenarios are used to evaluate the impacts of variants on the automotive supply chain dynamically.

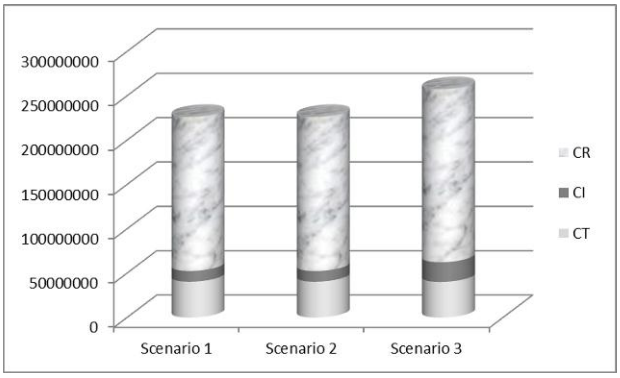


FIGURE 5 Components of total variant-driven variety costs

The research shows that the proliferation of part variants has a great impact on the logistics costs of automotive supply chains. Inventory complexity costs are particularly influenced by the variant-driven variety. Inventory costs and resources costs are also influenced significantly. In the light of the zero-based approach, the automotive manufacturing can choose the suitable number of variants by referring to the affordability line. The results of this project are also helpful for other industries to evaluate problems of variety.

As shown at the beginning of this paper, the impact of variant-driven variety on the automotive supply chain include costs, performance and the ecological burden, and that the evaluation should also be carried through these three aspects. As this paper only examines the evaluation of variant-driven variety complexity costs in the automotive supply chain, this is not sufficient to measure the impact of an increase of variants comprehensively and to make decisions on variants generally. Therefore, the impact of variant-driven variety on performance and the ecological burden of supply chains will be the next stage of study. Only after the evaluation of all three sides of such impact can manufacturers start the real and extensive evaluation of the variant-driven variety. Consequently, the manufacturing can choose the number of variants and variety more scientifically.

With regard to dynamic evaluation, this project achieves this by means of simulating and analyzing the change of impacts in three scenarios with different numbers of variants. This kind of simulation does not reflect the total and real change of impact with the gradual increase of variants. It is necessary that a stochastic simulation model of automotive supply chains should be developed that can simulate the impact of variants continually as well as stochastically. With the assistance of such a simulation model, an influencing graphic chart of variants can be achieved and the manufacturers will be able to make decisions regarding the number of variants and variety much more precisely.

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