Professional MBA
Automotive Industry

Analysis, selection and application of costing approach providing a transparent breakdown of the variety-induced complexity in the automobile inbound logistics cost calculation for the purpose of anticipative logistics planning at the OEM

A Master's Thesis submitted for the degree of
“Master of Business Administration”

supervised by
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ACADEMY FOR CONTINUING EDUCATION

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Affidavit

I, **JOZEF JAMBOR, M. SC.**, hereby declare

1. that I am the sole author of the present Master's Thesis, "ANALYSIS, SELECTION AND APPLICATION OF COSTING APPROACH PROVIDING A TRANSPARENT BREAKDOWN OF THE VARIETY-INDUCED COMPLEXITY IN THE AUTOMOBILE INBOUND LOGISTICS COST CALCULATION FOR THE PURPOSE OF ANTICIPATIVE LOGISTICS PLANNING AT THE OEM", 77 pages, bound, and that I have not used any source or tool other than those referenced or any other illicit aid or tool, and
2. that I have not prior to this date submitted the topic of this Master's Thesis or parts of it in any form for assessment as an examination paper, either in Austria or abroad.

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Abstract

Product innovations, globalization, accelerated product life cycles, electrification, sustainability, autonomous driving, connectivity, delivery shortages in the supply chain, increased competition due to market saturation and increasing customer requirements are just a few examples of the wide range of challenges the automotive industry is facing nowadays. Especially the customer demands for individuality and his behavior with respect to lifestyle, travel, and luxury underwent a tremendous change and therefore vary broadly, which in turn affects the automotive environment widely. In order to generate individual, unique, and consumer-specific products the Original equipment manufacturers (OEM) have enlarged their offer on models and configurable options considerably. As a result, the product variety has increased to an almost infinite number of options and thus becoming unmanageable.

The exploding number of product variants affects the logistics, being a vital element in the automotive sector, significantly. In particular, the inbound logistics systems respond to this impact by increasing costs and declining performance. It appears that currently used logistical cost calculation at one of the Premium OEM´s is not sufficient to meet the demands of the modern complexity and variant management, which is in turn an important tool for managing of the product variants. Hence, the analysis, evaluation and selection of the proper cost calculation method allowing to allocate variety-induced logistics costs – the latter often considered as hidden costs of doing business – to the individual product variants is performed within the framework of this research.

This thesis aims to find suitable cost calculation method to fill the gap in the missing link between the product variety-induced complexity and logistics costs accrued in the automotive inbound logistics at OEM-level. This model-based approach shall serve as an active complexity a variant management tool for the purpose of supporting product variety decisions at an early stage in the product design phase. The practicability of this method is demonstrated in the case study performed for the rear bumper system.

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List of abbreviations

ABC	Activity-based Costing
ABCII	Attribute-based Costing
CMA	Contribution margin accounting
EAD	Extended Axiomatic Design
gAMS	Genehmigtes Änderungsmanagement System
JIS	Just in sequence
LH	Left hand
OEM	Original equipment manufacturer
RC	Resource costs
RH	Right hand
SOP	Start of Production
SuMa	Supermarket
SUV	Sport utility vehicle
TD-ABC	Time-Driven Activity-based Costing
VBC	Volume-based Costing
VD-ABC	Variety-Driven Activity-based Costing
PC	Product costs
R&D	Research and Development

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1 Introduction

1.1 Initial situation

The global automotive industry is under constant pressure from customer and environmental demands. The industry is facing issues regarding fuel economy, gas emissions, safety and affordability. Moreover, the competitive pressures on cost, quality, performance and manufacturability of the vehicles are today bigger than ever before (Samodajev 2019). One of the crucial challenges of the today's automotive industry is customer individual mass production. There is a desire for personalization and uniqueness by the modern customer. He wants to stand out of the crowd by purchasing a unique product not available for everyone. This product should be perfectly tailored to his needs and his life situation.

In a reaction to the aforementioned customer demand the OEMs increased the number of individual products – this also in order to differentiate themselves from their competitors. The past few years have shown a tremendous increase in variants and derivatives as OEMs have tried to capture market niches and increase their profits per vehicle. This in turn has led to a bloated and complex product portfolio, with associated engineering demands for future facelifts and successor models (Bauer et al. 2020: 24). Figure 1 shows the example of one of the selected Premium SUV segments ~ 0,7 million of built vehicle configurations with 2,3 -million sold cars in 2020. The ratio between possible and the actual ordered configurations account for 65.000: ~ 10^{32}. The customers called-off only a fraction of the possible car configurations.

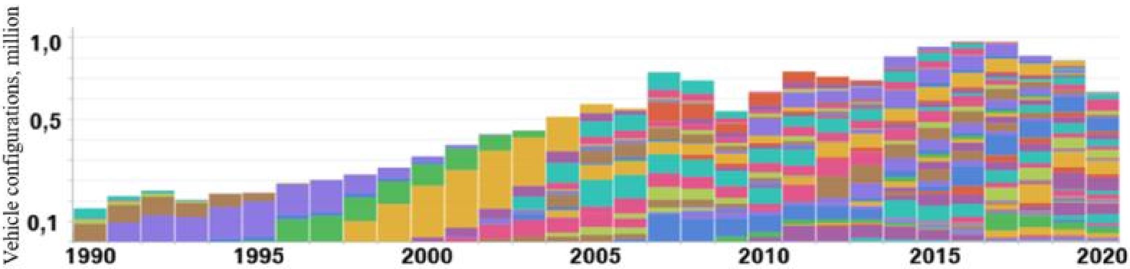

Figure 1: Number of the built vehicle configurations p.a. (Selected Premium SUV derivate).

In average each ordered configuration was only built three times and the variant of the top equipped vehicle amounts for ~ 5%. This chart exemplifies that there is an urgent need to tackle the problem of unprofitable product variants at the level of car producers ideally by reducing the complexity and by enhancing the variant's manageability.

Today's cars are very complex and technologically advanced products. According to the Motor & Equipment Manufacturers Association it takes approximately 3,800 different components (identified by unique part numbers) to build an average car. Many components, however, are used in large multiplicities; averagely it takes nearly 35,000 separate items to build one car. As the customized mass production plays an important role in the automotive industry, the effective management of the product variety and its inherent complexity is crucial for the success of the OEM´s (Pasek 2006: 5). According to Deloitte 5 % of profitable variants account for three quarters of total sales for vehicles with positive profit contribution and 80% of the profit account to one´s model series (Figure 2). The remaining vehicle configurations built increase the complexity significantly, but contribute to the profit only marginally. (Deloitte 2016: 2).

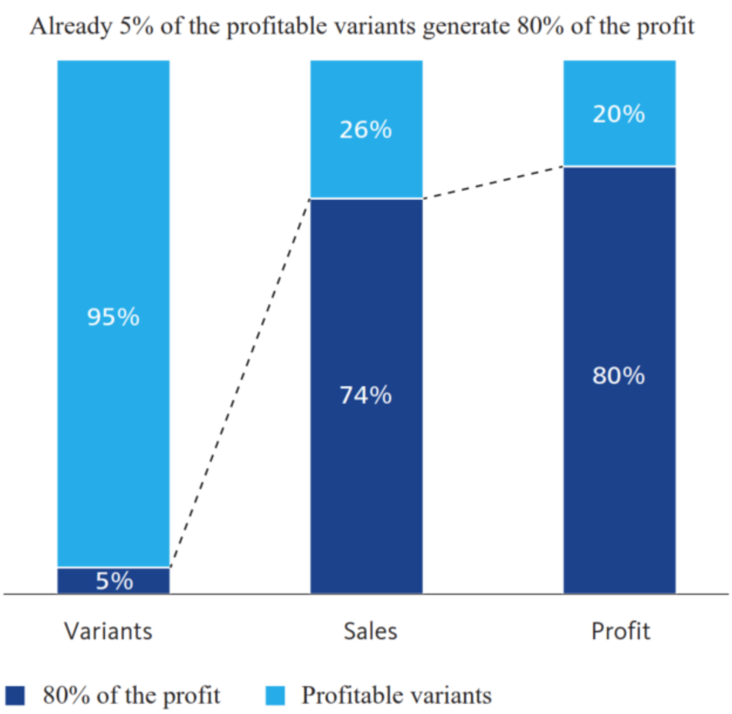

Figure 2: Relation between number of variants, sales and profit (Deloitte 2016: 2).

Due to individualization of the products spectrum by the car producers following the trend of increasing customer orientation, growth of complexity across the entire value chain was detected. Especially the information and material flow within the inbound logistics have been hit hard by this development. The measures for competitiveness of the OEMs are nowadays not only the traditional factors such as quality and prices, but rather the shortening of product life cycles and growing flexibility requirements (Hofmann & Nothardt 2009: 1). The rise in strategic relevance of logistics is accompanied by cost increase. Besides to the increase in costs for inventory and transport, the management and coordination efforts are becoming more and more demanding. Often, additional process steps for example like commissioning or sequencing due to lack of floor space along the assembly line are necessary to be implemented (Klug 2010: 170).

The uncertainties and fluctuations in demand relating to the product variants during the planning phase and operation are considered as one of the biggest challenges (Veldhuijzen und Schip 2011: 4; Kümmerlen 2011: 20). Whereas conversative approaches estimate the variant cost at OEM-level to amount to 15-20%, other studies calculate this cost to be more than 50% (Saemerov 2005: 45; Schaffer 2010: 183; Bohne 1998: 161). The above mentioned demonstrates clearly, that product variety does not only affects logistics costs and the performance itself, but also the design of logistics systems (Lechner et al. 2011: 3).

1.2 Problem description

Providing the "right" new products to the market is considered from an economical view as a critical factor for the actual success of manufacturing companies. In fact, the ability of the companies to create new products and product variants involving a low level of company resource consumption is regarded as one key factor to sustain a competitive advantage.

OEMs often try to tackle this challenge by offering multiple models and various options, but are inevitable faced with struggle in trade-off between benefits and efforts of variety-induced complexity. They are convinced that if they maximize the fit between available products and customer needs, it will allow them to defend or even increase the market share and therefore consequently enlarge their part range considerably. However, the rise in the number of product variants in turn leads to an increased product variety in the supply chain and consequently affects processes, resources, and structures in logistics. Main issue in the logistics systems of the OEMs is a lack of transparency regarding the impacts of product variety-induced complexity on costs and performance.

To evaluate logistics strategies in the product design phase at an early stage, e.g., the determination of an optimal order penetration point, the knowledge on the product variety's impacts is a pre-requisite. In order to provide transparency over product variety-induced complexity, relevant factors have to be identified and quantified in terms of costs and performance. Variant costs, often referred to as complexity costs, are generally regarded as overhead costs and are thus accepted as fix costs. Consequently, these fix costs account for the majority of supply chain costs. In practice, volume effects of variants are overestimated, whereas their impacts on costs actually remain underestimated. As a result, costs that are assigned to variants are generally deemed too low. Therefore, variant costs are often considered as hidden costs of doing business (Lechner et al. 2011: 2).

To provide transparency over product variety-induced complexity, individual product variants, product variety and their impacts on logistics costs and performance of inbound logistics at OEM, a tailored approach for the cost quantification must be applied. Most of the existing evaluation approaches implemented by OEMs´ reflect product variety in their costing by determining variant-induced percentages which are based on estimates or fixed ratios. However, this allocation is not fair according to the actual input involved. Because up to 80% of total vehicle cost in the automotive industry is determined already during the product development process and the increasing product variety affects predominantly the logistics sector, the knowledge regarding impacts of product variety is decisive to support strategic decisions at an early stage (Klug 2010: 105).

1.3 Aim of the research and research question

The aim of this research is to solve the aforementioned problem of inadequate cost calculation method and lacking transparency over product variety-induced complexity in the inbound logistics at OEM by **(1)** finding an appropriate evaluation approach to assess product variety-driven complexity in order to quantify the impacts of product variety on logistics costs and logistics performance without relying on estimates and **(2)** implementing the found method in praxis to enable an expedient product variety decisions in the product design phase at an early stage. The feasibility and usefulness of this approach is thereby demonstrated by a case study conducted in the rear bumper system of a particular German OEM.

Research conducted in the past in the field of variety-driven complexity focused more on the area of production and less on the analyses from a logistics point of view taking the automotive mass production into consideration. Based on the aim of this work the research question reads as follows and shall be answered in the context of it:

Research question: *(i) Does an evaluation approach already exist, which allows the quantification of inbound logistics cost and performance impacts dependent on the level of product variety according to the actual input involved and (ii) is this method applicable in the praxis at an OEM?*

The first research question is aimed at evaluating the most relevant approaches and indicators posed in scientific literature to measure variety-induced complexity.

1.4 Structure and methodological approach

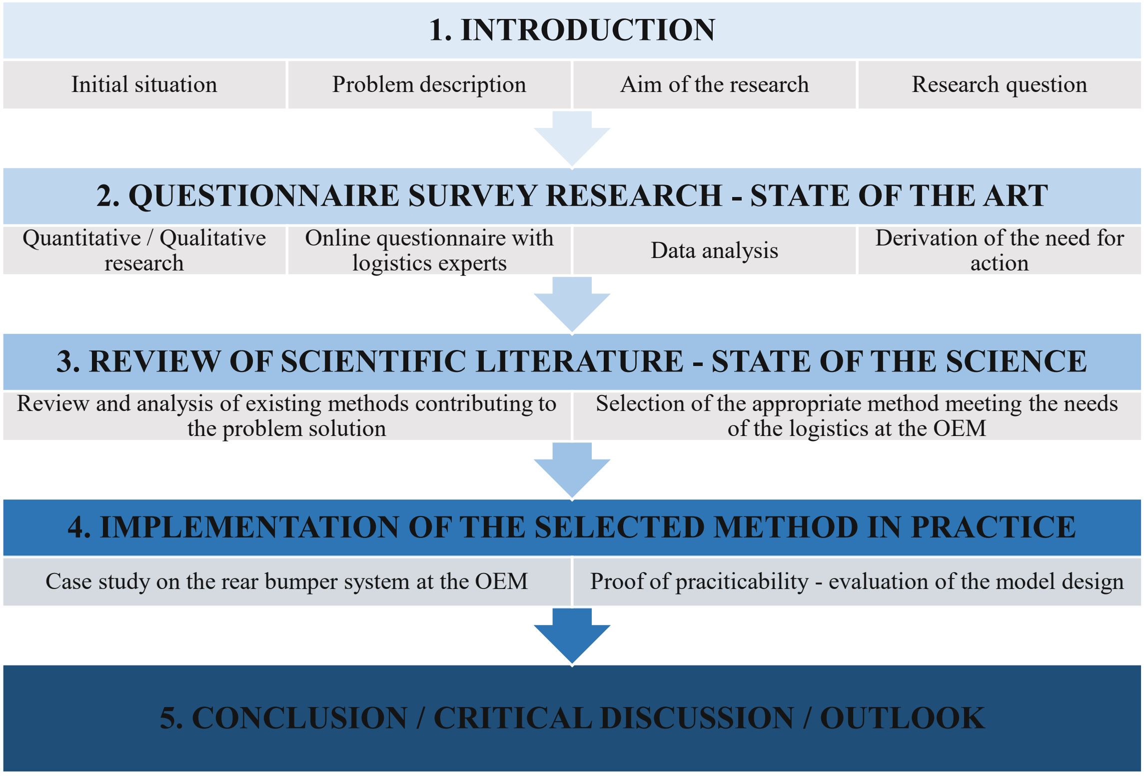

Figure 3: Structure and methodological approach of the thesis.

As illustrated in Figure 3 the structure of this Master Thesis is divided into five steps enabling the achievement of the aim and ultimately leading to the answer of the research question. A general view on the today´s situation in the automotive industry with regard to increasing product variants and consequences for the logistical sector, represents the introduction of this thesis. The first chapter is completed by the formulation of the research question.

Chapter 2 then demonstrates the State-of-the-art in the OEM´s logistics relating to the variant management and adequate cost calculation method providing transparency over product variety-induced complexity by describing the results of the online questionnaire survey which has been conducted with logistics experts. The results of the collected data underpin the author´s conclusions of the need for action. To meet the logistical requirements and to provide a sound basis for the answer of the first part of the research question, a review and assessment of relevant literature and empirical research studies as well as of a selection of appropriate cost calculation method was necessary to be performed by the author. The findings of such are outlined in chapter 3 accordingly. The fourth chapter – being the central part of this Master Thesis – finally describes the implementation of this method via the case study conducted at OEM. The summary of the findings and the answer of the second part of the research question are covered by the last chapter of the thesis.

2 Questionnaire survey research – State Of The Art

2.1 Motivation for quantitative, qualitative research and questionnaire design

In order to gain a better insight into the problem mentioned in the chapter 1.2, to collect the expert's opinion and to establish the basis for the review of scientific literature following in chapter 3, an anonymous online questionnaire survey with 10 experts from different logistical sectors at the OEM has been conducted. The research comprised 16 different kinds of questions, e.g., open ended, multiple-choice, rating scale questions, which were each formulated to gather detailed information on the problems encountered by the respondents.
This quantitative and qualitative experimental study was aimed to create generalizable knowledge on the practical experiences with regard to product variety, variety drivers and product variety induced cost in the automotive logistics sector.

2.2 Outcome of questionnaire survey research

The following chapter provides an overview on the survey questions and main findings. Ultimately, the survey results can be considered as a collective reflection of the experiences and knowledge of the surveyed experts.

Question 1:

Are you familiar with the term Complexity and Variant Management and how is it implemented in your logistic sector?

The survey showed that almost 89% of the respondents are familiar with complexity and variant management, but that phenomenon is only being actively addressed by a small fraction of their departments. It could be determined by the author, that it is often not possible to counteract the increasing product variety as the decision on the additional variant already has already been taken at an earlier stage in the OEM´s evaluation process. Higher resource consumption, directly connected to the product variety leads to cost increase in the logistic sector.

Question 2:

How high is in your opinion the possible influence of the logistical sector on the product variety / number of product variants at an early stage of the product development?

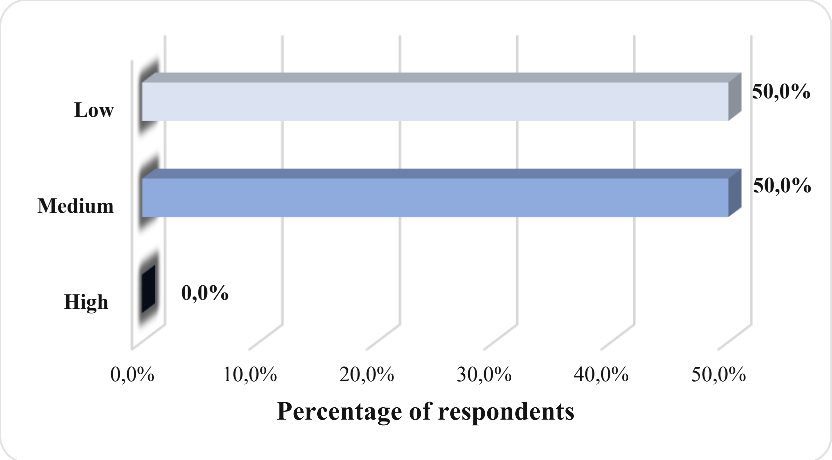

Figure 4: Results on the influence of the logistics on the product variety at an early stage of the product development.

Question 3:

Is in your opinion the current situation with regard to product variety in the automotive logistics manageable?

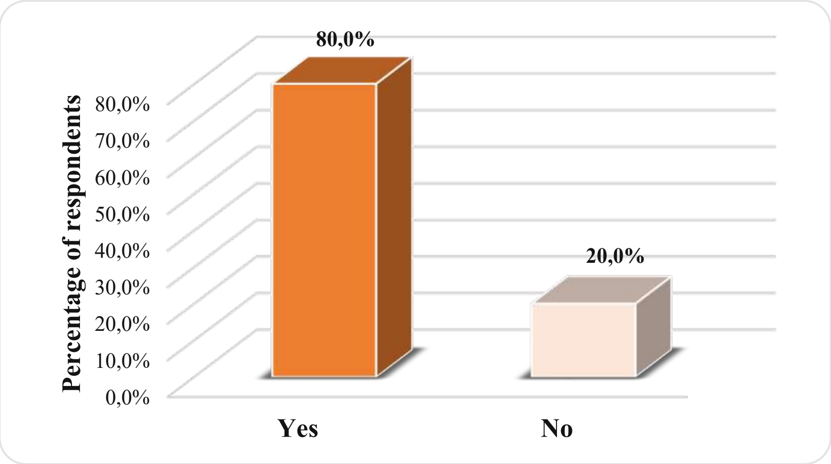

Figure 5: Results on the manageability of the current situation with regard to product variety in the automotive logistics.

Question 4:

What are in your view the biggest issues of the modern automotive logistics?

In addition to the number of variants and product variety, the experts also mentioned as major issues they are dealing with, i.a., the missing transparency over inventory across the supply chain, supply shortfalls and underestimate of serious impacts on the logistic processes.

Question 5:

What are in your view the main external product variety drivers?

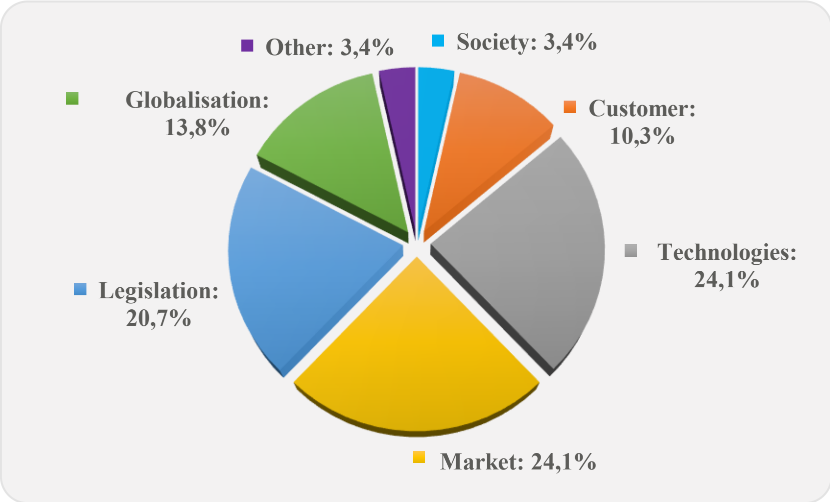

Figure 6: Results on the main external product variety drivers.

Question 6:

What are in your view the main internal product variety drivers?

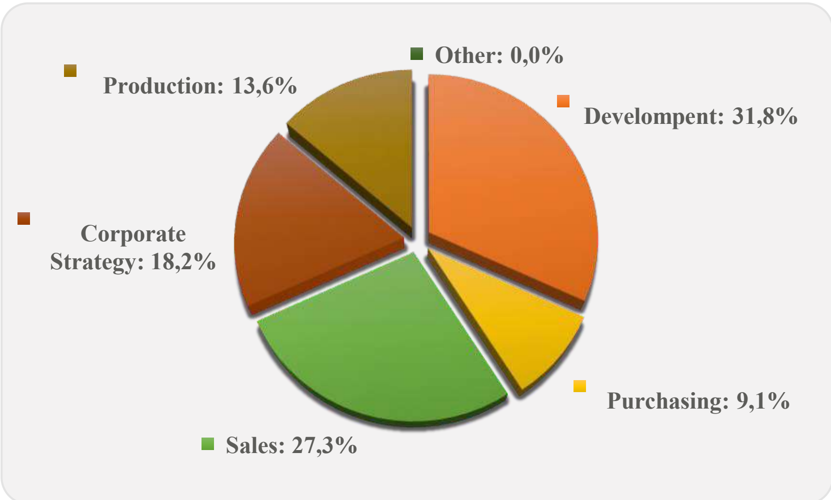

Figure 7: Results on the main internal product variety drivers.

Question 7:

What methods do you apply to calculate the costs in your logistic sector?

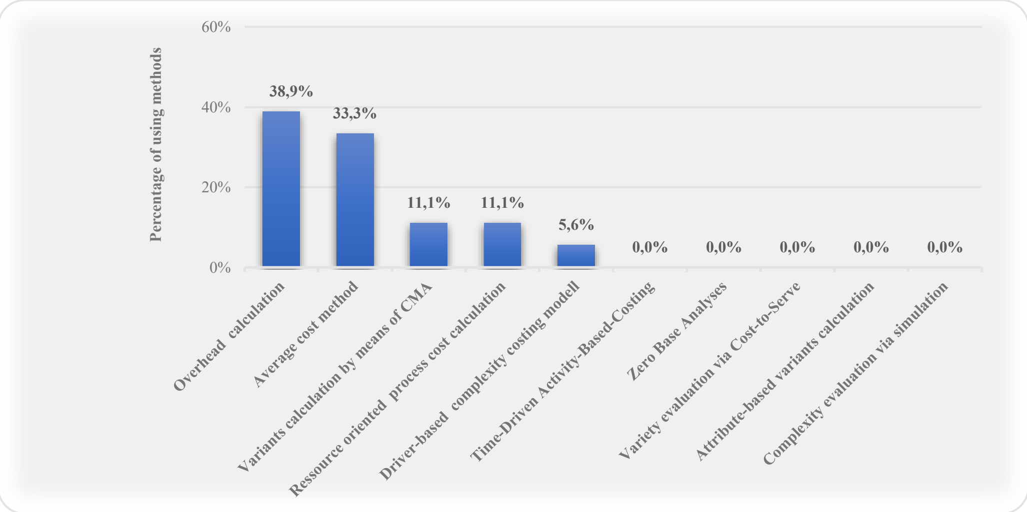

Figure 8: Results on the applied cost calculation methods in the logistical sector.

Question 8:

How would you describe the cost calculation method applying in your logistics planning? Does match any of the abovementioned methods?

The answers to this question had revealed, that the Overhead calculation, Average cost method, Mixed cost, Rule of three calculation and Business case calculation are the methods typically used for the purpose of planning costs determination. Chapter four is dedicated to the cost calculation methods and highlights some of the relevant approaches.

Question 9:

How flexible do you find your costing method in relation to change in number of variants and quantity of parts per variant?

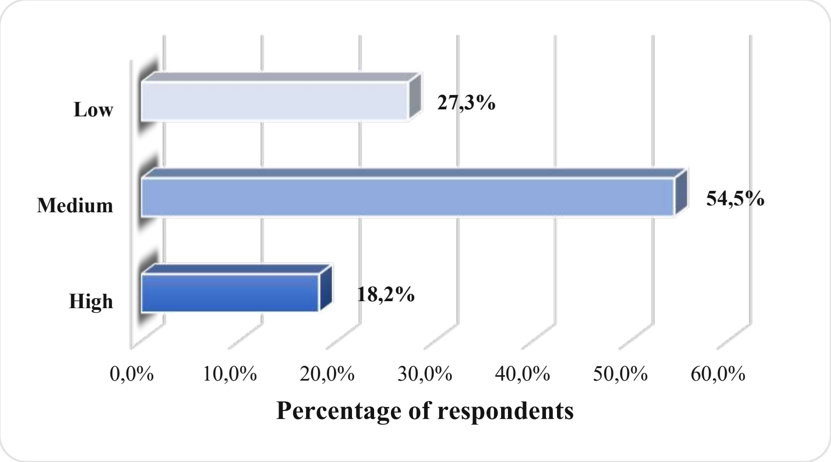

Figure 9: Results on the flexibility of the applied cost calculation methods in relation to product variance.

Question 10:

Do you consider the using cost calculation method as sufficient or is there still room for improvement?

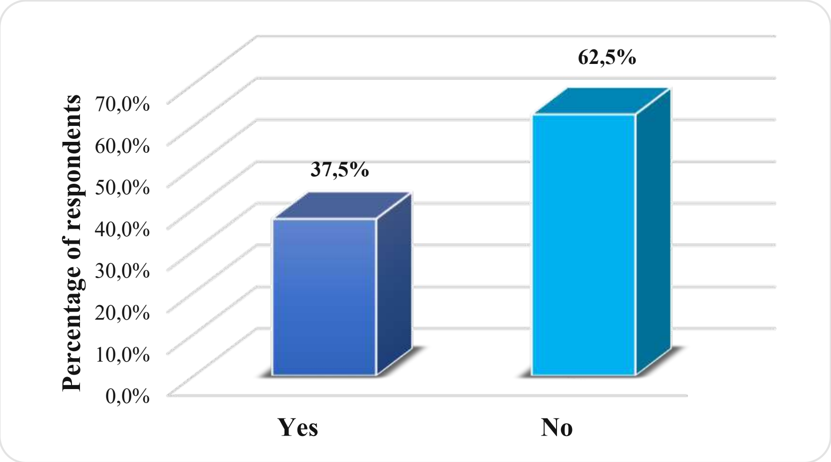

Figure 10: Results on the sufficiency of the applied cost calculation methods.

Question 11:

How are the uncertainties, especially possible changes relating to number of variants and quantity of parts per variant considered in your logistics planning cost?

The calculation approaches take place on a qualitative basis, very rarely uncertainty analysis as a reliable tool for supporting the cost estimation process is considered while logistical planning according to experts. Their future in the automotive industry is determined by the ability to adapt and to change operations with minimum damage in time, cost, resources and performance (Oliveira et al. 2008: 2) In this industry supply chain design strongly depends on the dynamics of markets, which in turn can lead to high levels of uncertainty. Consequently, there is a need to reflect this volatility appropriately in the cost estimation process, which ultimately will enable to manage the dynamic nature of the automotive operational business successfully.

Question 12:

Is the portion of the variety-induced complexity cost exact identifiable in the overhead costs calculated with your applying costing method?

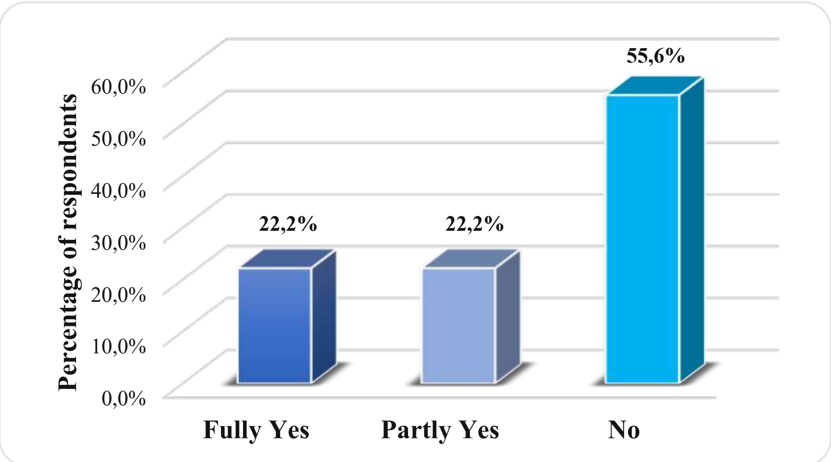

Figure 11: Results on the identifiability of the variety-induced complexity cost in the overhead cost.

Question 13:

What is in your opinion the percentage of the product variety-induced cost in the logistic overhead costs?

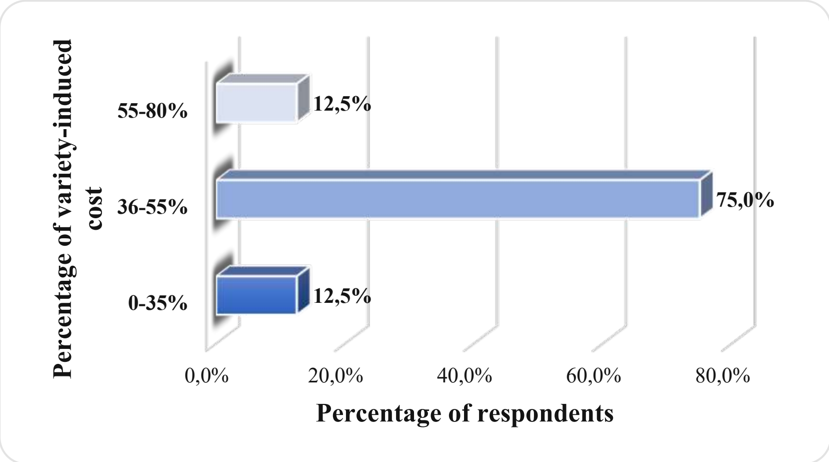

Figure 12: Results on the percentage of the variety-induced complexity cost in the logistic overhead cost.

Question 14:

Please, do name what are in your opinion the three biggest cost drivers in your logistic sector?

Handling of material, number of product variants and their quantities, transport, packaging and floor space are the cost drivers, which had been listed by the logistics representatives multiply times. Consequently, the proper identification of the cost drivers is a key-factor for the cost reduction and may foster a company´s competitiveness.

Question 15:

When and how often do you conduct (or do you think should be conduct) an update on the calculation of the logistical planning cost?

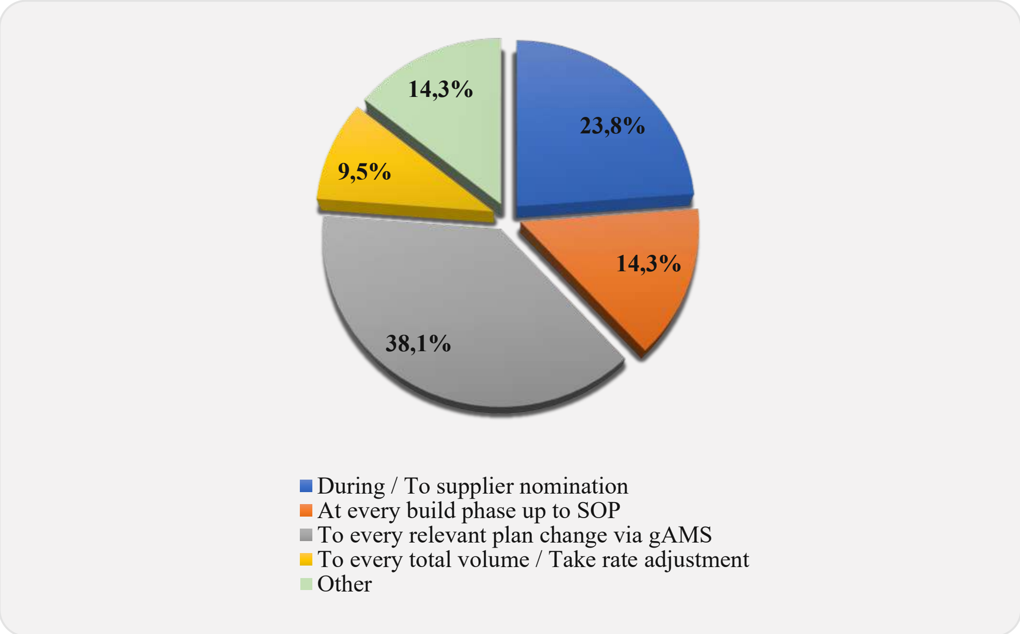

Figure 13: Results on the frequency of updates performed on the cost calculation in the framework of the logistical planning.

Question 16:

How does the product variety affect the logistical performance, cost and logistics system?

In contrast to driver of innovation, which is regarded by the respondents as a positive effect, product variety has been considered as impacting the logistical performance mostly in a negative manner. Logistics systems become more complex, leading to an increased resource consumption, which in turn triggers higher costs.

2.3 Summary of the questionnaire survey

The extensive questionary survey conducted with experts working in the logistic sector, presented in detail in the previous chapter, enabled the author to gain a deeper knowledge on the challenges of modern logistics with regard to product variants, especially on the transparency of costs induced by product variety. The findings of the survey contributed to determination of premises for the transparent cost calculation method – such which are described in the following chapter.

The main findings of the survey are the following:

- Despite the fact that the majority of the respondents are familiar with the complexity and variant management, there currently does not exist an appropriate tool to capture this. Consequently, there is a need for a centralized communication tool which reflects consequences of the increasing product variety in the area of inbound logistics at the OEM transparently and therefore positively influences the decisions on product variety already at an early stage in the product design phase. Regardless of the lacking approach to tackle these costs, 80% of the surveyed experts consider the current situation with regard to product variety in the automotive logistics as manageable. A perception which is taken though the increase in numbers of variants lead to a higher resource consumption driving costs upwards.
- The survey conducted, confirmed the common opinion about the logistics as being a non-product variety driver, but also revealed that the logistics sector bearing a significant portion of the variety induced cost. The R&D, sales and market were ranked as the main product variety drivers for the modern automotive sector.
- The logistics departments which had participated in the survey applied conventional cost calculation methods mostly for the purpose of planning costs calculation. These calculation methods predominantly indicate the actual overhead costs in a precise manner but lack the detailed allocation of the variety costs induced by product variant. Only 22,2% of the survey respondents consider their cost calculation methods as being in conformity with the aforementioned cost allocation condition.

- The predictions of future events being relevant for the logistic sector are very reflected in costing methods. Scenario-based approaches capturing the logistical uncertainties are generally disregarded.

2.4 Derivation of the key premises for the costing method

Based on the initial outlined issue and findings of the conducted survey, which had been presented in the previous chapter, the author concludes that the costing method being sought should cover the following aspects:

- Quantification of variety-induced logistics complexity.
- Transparency on the allocation of overhead costs (in the meaning of cost causation principle) to the level of product variety according to the actual input involved.
- Illustration of product variety impacts on logistical processes, resources and structures and their interdependencies.
- Consideration of uncertainties influencing the logistical processes, resources and structures.
- Straightforward adaptability of the model to different product families and product groups at OEM.
- Feasibility of the approach roll out on a large scale enabling a use on an ongoing basis (department, plant, location).
- Acceptable time and cost demands for the creation and maintenance of the cost model on a large scale – possible low data collection effort.
- Easily updateable based on the latest input.
- Practicability of the costing method.

The following chapter will assess to what extent the above defined aspects are covered by the existing methods posed in relevant scientific literature. The fourth chapter will then asses the best fitting method. The appropriateness and expedience of such method´s criteria, e.g., adaptability, scalability, updatability and practicability, are substantiated by the result of case study conducted at the OEM.

3 Review of scientific literature - State Of The Science

3.1 Costing methods for evaluation of product variety effects

This chapter presents an overview of the relevant approaches for evaluating additional complexity costs. The predominant approaches consist of (i) mathematical valuation methods (each with different levels of detail), (ii) approach and field application, (iii) evaluating the implications of the product variety (Lechner et al. 2012: 42). One of the general subdivisions into **direct** and **indirect** approaches for variety cost evaluation differentiates between the allocation of costs to diversified products according to certain allocation bases and the use of certain indices e.g., part indexes to indicate the potential cost levels of product variety. One of the benefits of indirect approaches is, that it can help managers to better estimate the potential variety cost levels involved; on the downside such methods lack relevant details for the further decision-making process as they do not comprise information relating to dimensional contribution of the product design to variety cost (Zhang & Tseng 2007: 132).

Lechner distinguishes between the following groups of existing evaluation methods for the product variety costs: fundamental methods, Process-oriented methods, Attribute- and Driver-Based approaches and Scenario-Based methods. (Lechner et al. 2012: 42).

Even the application of static (not changing over time) evaluation models is still much more common in science and praxis, dynamic models are becoming increasingly important as such usually address a number of differential equations.

3.1.1 Volume-based Costing

The traditional volume-based costing (VBC) is the most commonly used direct method of product costing which divides between product-related direct costs (material, labor) and indirect costs (manufacturing overhead). The overhead costs considered as non-traceable are allocated to the products based on certain predefined overhead rate which in turn is calculated by the total overhead cost divided by the total labor hours or machine hours. Applying VBC, overhead is charged indiscriminately to all products disregarding possible differences in resources utilized in manufacturing by one product versus another. These types of costing methods are widely used and understood to be simple, but only fairly accurate when direct labor cost or machine cost constitute a large portion of product costs. However, they assume a proportional relation between the product number manufactured and the cost induced by these products. With the increasing proliferation in product variety such as in mass customization, overhead activities omit to link production volume in contrast to other setups. As a result, the distortion of reported product costs by traditional volume-based costing systems is of significance (Zhang & Tseng 2007: 131).

3.1.2 Contribution margin accounting

The Contribution margin accounting (CMA) is a cost calculation method which is widely applied in the automobile industry. The contribution margin differentiates between a company´s revenue and the direct variable costs. The remaining revenue left to pay for fixed costs and other non-operating expenses. Instead of considering the profitability of a company on an overall basis with all products grouped together, the contribution margin allows margin analysis on an individual product line basis. The formula for the calculation of the contribution margin is relatively straightforward and is defined as follows:

$$\textit{Contribution Margin} = \textit{Sales Revenue} - \textit{Variable Costs}$$

The single-level contribution margin accounting – known as the Direct costing – sums up all of product-specific overhead cost and then deducts them form the contribution margin of all products (i.e., total contribution margin). Contrary to the single-level CMA, the differentiated capture and allocation of the overhead cost to each product enables a multi-level CMA.

3.1.3 Overhead calculation

In contrast to other cost unit accounting, the Overhead calculation is based on the principle of a total cost subclassification into direct costs and overhead costs. The direct costs are allocated to the cost objects according to the causation principle, whereas the allocation of the indirect costs to the direct costs follows the principle of averages with overhead rates determinable via different methodical approaches. The elemental principle is as follows:

$$\textit{Overhead rate} = \textit{Overheads} \,/\, \textit{Direct costs}$$

In principle the overhead calculation, alias single-level calculation assumes relatively low overheads and is for this reason less applicable in the automotive industry. The elective (differentiated) overhead calculation meets better the requirements of the automotive mass-production offering diverse products. This method enables the division of overheads into several partial amounts based on the principle of origin, which in turns enables different surcharge bases for the allocation of this costs to each cost object. This is the main advantage of the elective overhead calculation. The calculation approach involves the following steps:

- Allocation of the direct costs (material and production cost) to the cost objects (products and services)
- Separation of the overhead costs into the following typical groups: material overheads, production overheads, administrative overheads and selling overheads.
- Calculation of the manufacturing cost (per cost object) including the material costs, production costs and accordingly allocated material overhead cost and production overhead costs calculated on the respective surcharge rate.
- Determination of the final cost price on the basis of the calculated manufacturing cost by adding the administrative and selling overheads (using respective overhead rates).

3.1.4 Activity-based Costing

The Activity-based Costing (ABC) method being one of the most well-known management accounting innovation was developed in the United-States during the 80's by Cooper and Kaplan. It is a refined cost system which not only enables the broader classification of costs as direct costs, but also the identification of number of indirect-cost pools and cost drivers (Wegmann 2009: 2). The ABC is a common method to trace the costs to the activities actually causing the occurring costs. In ABC-systems, an activity is qualified as an event, task or unit of work with a specified purpose, for example, designing products, setting up machines, operating machines and distributing products. Consequently, the ABC links the costs of relevant resource to the actual activity, the activity costs are in turn linked to components and products (Bauer et al. 2015: 3). Figure 14 shows a comparison between the traditional cost price systems and the ABC.

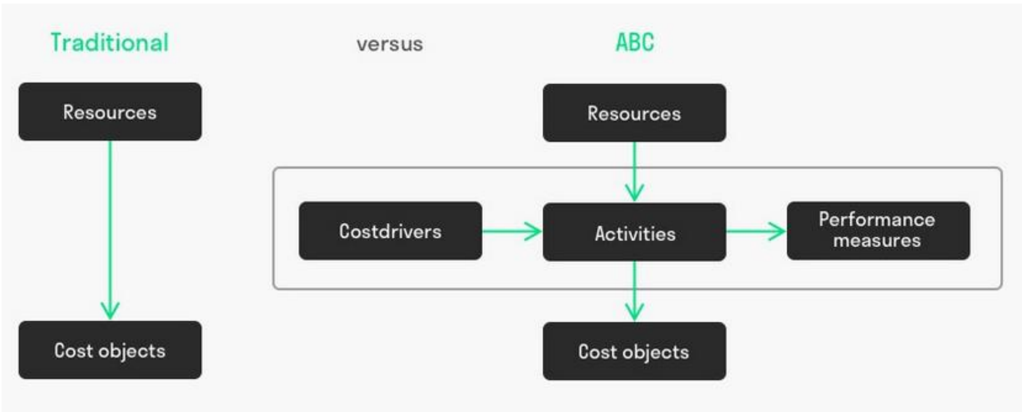

Figure 14: Traditional cost price systems versus ABC (Van Vliet 2009).

The process of an ABC is guided by the gathering of accurate data on materials and direct labor costs, which is then followed by the examination of the demands triggered by a particular product with regard to indirect resources. The ABC calculation may be separated into six steps:

1. Identification of the activities being performed by the organizational resources to manufacture the product or to provide the service.

2. Allocation of the activities into cost pools, which include all individual costs related to each activity and subsequent calculation of the total overhead cost of each cost pool.
3. Attribution of each cost pool activity cost drivers, such as hours or units.
4. Calculation of the cost driver rate by dividing the total overhead costs to each cost pool according to the total cost drivers.
5. Calculation of the cost driver rate by dividing the total overhead costs of each cost pool with the total cost drivers.
6. Multiplication of the cost driver rate with the number of cost drivers (Kenton 2020).

The application of activity-based cost system can lead to radical different evaluations on product costs and on profitability in comparison to more simplistic approaches (Cooper & Kaplan 1988). Basically, this method changes the basis for assigning overhead costs to products. Rather than calculating costs based on the measure of volume, the costs are attributed according to activity generating the costs. Costs considered formerly as indirect (depreciation, power, inspection) are being able to be traced back to specific activities (Pforsich 2009: 8). This approach allows to pool the costs by activity, instead of accumulating all costs in one company-wide pool (Kenton 2020).

This approach works well in limited settings in which it was initially applied, typically a single department, plant, or location. Difficulties arise, however, when you try to roll out this approach on a large scale enabling a use on an ongoing basis. The demands in time and cost when creating and maintaining an ABC model appear to be a major barrier for a widespread adoption by companies (Kaplan & Anderson 2004). Many companies are rather reluctant in using ABC because the cost of such implementing exceed the benefits gained from using it.

3.1.5 Time-Driven Activity-based Costing

The aforementioned barrier of the ABC was overcome by the development of so-called Time-Driven Activity-based Costing (TD-ABC) through Kaplan & Anderson. This method is based on the estimation of two parameters for each group resources:

- costs per time unit of resource capacity deployed
- unit times of resource capacity deployed by product, services and customer.

The unit times of activities describes the time required to fulfil a task and is estimated based on observations or interviews. The cost driver rate is calculated by multiplying the two above-described variables. Multiplying the cost driver rate with the incurred cost rates reveal the final object costs (Bauer et al. 2015: 3). This approach seems more expedient as it relies on informed managerial estimates rather than on employee surveys. It also provides managers with a far more flexible cost model as it enables capturing the complexity of their operations. Managers can review the cost of the unused capacity and contemplate actions to determine whether and how to reduce the costs of supplying unused resources in subsequent periods. They can then monitor those actions over a longer period. Changes in operating conditions are easily captured by the managers by simply updating the TD-ABC. In contrast to other methods reinterviewing of relevant personnel is not necessary for adding new department´s activities; instead, an estimation of the unit time required for each additional activity is preformed (Kaplan & Anderson 2004).

The approach taken by TD-ABC can capture complexities of business far more simply than the traditional ABC system would do. Managers can tackle complexity issues by simply adding new elements to the time equations used by the model, which in turn is less demanding than incorporating new activities. The method provides a powerful tool which enables to identify and to report complex processes in a simple way (Kaplan & Anderson 2004). Figure 15 demonstrates the procedure TD-ABC at a small- size logistics company.

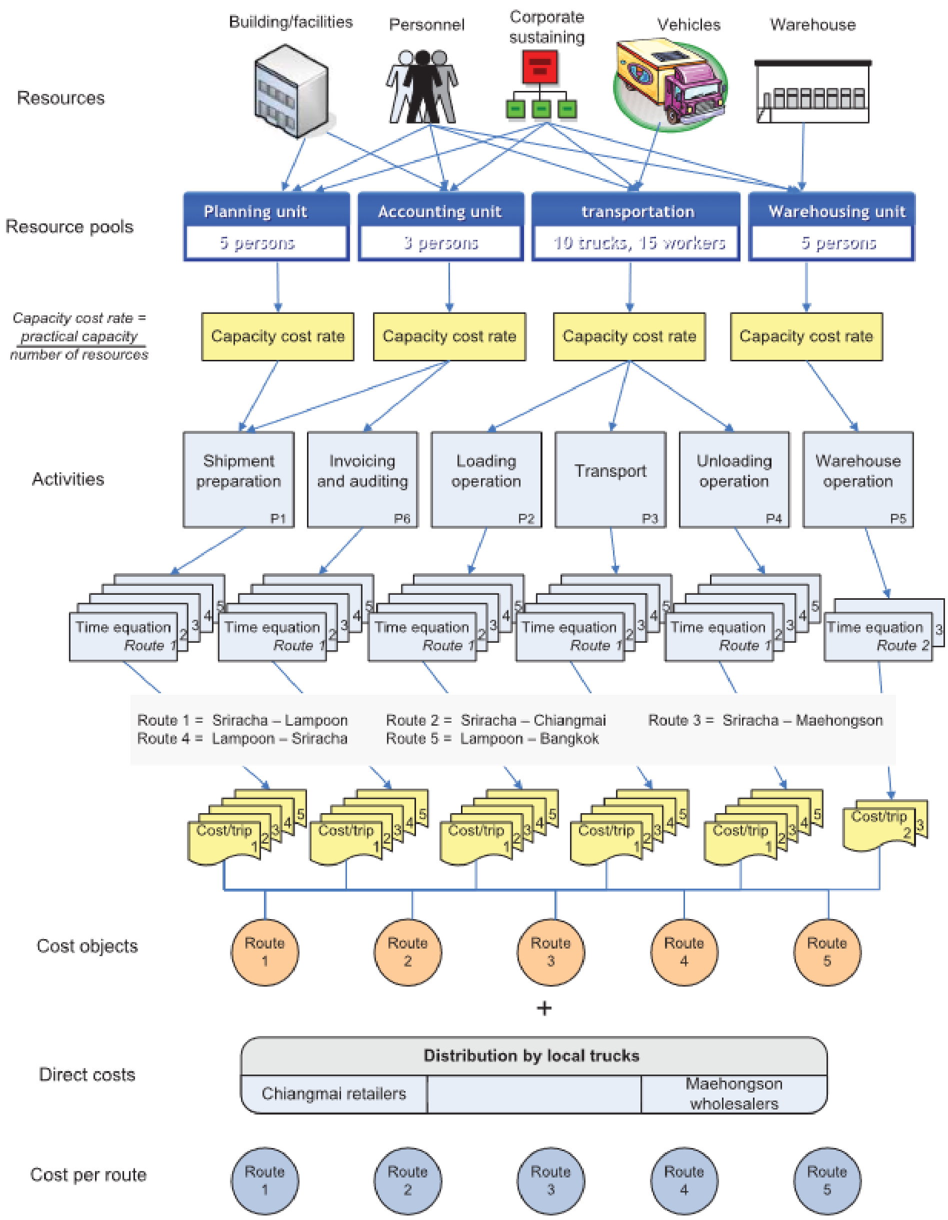

Figure 15: TD-ABC procedure demonstrated by the model in a small-sized road transport and logistics company (Somapa et al. 2012: 311).

3.1.6 Variety-Driven Activity-based Costing

The research conducted by Lechner, Klingebiel, and Wagenitz integrate static and dynamic influences arising in the development of a quantification method and provides a unique evaluation approach in automotive logistics. The main idea of Variety-driven Activity-based Costing (VD-ABC) and a Zero-base Approach is to shape the developed costing method in a way that allows the quantification of logistics costs and performance impacts depending on the level of product variety according to the actual input involved. The logistics costs are quantified and the reciprocal effects between the number of part variants, resource demands and supply processes are depicted based on the latter approach combination (Lechner et al. 2012: II). This method is an advancement of the TD-ABC framework, which enables the calculation of incremental complexity costs associated with variants in different logistical operations (Hvam et al. 2020: 352).

Taking into account specific characteristics of automotive logistics systems, Lechner developed the following variety equations:

- *Process time equations:* assign the required time to each process, adjusted to the degree of the handled product complexity, i.e. variety. Process equations account for demands of the logistics resources personnel and equipment as their consumption is dependent on time (see Figure 16).
- *Inventory equations*: assign individual inventory levels to variants based on the inventory strategy and product variety.
- *Floor space equations:* allocate the required space for each variants' processes (Lechner et al. 2011: 4).

Also, variability in demand is reckoned in inventory equations (Lechner et al. 2011: 8)

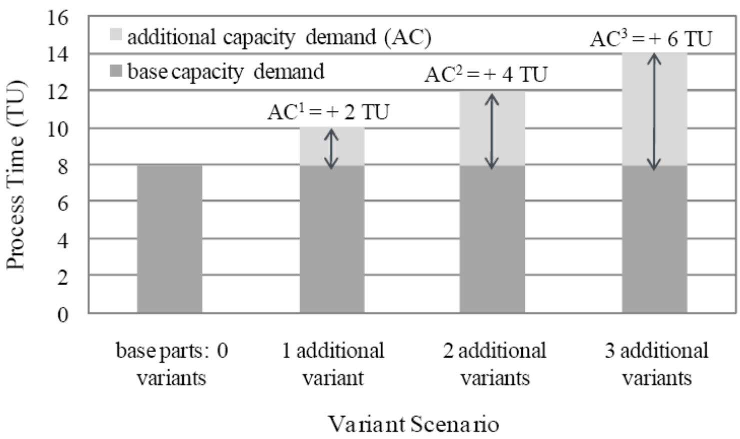

Figure 16: Process times subject to Product variety (Lechner et al. 2011: 5).

The capacity equations comprise the base capacity (needed in a zero-variant scenario) consumption and terms of additive incremental capacity (required in a variety-scenario) consumption. The resource demands of each different level of product variety are consequently captured by the interdependent capacity equations, which calculate the variant-driven complexity costs. The difference between a scenario having v variants and a zero-variant-scenario is considered as variant-driven complexity and therefore quantified in terms of complexity costs for each variant and resource (Lechner et al. 2011: 4). Neither the ABC nor TD-ABC account for such a scenario, whereas VD-ABC method determines such a scenario and adds up the complexity costs by the additional required capacity (Bauer et al. 2015: 4).

3.1.7 Process cost calculation

The Activity-based costing approach developed in the US by Johnson, Kaplan und Cooper was later modified by Horvath und Mayer and evolved to Process cost calculation.

Through this calculation method is often considered as an alternative to the ABC however, the approaches differ from each other essentially. The Process cost calculation can be used solely in the indirect corporate division, whereas the ABC is designed for being applied at whole company level. Furthermore, in contrast to the ABC method the Process cost accounting does not refer to activities, but to the company´s cost centers to define the processes.

It had already been pointed out, that the Process cost calculation focuses on the cost transparency in the indirect company´s performance areas, such as sales, quality, R&D, logistics and purchasing. The main idea of this approach is to allocate as exact as possible the overheads to the business units by following the causation principle (Kersten 2015: 24-25). The Process cost method is carried out in the following steps:

- Identification of the processes
- Cost allocation to the processes
- Cost-driver identification
- Process cost rate calculation
- Aggregation of the sub-processes to the main processes
- Calculation of the overhead cost (Ernst et al. 2017: 99-102)

3.1.8 Resource-oriented process cost calculation

This approach represents an advancement of the aforementioned Process cost calculation and was developed to determine the resource consumption based on the causation principle. Unlike the Process cost calculation, the Resource-oriented process cost calculation considers the processes at the whole company. The determination of the process cost is also performed in different way. The analytically calculated costs for the sub-processes are summed up following the "bottom-up" principle – this approach is taken in order to determine the overheads. Schuh developed a model for the quantification of the variant-induced resource consumption via cost- and consumption-function which is demonstrated by the nomogram showed in Figure 17. The benefit of this method is that the Nomogram enables an exact and transparent interrelation between the resource (cost) driver and costs. This way allows in particular to calculate the variant-related process cost. For this reason, the application of this approach is also interesting for the cost management of individualized products. An enormous drawback for the application is that this method involves considerable effort in relation to collection of data needed to create a Nomogram. Consequently, the Resource-oriented process cost calculation is more suitable for the consistent production processes of multi-variant series products (Lindemann et al. 2006: 185-186).

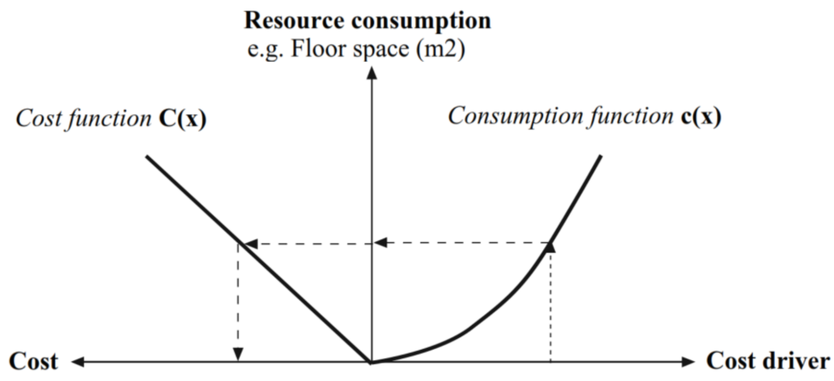

Figure 17: Consumption- and Cost-function of the Nomogram (Lindemann et al. 2006: 185).

3.1.9 Attribute- and Feature-Based approaches

The Attribute-Based Costing (ABCII) has been introduced as an extension of the ABC and is supposed to assess the cost implications at product attribute level. The main objective of this method, which had been developed at the beginning of the 2000s, is to improve organizational effectiveness and efficiency. The attribute-based analysis requires the identification of the physical, service and intangible benefits deriving from a cost object. This new adaptation was aimed at solving the fundamental problems inherent to the ABC and its implementation: full costing and idle capacity. The ABCII provides a detailed cost-benefit analysis of the customer needs. This approach breaks down the customer needs into the specific product attributes and focuses on planning rather than analyzing past costs (Gosselin 2007: 649).

Similar to the aforementioned method, feature costing breaks down product costs into feature costs. This method allows an easier differentiation between the part costs incurred by design costs and incurred by manufacturing within the budget; the costs related to standard parts can be re-used. The main disadvantage of this costing method is the difficulty in estimating the of small and complex parts (Huang 2012: 427).

Although the ABCII and feature costing have pointed out the importance in tracking the link between variety dimensions in terms of product design (e.g. attributes or features), an expedient systematic approach understanding product variety and tracing the relationship between product variety and costs is still missing (Zhang & Tseng 2007: 132).

However, all the above-mentioned approaches have in common, that they present the end products as the calculation objects in place of individual parts or groups of parts. This results in a reduction of calculation objects compared to the theoretical combination options. A major benefit of the ABCII is the ability to use exiting costing systems and thus not requiring an extensive data collection. In practice, the quantification of the complexity cost induced by each attribute is difficult and is generally influenced by subjective judgement. The consideration of the finished vehicle with no complexity costs of the individual parts available is not useful for the inbound logistics (Lechner 2012: 50-53).

3.1.10 Extended Axiomatic Design to model variety-induced complexity

The axioms were developed in the late seventies by Prof. Nam P. Suh. He studied design processes and the quality of design solutions. He found that the best designs had two things in common and thus these became Suh’s design axioms:

- Maintain the independence of the functional elements
- Minimize the information content

If these axioms are applied properly, the design solution evolving is the best suitable one for a given set of functional requirements and candidate design parameters (Matt et al. 2020: 383-384).

Meßerschmidt et al. suggests using the Extended Axiomatic Design (EAD) framework to explore the behavior of complexity cost under various product designs and thus tackling economic consequences of variety-induced complexity. The EAD incorporates engineering design theory and economic principles in order to link interdependencies between customer´s needs, functional requirements, components, processes and resources. The classical axiomatic design theory and the economic modelling are the essential elements of this framework. The EAD demonstrated in Figure 18, divides the system-of-systems (a market system in which the firms´ system is embedded) into domains (subsystems) coupled together by the means of domain mapping matrices containing the relevant dependencies. Due to the domains’ interdependencies, changes in the market (customer domain), in the product design (functional and physical domain) or the processes (process domain), trigger economic consequences. Defining a vector of the resource costs (RC) (i.e., cost per consumed unit) allows the calculating of the process, components, and functional costs, as well as the product costs of each variant (PC). The customer demands in favor or against functionalities in the functional domain are mirrored in rows customer preference matrix M_{CD}. The demand vector d reflects the demand complexity in terms of distribution, uncertainty, and time dependency. The EAD model can be used as a product planning tool, starting by defining the market requirements. Further development of this approach is needed in relation to allocating of the complexity costs – depending on their cause to each single product variants. (Meßerschmidt et al. 2020: 647,653-654).

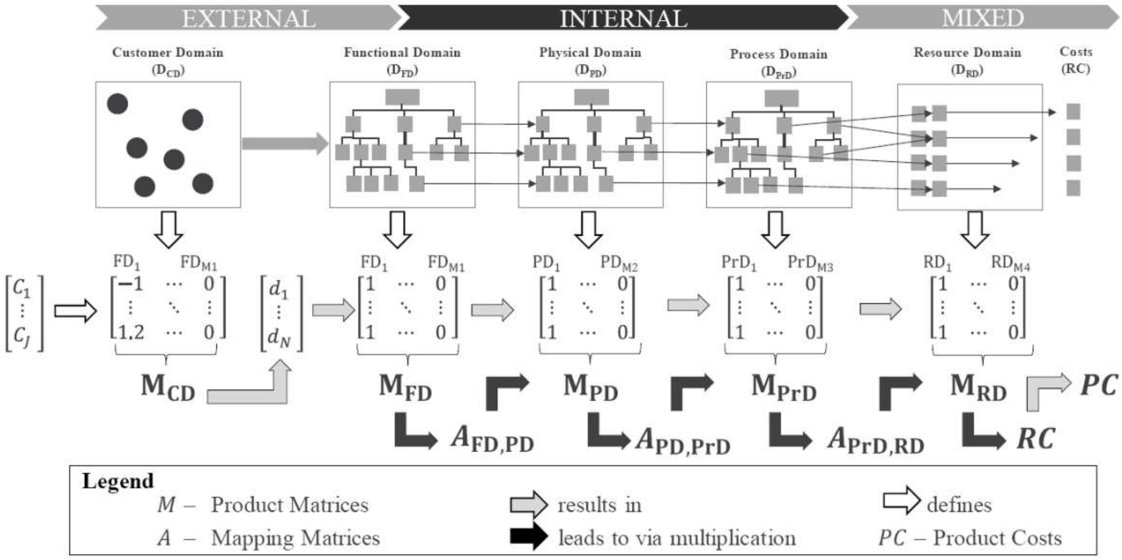

Figure 18: The Extended Axiomatic Design with the market perspective being in the customer domain, the firms' internal perspectives presented by the functional, physical, and process domain and the economic perspective represented by the resource domain (Meßerschmidt et al. 2020: 7).

3.1.11 Life Cycle Complexity Factors

The gross margin's distribution across a product portfolio is analyzed by this factor-based approach. The Life Cycle Complexity Factors (LCCF) illustrates the asymmetry in resource usage between products with the smallest, i.e., 5%, margin and those with higher margins. These factors are then used to allocate the indirect costs to individual product variants based on the LCCFs' consumption and thus helping to understand their negative effects and consequently enabling a better measuring of their profitability. The method comprises the following five steps:

- Scoping of analysis (selection of the focused number of product families)
- ABC analysis of product profitability (displaying of net revenue per variant)

- Life Cycle Complexity Factors (*analyze* the LCCFs and find *quantification* objects that allows for approximations of the indirect costs in order to *allocate* them directly to product variants where applicable)
- Short-term fixing (calculation of different scenarios of "fixing" the product program by means of the reactive measures)
- Complexity reduction program (clean-up of the product program reactively) (Hansen et al. 2012: 1,5-7).

3.1.12 Evaluation by the product complexity dimensions

Ofri et al. developed a further factor-based approach by considering the cost impact of the product complexity dimensions via proposed set of main product complexity dimensions: variety, functionality index, structural index, design index, and production index. These complexity indicators are for each dimension identified based on the examination of different sources of product complexity and of associated negative impacts. Ofri et al. suggested potential mathematical models to capture the interdependencies between indicators and complexity. A mathematical model for measuring product complexity should be aim of the further research (Ofri et al. 2011: 59,61).

3.1.13 Product and Process Modeling Based Approach

Zhang and Tseng analyzed the cost implications of product variety in mass customization and proposed a systematic approach based on product and process modeling. Their approach includes two phases. The relationship of the modeled product and process variety is studied in the first phase. The second phase comprises the investigation of the relationships between product variety and costs and identifies major additional cost contributors, namely variety cost drivers in the product family design. This method is confined to include manufacturing costs (Zhang & Tseng 2007: 130).

3.1.14 Value-oriented evaluation approach of complexity

Wilson and Perumal provide several top-down approaches to assess interrelated product-process-organizational complexity from a managerial point of view by differentiating between value adding (VA) and non-value adding (NVA) complexity costs. VA costs increase a product's usefulness from a customer perspective and consequently enhance the product´s value. Then again, customers cannot directly detect NVA costs. The view taken by Wilson and Perumal differs fundamentally from traditional accounting. NVA costs are assumed to be a proxy for complexity costs and are determined by subtracting the VA costs – which in turn are defined as all the costs for raw material and the additional, directly related costs for converting them into a product – from the total costs (Meßerschmidt et al. 2020: 651).

3.2 Summary of the presented approaches

Figure 19 summarizes the different approaches and illustrates their strengths and weaknesses which have been identified with regard to the pre-defined criteria. Most of the examined approaches are fully or at least partially applicable within automotive industry, but less expedient in the logistics sector. Interestingly, nearly all the presented costing models do not consider time as a parameter. There are only two dynamic methods which address such changes. Also, the factor uncertainty is very rarely covered. The VD-ABC and EAD approaches are the only exemptions from this – these methods capture uncertainties as a relevant factor for their evaluation. However, the majority of the presented evaluation approaches apply a cost allocation based on the causation principle and capture of impacts on logistical processes, resources and structures and addresses their interdependencies **only partially**. The quantification of variety-induced logistics complexity is another advantage of the VD-ABC.

Evaluation criteria	Volume-based Costing	Contribution margin accounting	Overhead calculation	Activity-based Costing	Time-Driven Activity-based Costing	Variety-Driven Activity-based Costing	Process cost calculation	Resource-oriented process cost calculation	Attribute- and Feature-Based approaches	Extended Axiomatic Design to model variety-induced complexity	Life Cycle Complexity Factors	Evaluation by the product complexity dimensions	Product and Process Modeling Based Approach	Value-oriented evaluation approach of complexity
Field of application: Automotive Industry	○	◐	◐	◐	○	●	◐	◐	◐	●	●	◐	◐	◐
Field of application: Logistics	○	◐	◐	●	●	●	●	●	○	○	◐	○	◐	○
Static approach	●	●	●	●	●	○	●	●	●	○	●	◐	●	●
Dynamic approach	○	○	○	○	○	●	○	○	○	●	○	◐	○	○
Quantification of variety-induced logistics complexity	○	○	○	○	○	●	○	○	○	○	◐	○	○	○
Cost allocation based on causation principle	◐	◐	◐	◐	◐	●	◐	◐	○	○	◐	○	○	○
Capture of impacts on logistical processes, resources and structures and their interdependencies	◐	◐	◐	◐	◐	●	◐	◐	○	○	○	○	○	○
Consideration of uncertainties	○	○	○	○	○	●	○	○	○	●	○	○	○	○

Costing approaches for evaluation of product variety effects

Legende:
- ● Reqirement fulfilled
- ◐ Reqirement partially fulfill
- ○ Reqirement not fulfilled

Figure 19: Evaluation matrix of the examined costing approaches.

3.3 Answer the first part of the research question

The relevant costing approaches have been examined in order to answer the first part of the research question of this thesis. The TD-ABC method, developed by Lechner, is a unique evaluation approach integrating static and dynamic influences in the automotive logistics. TD-ABC allows for the quantification of inbound logistics costs and performance impacts according to the level of product variety, which in turn depends on the actual input involved. This method appears to be the most expedient approach and is therefore selected by the author of this research paper to be implemented via the case study conducted at OEM in the following chapter.

4 Application of the Variety-induced Activity-based Costing approach in practice

In order to answer the second part of the research question, Lechner´s evaluation approach of variety-induced logistics complexity in the automobile series production had been selected and will subsequently be applied in a case study for a defined assembly group at OEM.

4.1 Model-based approach for evaluation of variety-induced logistics complexity in the automotive industry developed by Lechner

To determine the variety induced logistical complexity, the structure and behavior of logistics systems, which in turn depend on product variety, are to be evaluate. Lechner overcame this challenge by taking the **structural** (product-related) and **operational** (system-related) components of logistics complexity into consideration in evaluation approach she had developed. The determined complexity key figures and the Zero-Base approach were combined with the VD-ABC in order to capture the implications of **static** logistics complexity for the logistics costs and logistics performance. In addition, a model for evaluation of **dynamic** (changing over time) complexity by considering uncertainties as relevant factors was developed by Lechner (Lechner 2012: 81-82).

4.2 Structure of model design

The author of this thesis divided the model design into the following steps:

- Identification of assembly group for the case study.
- Breakdown of assembly group into the lowest variant reference level.
- Illustration of product variants.
- Identification of main process steps for the delivery processes.
- Development of a model-based calculation for the determination of complexity cost incurred by consumption of logistics resources.

- Validation of calculation model´s behavior.
- Integration of uncertainties in the developed model via simulation software @Risk.
- Evaluation of model´s practicability.

4.3 Identification of assembly group for the case study

The decision to demonstrate the possible applicability of the VD-ABC approach the rear bumper system (see Figure 20), was taken based on the author's almost 10 years of experience in the development sector of this assembly group. The combination of different geometric, functional and design characteristics result in multiple product variants inducing complexity over the whole automotive value chain. In particular, the logistics costs and the performance are impacted by the increasing product variety. The basic structure of the rear bumper system consists of several brackets and modular assembly of bumper skin parts.

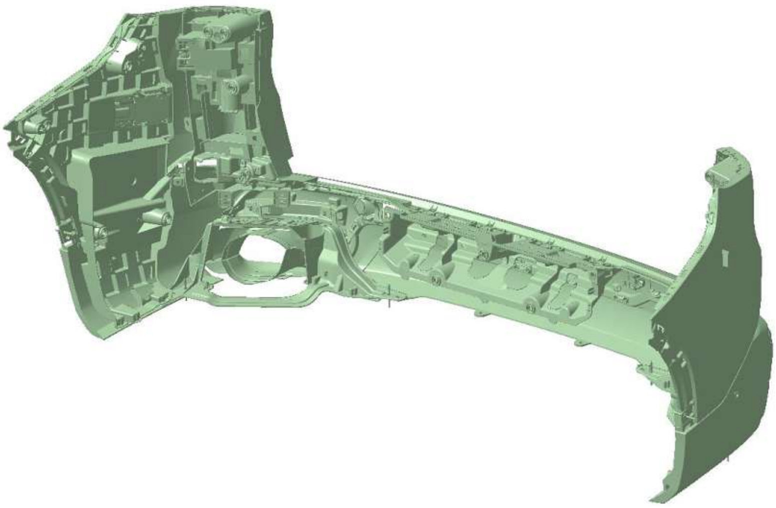

Figure 20: Example of automobile rear bumper system.

4.4 Breakdown of assembly group into the lowest variant reference level

One of the complexity phenomena is product variety, which is induced by the product variants. The product variety and product variants are both in practice and in the literature often discussed terms, but a uniform definition does not exist. Due to the variety of processes in the automotive industry different product levels are necessary to be considered when dealing with product variety. In order to provide the inbound logistics with a solid basis for calculation of complexity costs, a variety hierarchy comprising several reference levels of variants which in turn can be assigned to different processes has to be ascertained. The variety hierarchy is based on diverse objects of the automotive processes for planning and material flow. The internal or endogen variety – often not apparent for the end customer – materialized in company´s value creation process on the end product-, assembly group- and part-level. The internal variety comprises the technical variants on the vehicle level, which are presented by the means of hierarchical variety structure shown in Figure 21. Within the automotive logistics the product level 2 (assembly groups) and 3 (individual parts) is to be manage (Lechner 2012: 9,10).

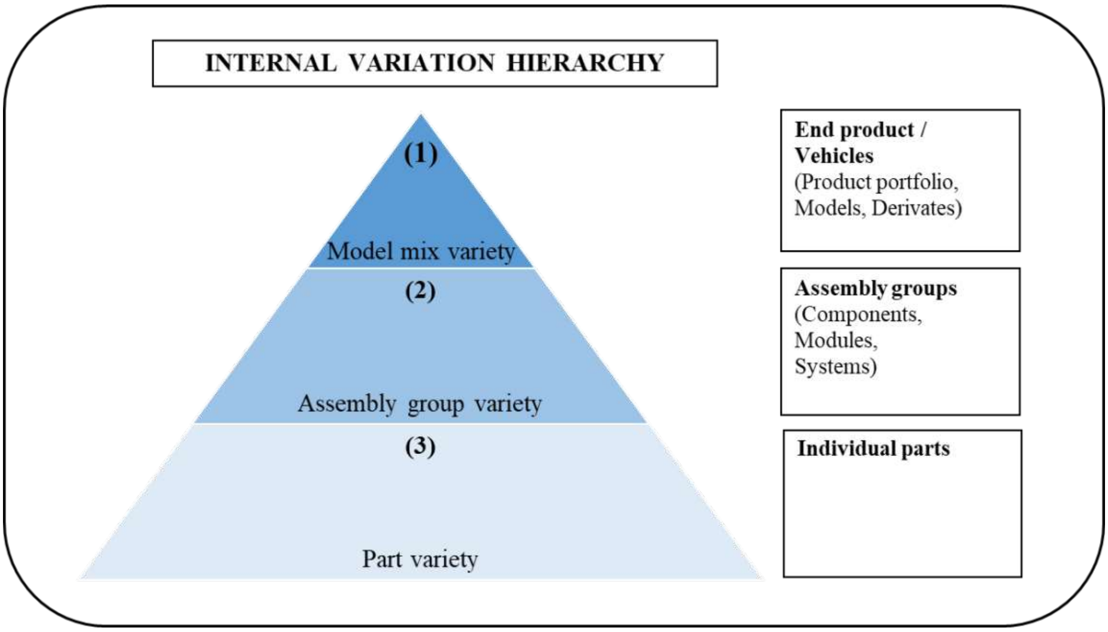

Figure 21: Internal variety hierarchy with variant reference level (Lechner 2012: 9).

The breakdown of the assembly group (see Figure 22) into the lowest variant reference level is depicted as follows: **(1)** Lateral rear bumper bracket left-hand (LH) and right-hand (RH) side, **(2)** Corner rear bumper bracket left- and right-hand side, **(3)** Middle rear bumper bracket and **(4)** Assembly module rear bumper.

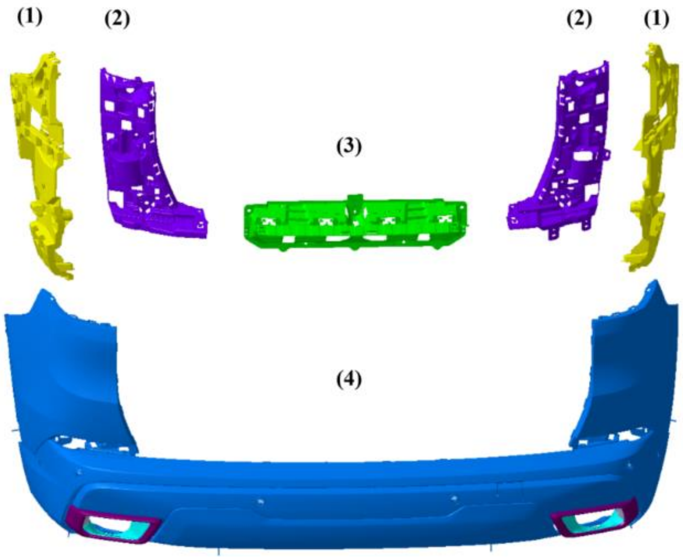

Figure 22: Breakdown structure of rear bumper system.

4.5 Illustration of product variant

A further crucial step for the transparent quantification of complexity costs and their fair allocation to each cost objects (products) in relation to resources consumed, is determination of the product characteristics and their combinations. The identification of product structuring by mapping variant trees is one of various approaches taken in practice. Figure 23 provides information on the structure, the number and the source of product variants via variant trees. In particular, the assembly rear bumper being characterized by 279 options stands out. The conducted analysis of product variety proves how essential such for the capture of the structural logistics complexity and its consequences for the logistical costs and performance is. Subsequently, the base parts are identified and separated from the variant parts. The created reference scenario with zero variants allows comparison to existing scenarios with variety (Lechner et al. 2011: 5).

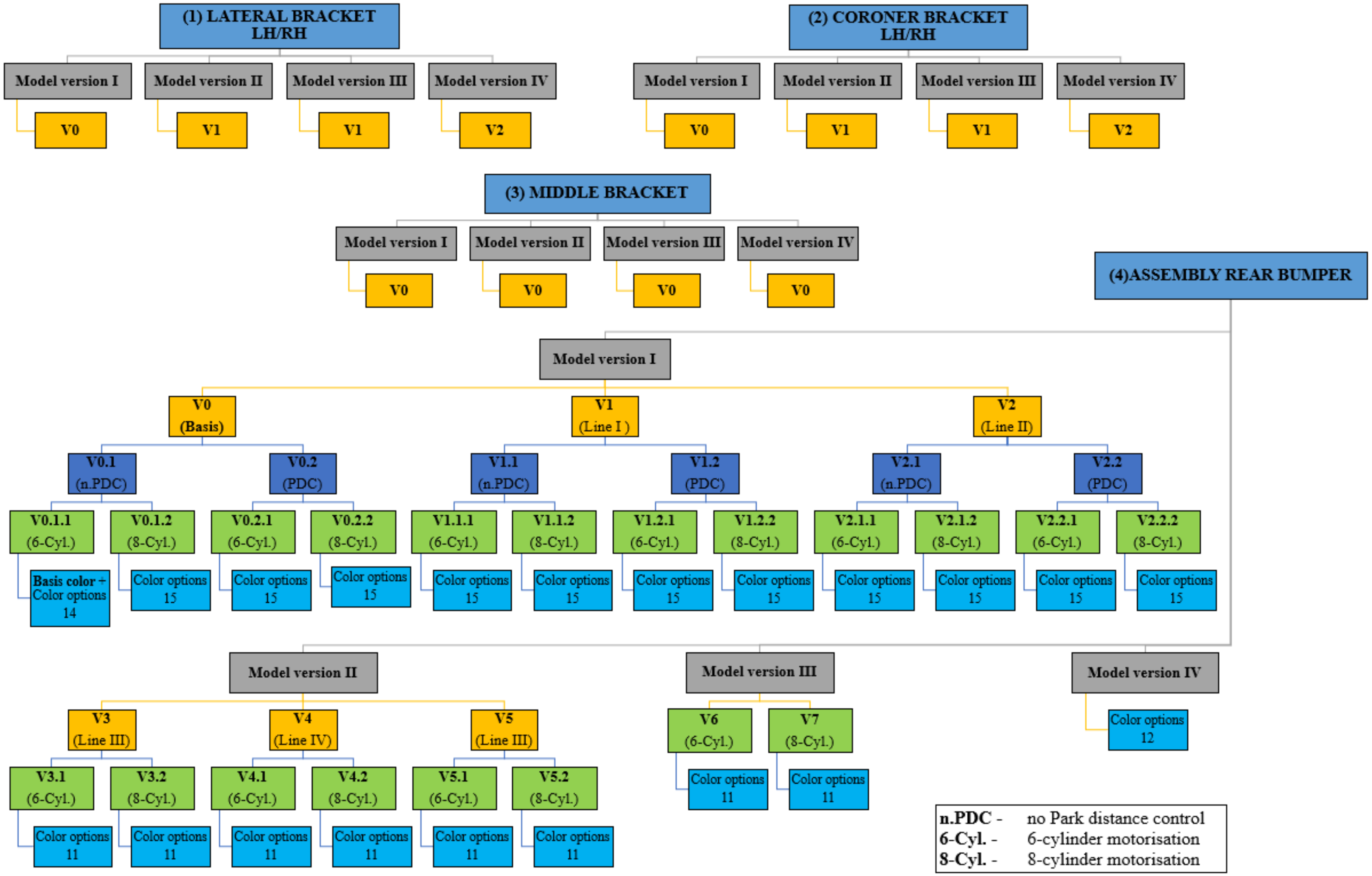

Figure 23: Overview of actual product variants within the assembly group via products tree mapping.

4.6 Identification of main delivery process steps in the inbound logistics

Whereas the structural complexity cost comprises only the product variety increase, the logistics system remains unconsidered. The structural, processual and resource-related changes of logistics system are represented by the operational complexity cost (Lechner 2012: 85). The identification of main logistical processes for the defined assembly group following three main delivery principals form the supplier to OEM is presented in Figure 24. The basis processes may deviate from the actual processes. The consumption of logistical resources by each process usually leads to different resource demands with regard to basis processes. If the basis process corresponds with the actual process, a system-related logistics complexity basically does not exist and therefore the complexity induced cost equals to zero.

4.7 Development of a model-based calculation for the determination of complexity costs incurred by consumption of logistics resources via VD-ABC

The VD-ABC enables the calculation of logistical resources through three developed capacity equations (see chapter 3.1.6. for details), which do not only depend on the parameter **time,** but also on **square meter** and **number of parts**. Different logistical resources consumed during the transformation of logistics objects in processes and capacity equations enabling the capture of resource demand are illustrated in Figure 25. The capacity equations comprise the **base** capacity consumption needed for the zero variant scenario and the **incremental** capacity consumption required in variety scenario. Consequently, the capacity equations of the VD-ABC capture resource demands for different levels of product variety via bottom-up method. Variant-driven complexity costs are determined using the capacity equations. The difference between a scenario having **v** variants and a **zero**-variant-scenario is considered as a variant driven complexity and therefore quantified in terms of complexity costs for each variant and each resource (Lechner et al. 2011: 5).

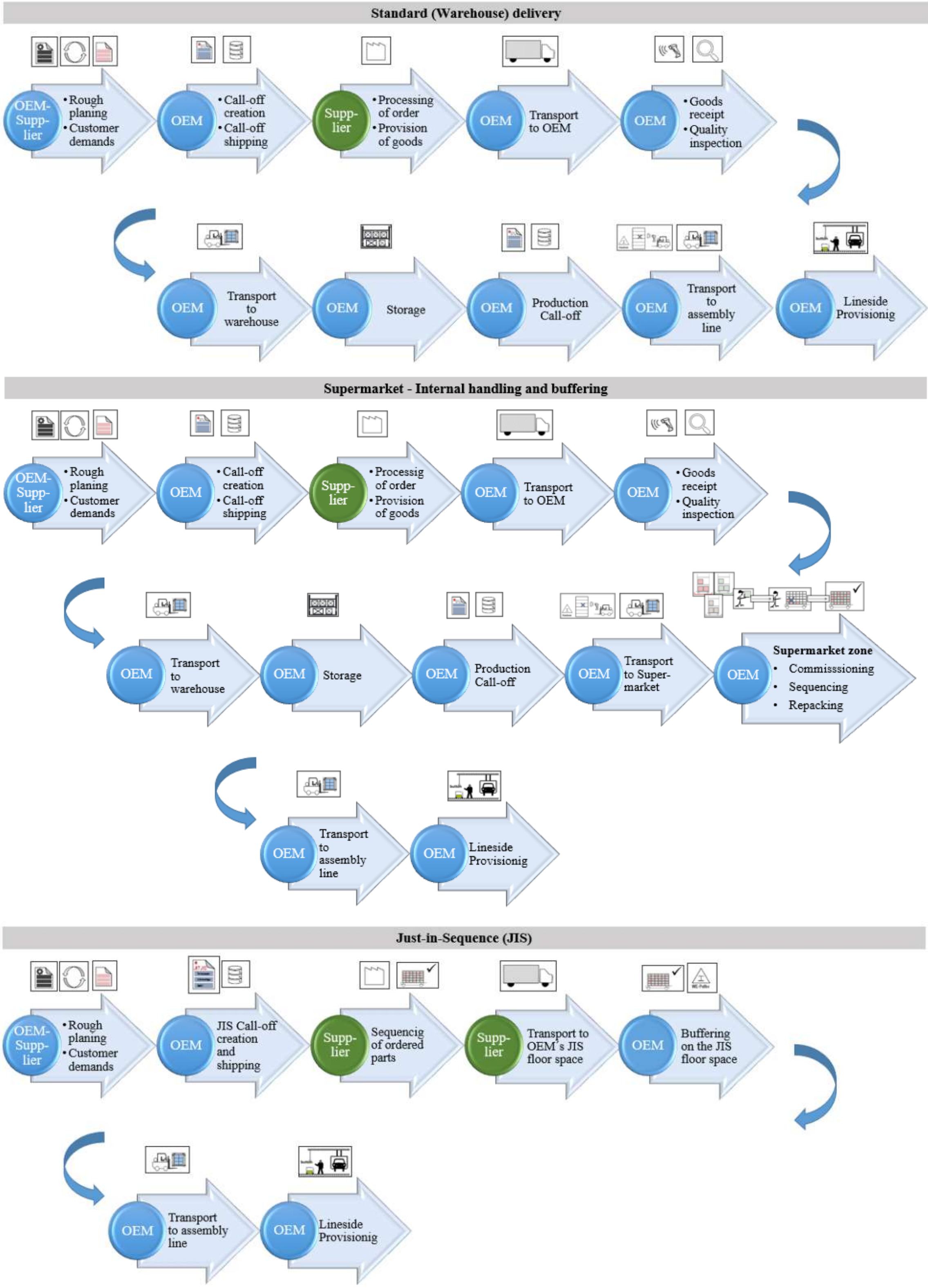

Figure 24: Schematic illustration of main logistical processes for the rear bumper system.

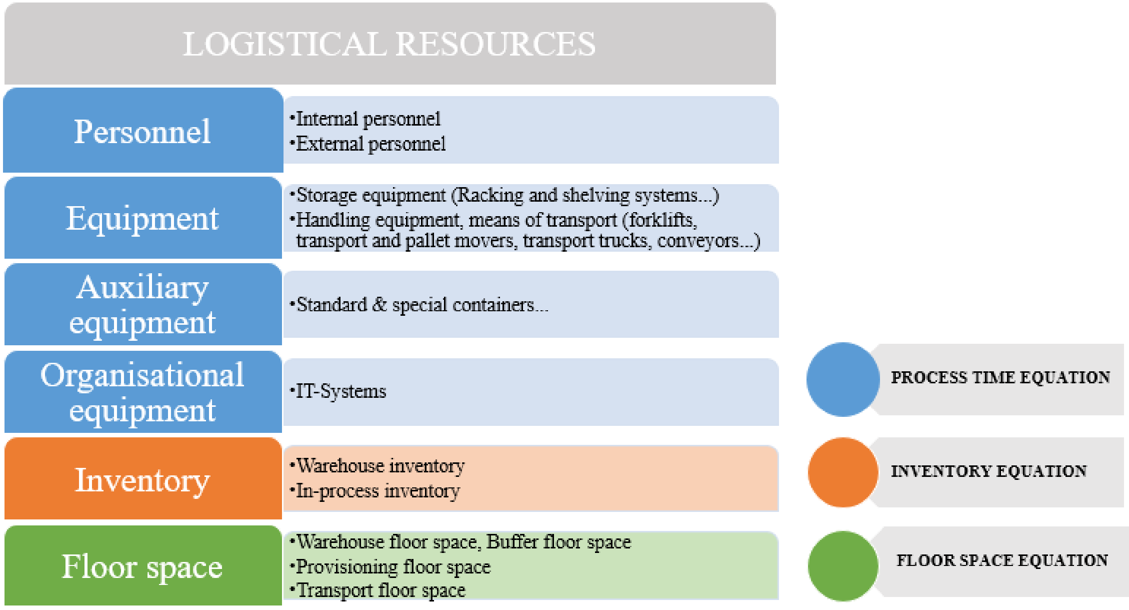

Figure 25: Logistical resources with allocated capacity equations.

4.7.1 Variables of variety-induced consumption and cost equations

The following chapter provides an overview on variety-induced consumption and cost equations including their variables which had been developed by Lechner. The time consumption equations as depicted in Figure 26 enable the allocation of times and consumptions to each variant. In line with this, the process time T, basis time t_0 as well as additional process times are defined. The total sum of each individual process

Variety-induced time consumption equations and time cost equations and their variables		
DIVISION	**EQUATIONS AND VARIABLES**	**DESCRIPTION**
Time equation	$T^0{}_P = t_0 * x^0{}_0$	Process time of the process P by zero variety
	$T^1{}_P = t_0 * x^1{}_0 + t_1 * x^1{}_1 * y^1{}_1 = t_0 * x^0{}_0 + t_1 * \; y^1{}_1 * (x^1{}_1 - x^1{}_0 - x^0{}_0)$	Process time of the process P by 1 variety
	$T^V{}_P = t_0 * x^0{}_0 + \Sigma^n{}_{i=1}\, t^V{}_i * y^V{}_i * (x^V{}_i - \Sigma^{nV}{}_{V=0}\, x_0{}^V)$	Total process time of the process P by variety V
	$T^V{}_p = t_0 * x^0{}_0 + \Sigma^n{}_{i=1}\, t^V{}_i * y^V{}_i * (x^V{}_i - \Sigma^{nV}{}_{V=0}\, x_0{}^V)$	Process time of the process p by variety V
	$T = t_0 + t_1 y_1 + t_2 y_2 + \ldots + t_i y_i \quad (i=1,\ldots..I)$	Process time
	$t^V{}_0$	Process time by zero variety
	t_k	Process time of incremental activity k required due to product variety or individual variants
	$y^V{}_0$	Binary variable which equals 1 if an incremental activity is necessary and zero otherwise
	$x^V{}_v$	Quantity of variants of variant v during the evaluation period by variety V
	$TK^1{}_P = t_1 * y^1{}_1 * (x^1{}_1 - x^1{}_0 - x^0{}_0)$	Incremental time increase due to one additional variant
	$TK^V{}_P = \Sigma^n{}_{i=1}\, t^V{}_i * y^V{}_i * (x^V{}_i - \Sigma^{nV}{}_{V=0}\, x_0{}^V)$	Variety-induced portion of process time of the process P by variety V
	$KK^V{}_R = TK^V{}_R * CR_R \quad (R \in \{M,A, H, O\})$	Complexity costs of resources

Figure 26: Capacity and cost equations of variety-induced time (Lechner 2012: 89-91).

reveals the total process time of each variant. The product variety and the processes correlate in two ways: process work content and number of processes. The increase of product variety leads either to prolongation of the processes or the creation of new processes. Consequently, additional costs for these processes accrue (Lechner 2012: 89-91).

The internal floor space plays a key role in the OEMs´ inbound logistics. Because short transport times are decisive, the nearer is the floor space is located to the assembly line, the more valuable it is. The floor space demand for a process depending on the number of variants defined as $F^V{}_P$ consists of basis floor space demand by zero variety $F^0{}_P$ and the additional floor space demand $FK^V{}_P$ by variety V. The developed variety-induced floor space consumption and cost equations are showed in Figure 27. The total cost and the complexity cost of the floor space are calculated by using a floor space cost rate (Lechner 2012: 94).

Variety-induced floor space consumption equations and floor space cost equations and their variables		
DIVISION	**EQUATIONS AND VARIABLES**	**DESCRIPTION**
Floor space	$F^V{}_P = F^V{}_{VB0,P} * y^V{}_{VBO,P} + F^V{}_{VBN,P} * y^V{}_{VBN,P} + F^V{}_{VBF,P} * y^V{}_{VBF,P} + F^V{}_{E,P} * y^V{}_{E,P}$	Floor space required for the process P by variety V
	$F^0{}_P$	Floor space required for the process P by zero variety
	$FK^V{}_P = F^V{}_P - F^0{}_P$	Additional variety-induced floor space capacity consumption by variety V
	$F^V{}_{VB0} = b_f * b^0{}_0 + b_f * \Sigma^V{}_{i=1} b^V{}_i$ (Large load carrier - GLT) $F^V{}_{VB0\ (Shelves)} = (b^0{}_0 / b_r + \Sigma^V{}_{i=1} (b^V{}_i / b_r)) * 1/r_h$ (Small load carrier KLT)	Floor space required in by variety V (Incremental floor space increase due to additional variants)
	$F^V{}_{VBN}$	Floor space required near to assembly line by variety V
	$F^V{}_{VBF}$	Floor space required far from the assembly line by variety V
	$F^V{}_E$	External floor space required by variety V
	$y^V{}_{F,P}$	Binary variable which equals 1 if an incremental activity is necessary and zero otherwise
Containers	b_F	Container area, computed by multiplication of containers´ length b_l and width b_b
	$b^V{}_V$	Number of containers of variant v by variety V
Shelves	b_r	Number of containers per shelves
	r_h	Number of shelves per row of shelves
Cost	CR_F	Floor space cost rate p.a.
	$K^V{}_{F,v}$	Floor space cost of variant v by variety V
	$KK^V{}_F = FK^V{}_F * CR_F$	Variety-induced floor space complexity cost by variety V

Figure 27: Capacity and cost equations of variety-induced floor space (Lechner 2012: 94,95).

The increase in product variety usually results in higher inventory as such requires additional safety stock. To model the inventory changes depending on number of variants and demand fluctuations, the inventory consumption equations as depicted in Figure 28 were developed. These equations comprise the basis capacity consumption and the additive incremental capacity progression. In the following figure the inventory is divided in dependency of product variety B^V into inventory by zero variety B^0 and into additional variety-induced inventory BK^V by variety V (Lechner 2012: 91-93).

Variety-induced inventory consumption equations and inventory cost equations and their variables		
DIVISION	**EQUATIONS AND VARIABLES**	**DESCRIPTION**
Inventory	$B^V = BL^V + BU^V$	Inventory by variety V
	BU^V	In-process inventory by variety V
	$BL^V = \mu^0_0 + z * \Sigma^n_{i=1}\, \sigma^V_i$	Warehouse inventory level by variety V (Variety-induced inventory equation)
	B^0	Inventory by zero variety
	$BL^0 = \mu^0_0 + z * \sigma^0_0 = \mu^0_0$	Warehouse inventory by zero variety
	$BL^1 = \mu^1_0 + \mu^1_1 + z * (\sigma^1_0 + \sigma^1_1)$	Warehouse inventory by variety 1
	$BL^V = \mu^0_0 + z * \sigma^V_i$	Warehouse inventory by variety V
	$BK^V = BLK^V + BUK^V = BL^V + BU^V - BL^0 - BU^0$	Additional, variety-induced inventory by variety V
	BUK^V	Additional, variety-induced in-process inventory by variety V
	BLK^V	Additional, variety-induced warehouse inventory by variety V
Warehouse stock	μ^V_v	Average demand of the variant v per unit time by V
	σ^V_v	Standard deviation of the variant v per unit time by V
	z	Service level factor
Inventory cost	e^V_v	Purchase price of the variant v by the variety V
	z_K	Imputed interest rate
	$K^0_{BL} = \mu^0_0 * e^0_0 * z_k$	Cost of warehouse inventory by zero variety
	$KK^V_{BL,v}$	Variety-induced complexity cost of the warehouse inventory by variety V
	$KK^V_B = K^V_B - K^0_B = KK^V_{BL} + KK^V_{BU}$	Variety-induced complexity cost of the inventory by variety V (Difference between cost of inventory by V and zero variety)
	KK^V_{BL}	Variety-induced complexity cost of the warehouse inventory by variety V
	KK^V_{BU}	Variety-induced complexity cost of the in-process inventory by variety V
	$K^1_{BL} = K^1_{BL,0} + K^1_{BL,1} = \mu^0_0 * e^1_0 * z_k + [e^1_1 * (\mu^1_1 + z * \sigma^1_1) + e^1_0 * (z * \sigma^1_0 - \mu^1_1) * z_k]$	Inventory cost by variety 1
	$K^V_{BL} = \mu^0_0 * e^1_0 * z_k + z_k * [\Sigma^n_{i=1}\ \Sigma^{nV}_{V=1} e^V_i * (\mu^V_i + z * \sigma^V_i) + \Sigma^n_{i=1}\ \Sigma^{nV}_{V=1} e^V_0 * (z * \sigma^V_0 - \mu^V_i)]$	Inventory cost by variety V

Figure 28: Capacity and cost equations of variety-induced inventory (Lechner 2012: 91-93).

4.7.2 Model design and data input for the cost calculation

The following chapter demonstrates the structure of the developed calculation model and the data input required for the further calculation of logistical complexity costs.

The application of the VD-ABC has been carried out with Microsoft Excel. The created costing model is parameterized by using various functions provided by the aforementioned software. Figure 29 gives an overview on pre-calculated outputs and

MODEL DATA INPUT AND PRE-CALCULATIONS					
DIVISION	**DATA INPUT / CALCULATED VALUE**				**MEASURING UNIT**
Total quantity	1.249.074	1.249.074	1.249.074	1.249.074	vehicles
Peak quantity per day	854	854	854	854	vehicles
Take rate	33,33333	33,33333	33,33333	0,99010	%
Part name	**Lateral bracket LH/RH**	**Corner bracket LH/RH**	**Middle bracket**	**ASS Rear bumper**	-
Number of parts per car	2	2	1	1	-
Number of variants V	**2**	**2**	**2**	**100**	-
STANDARD (WAREHOUSE) DELIVERY PRINCIPLE					
Type of container	Universal container	Universal container	Universal container	Universal container	-
Container length b_l	**1220**	**1220**	**1220**	**2790**	mm
Container width b_b	**1143**	**1143**	**1143**	**2300**	mm
Container height b_h	**991**	**864**	**864**	**1600**	mm
Provisioning method	Floor	Floor	Floor	Floor	-
Provisioning type	2-Container principle	2-Container principle	2-Container principle	2-Container principle	-
Weight per loading unit (LU) gross	**455**	**445**	**521**	**550**	kg
Filling quantity of the container	**40**	**40**	**48**	**15**	pcs./LU
Stacking factor LU	**2**	**3**	**3**	**2**	LU
Number of containers per working day (WD) by zero variety	43	43	18	57	pcs.
Number of containers per WD by variety V	45	45	20	157	pcs.
Total number of containers to procure	428	428	190	1492	pcs.
Working days per week	**6**	**6**	**6**	**6**	day(s)
Weight restriction	heavy cargo	heavy cargo	heavy cargo	no heavy cargo	-
Container volume LU	1,38	1,20	1,20	10,27	m^3
Volume supplied per WD	12,0	11,8	6,1	50,8	Loading meter
Volume supplied per WD by zero variety	59,42	51,8	21,7	585,2	m^3
Volume supplied per WD by variety V	62,2	54,2	24,1	1612,0	m^3
Volume supplied per week	373,1	325,3	144,6	9671,7	m^3
Volume supplied per vehicle	0,06910	0,06024	0,02510	0,68448	m^3
Delivery frequency	**6**	**6**	**6**	**6**	a week
Volume supplied per delivery	12,0	11,8	6,1	50,8	Loading meter
Distance delivery location to OEM	**5**	**5**	**5**	**5**	mls
Replenishment time	**9,5**	**9,5**	**9,5**	**9,5**	day(s)
Product investment per LU	**163,67 €**	**122,32 €**	**122,32 €**	**500,00 €**	-
Standard range	**2,00**	**2,00**	**2,00**	**2,00**	-

Figure 29: Data input and pre-calculations required for the logistical calculation model (Standard delivery).

associated data input for the rear bumper system components as described in the chapter 4.4, and represents the standard delivery logistics principle. For clarification purpose, all inputs are depicted as **underlined** values. The cost values used as an input **do not match** actual prices of the OEM. The Standard delivery, taking place by warehouse and variety homogenous lineside provisioning of the parts, represents the basic logistics system. One of the crucial factors affecting the consumption of logistical resource floor space is the size of the container which in turn depends on the parts´ dimensions and geometry. Moreover, the quantity of the daily produced vehicles is another important parameter influencing the logistics´ performance and cost.

Because the capacity of the floor space, especially along the assembly line, is usually very limited and therefore considered as a valuable logistical resource, even minor increases in product variants may lead to exceeding capacity limits. Consequently, the existing logistics system needs to be shifted to the next level – SuMa. This situation is simulative considered in Figure 30, listing the relevant data input and pre-calculations analogous to the standard delivery. As a result of SuMa or In-house sequencing, additional logistical resources in the form of personnel, floor

SUPERMARKET (INTERNAL HANDLING AND BUFFERING)					
Type of container	Special container SuMa	Special container SuMa	Special container SuMa	Special container SuMa	-
Container length b_l	**1220**	**1220**	**1220**	**2790**	mm
Container width b_b	**1143**	**1143**	**1143**	**2300**	mm
Container height b_h	**991**	**864**	**864**	**1600**	mm
Provisioning method	Floor	Floor	Floor	Floor	-
Provisioning type	1-Container principle	1-Container principle	1-Container principle	1-Container principle	-
Weight per loading unit (LU) gross	-	-	-	-	kg
Filling quantity of the container	40	40	48	15	pcs./LU
Stacking factor LU	**2**	**3**	**3**	**2**	LU
Number of containers per WD by variety V	45	45	20	157	pcs.
Total number of containers to procure	428	428	190	1492	pcs.
Working days per week	**6**	**6**	**6**	**6**	day(s)
Volume supplied per WD	12,0	11,8	6,1	50,8	Loading meter
Volume supplied per WD by variety V	62,2	54,2	24,1	1612,0	m^3
Volume supplied per week	373,1	325,3	144,6	9671,7	m^3
Volume supplied per vehicle	0,06910	0,06024	0,02510	0,68448	m^3
Delivery frequency	**6**	**6**	**6**	**6**	a week
Volume supplied per delivery	12,0	11,8	6,1	50,8	Loading meter
Distance delivery location to OEM	**0,5**	**0,5**	**0,5**	**0,5**	mls
Replenishment time	**9,5**	**9,5**	**9,5**	**9,5**	day(s)
Product investment per LU	**150,00 €**	**105,00 €**	**105,00 €**	**450,00 €**	-
Standard range	-	-	-	-	-

Figure 30: Data input and pre-calculations required for the logistical calculation model (SuMa).

space, auxiliar and organizational equipment are occupied by the processes. The JIS call-offs from the production require commissioning, sequencing and repacking of the components into SuMa containers prior to the provisioning in the lineside area.

When the capacity limits of the logistical system maintaining the SuMa are reached, the application of JIS delivery principle is an inevitable consequence in order to maintain the level of logistics performance. Figure 31 depicts the simulated JIS status including data input. The warehousing process is eliminated, the components are delivered sequenced on a daily basis according to JIS call-offs from the production directly to the OEM´s buffer floor space prior to the provisioning in the lineside area. A portion of the costs for sequencing is shifted from the OEM to the supplier.

JUST-IN-SEQUENCE DELIVERY PRINCIPLE					
Type of container	Special container JIS	Special container JIS	Special container JIS	Special container JIS	
Container length b_l	1220	1220	1220	2890	mm
Container width b_b	1143	1143	1143	2400	mm
Container height b_h	991	864	864	1600	mm
Provisioning method	Floor	Floor	Floor	Floor	-
Provisioning type	1-Container principle	1-Container principle	1-Container principle	1-Container principle	-
Weight per loading unit (LU) gross	420	420	420	426	kg
Filling quantity of the container	25	25	32	8	pcs./LU
Stacking factor LU	2	2	2	1	LU
Number of containers per WD by variety V	69	69	27	107	pcs.
Total number of containers to procure	69	69	27	97	pcs.
Working days per week	6	6	6	6	day(s)
Weight restriction	heavy cargo	heavy cargo	heavy cargo	no heavy cargo	-
Container volume LU	1,38	1,20	1,20	11,10	(m^3)
Volume supplied per WD	17,0	17,0	6,7	26,8	Loading meter
Volume supplied per WD by variety V	95,4	83,1	32,5	1187,4	m^3
Volume supplied per week	572,1	498,8	195,2	7124,7	m^3
Volume supplied per vehicle	0,11055	0,09639	0,03765	1,38720	m^3
Delivery frequency	6	6	6	140	a week
Volume supplied per delivery	17,0	17,0	6,7	1,1	Loading meter
Distance delivery location to OEM	0,5	0,5	0,5	0,5	mls
Replenishment time	1,0	1,0	1,0	0,9	day(s)
Product investment per LU	2.100,00 €	2.100,00 €	2.100,00 €	2.100,00 €	-
Standard range	0,20	0,20	0,20	0,20	-

Figure 31: Data input and pre-calculations required for the logistical calculation model (JIS).

4.7.3 Calculation model of variety-induced complexity cost for the floor space by zero variant and variant V

The floor space as one of the most valuable logistical resources represents for the OEM the opportunity cost. The next step in the application of the VD-ABC involves the calculation of the cost by zero variant. The zero-base analyses conducted in chapter 4.5 and 4.6 enabled the identification of the basis parts and the basis logistics system. The results of calculated zero-base floor space demands and the costs for the different components of the rear bumper system are demonstrated in Figure 32. The required floor space and the costs for the different variant scenarios (for v = 1 to 150) are calculated as well. Figure 32 represents as an example the static model condition for two and one hundred variants (v = 2;100). The input relating to the number of variants is freely selectable within the variant range v = 0 to 150. The model is automatically updated based on the actual data input. The extension of the model to > 150 variants is easily reached. The predefined values for the maximal capacity for each different kind of floor space at OEM are crucial factors for the calculation of SuMa (i^{V}_{SuMa}) and JIS (i^{V}_{JIS}) breakeven, which is also captured by this model. The floor space cost rate is estimated as an average value of all kinds of floor spaces at OEM. Finally, the variety-induced complexity cost by variety V (KK^{V}_{F}) is calculated as a difference between the floor space cost by variety V (K^{V}_{F}) and the floor space cost by zero variety (K^{0}_{F}).

An overall picture of the interrelation between increasing product variety and floor space demand, which in turn affects the costs, is provided in Figures 33-35. The component lateral bracket is used as an example for the graphic illustrations of the influence of product-relevant and system-relevant logistics complexity.

VARIETY-INDUCED FLOOR SPACE CONSUMPTION AND COST EQUATIONS AND THEIR VARIABLES						
DIVISION	**EQUATIONS AND VARIABLES**	**DATA INPUT / CALCULATED VALUE**				**DESCRIPTION**
Part name		Lateral bracket LH/RH	Corner bracket LH/RH	Middle bracket	Rear bumper	
Number of variants **V**		2	2	2	100	
	$F^V_P = F^V_{VB0,P} * y^V_{VBO,P} + F^V_{VB0,SuMa,P} * y^V_{VB0,SuMa,P} + F^V_{VB0,JIS,P} * y^V_{VB0,JIS,P} + F^V_{VBN,SuMa,P} * y^V_{VBN,SuMa,P} + F^V_{VBN,JIS,P} * y^V_{VBN,JIS,P} + F^V_{VBF,P} * y^V_{VBF,P} + F^V_{E,P} * y^V_{E,P}$ (m^2)	246,82	175,70	79,95	310,73	Floor space required for the process P by variety V
	F^0_{VBO} (m^2)	11,16	11,16	5,58	25,67	Floor space required in the **assembly line** by zero variety
	F^0_{VBN} (m^2)	0,000	0,000	0,000	0,000	Floor space required for the **supermarket (SuMa)** by zero variety
	F^0_{VBF} (m^2)	203,87	135,91	56,89	1243,61	Floor space required in the **warehouse** by zero variety
	F^0_E (m^2)	0,000	0,000	0,000	0,000	**External** floor space required by zero variety
	$FK^V_P = F^V_P - F^0_P$ (m^2)	31,79	28,63	17,48	-958,55	Additional variety-induced floor space capacity consumption by variety V
	i^V_{SuMa}	2	2	2	0	Breakeven for the **SuMa** by the variant V
	i^V_{JIS}	11	11	12	5	Breakeven for the **Just in sequence (JIS)** by the variant V
	$F^V_{VB0} = b_f * b^0_0 + b_f * \Sigma^V_{i=1} b^V_i$ (m^2)	33,47	33,47	16,73	2592,47	Floor space required in the **assembly line** by variety V (Incremental floor space increase due to additional variants)
	$F^V_{VB0,SuMa}$ (m^2)	5,58	5,58	2,79	12,83	Floor space required in the **assembly line (SuMa)** by variety V (Incremental floor space increase due to additional variants)
	$F^V_{VB0,JIS}$ (m^2)	5,58	5,58	2,79	13,87	Floor space required in the **assembly line (JIS)** by variety V (Incremental floor space increase due to additional variants)
	$F^V_{VBN,SuMa}$ (m^2)	39,04	39,04	19,52	2605,30	Floor space required for the **SuMa** by variety V
	$F^V_{VBN,JIS}$ (m^2)	19,24	19,24	9,76	296,86	Floor space required for the **JIS** by variety V
Floor space	F^V_{VBF} (m^2)	213,35	142,23	63,22	3425,39	Floor space required in the **warehouse** by variety V
	F^V_E (m^2)	0	0	0	0	**External** floor space required by variety V
	$F^V_{VB0,max.}$ (m^2)	**40**	**40**	**20**	**48**	Capacity of the floor space in the **assembly line**
	$F^V_{VBN,max.}$ (m^2)	**150**	**150**	**80**	**180**	Capacity of the floor space in the **SuMa**
	$F^V_{VBF,max.}$ (m^2)	**500**	**500**	**250**	**1500**	Capacity of the floor space in the **warehouse**
	$F^V_{E,max}$ (m^2)	**0**	**0**	**0**	**0**	Capacity of the **external** floor space
	$y^V_{VB0,P}$	1	1	1	0	Binary variable which equals 1 if an incremental activity is necessary and zero otherwise (**assembly line** floor space)
	$y^V_{VB0,SuMa}$	0	0	0	0	Binary variable which equals 1 if an incremental activity is necessary and zero otherwise (**assembly line SuMa** floor space)
	$y^V_{VB0,JIS}$	0	0	0	1	Binary variable which equals 1 if an incremental activity is necessary and zero otherwise (**assembly line JIS** floor space)
	$y^V_{VBN,SuMa,P}$	0	0	0	0	Binary variable which equals 1 if an incremental activity is necessary and zero otherwise (**SuMa** floor space)
	$y^V_{VBN,JIS,P}$	0	0	0	1	Binary variable which equals 1 if an incremental activity is necessary and zero otherwise (**JIS** floor space)
	$y^V_{VBF,P}$	1	1	1	0	Binary variable which equals 1 if an incremental activity is necessary and zero otherwise (**Warehouse** floor space)
	$y^V_{E,P}$	0	0	0	0	Binary variable which equals 1 if an incremental activity is necessary and zero otherwise (**External** floor space)
Universal container	b_F (m^2)	1,394	1,394	1,394	6,417	Container area, computed by multiplication of containers´ length b_l and width b_b
	b^V_V (pcs.)	4	4	2	2	Number of containers of variant v by variety V
Special container SuMa	b_F (m^2)	1,394	1,394	1,394	6,417	Container area, computed by multiplication of **SuMa** containers´ length b_l and width b_b
	b^V_V (pcs.)	2	2	1	1	Number of **SuMa** containers of variant v by variety V
Special container JIS	b_F (m^2)	1,394	1,394	1,394	6,936	Container area, computed by multiplication of **JIS** containers´ length b_l and width b_b
	b^V_V (pcs.)	2	2	1	1	Number of **JIS** containers of variant v by variety V
	CR_F	**1.350,00 €**	**1.350,00 €**	**1.350,00 €**	**1.350,00 €**	Floor space cost rate p.a.
Cost	K^0_F	290.285 €	198.543 €	84.337 €	1.713.532 €	Floor space cost by zero variety
	$K^V_{F,v}$	333.206 €	237.198 €	107.931 €	419.489 €	Floor space cost of variant v by variety V
	$KK^V_F = FK^V_F * CR_F$	42.921 €	38.654 €	23.594 €	-1.294.042 €	Variety-induced floor space complexity cost by variety V

Figure 32: Calculation model of variety-induced complexity cost for the **floor space** by variant zero and V.

Whereas the increase of **incremental cost** is a consequence of product-relevant complexity, the rise in **step-fix cost** is triggered by changes in the logistics system and thus is a result of the system-relevant complexity. The calculation of variety-induced floor space demand and complexity cost has been applied for other components of the bumper system in a similar manner.

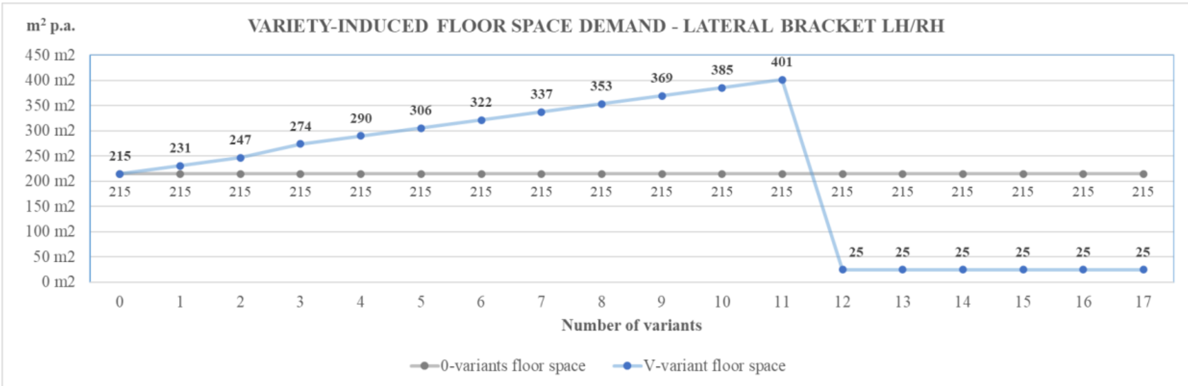

Figure 33: Comparison of zero-base and variety-induced floor space calculated for the lateral bracket LH/RH.

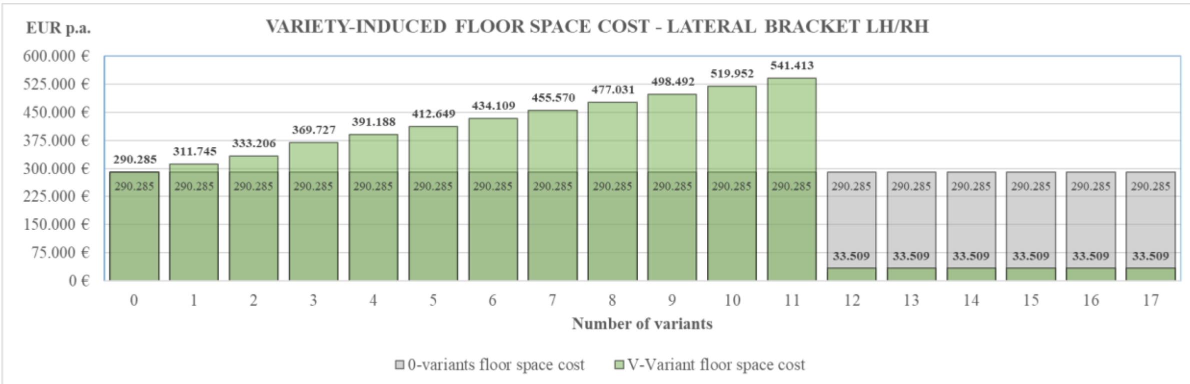

Figure 34: Comparison of zero-base cost and variety-induced cost calculated for the floor space of the lateral bracket LH/RH.

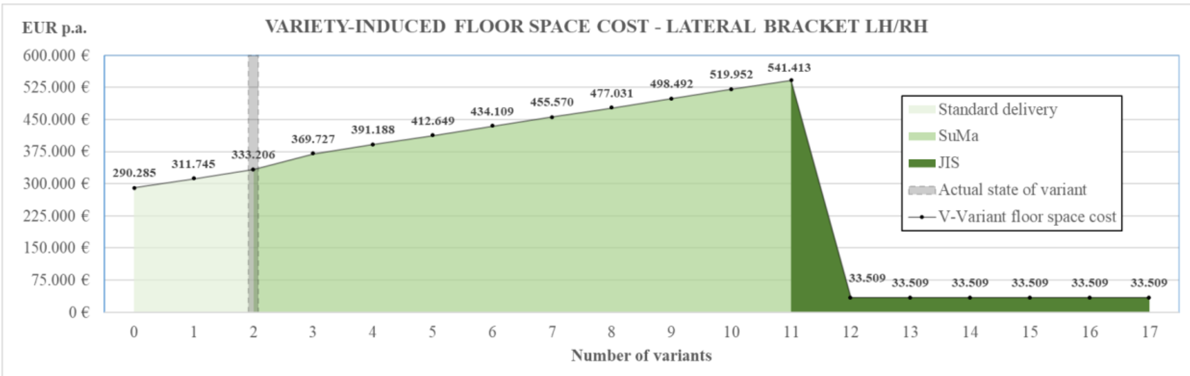

Figure 35: Variety-induced floor space cost calculated for the lateral bracket LH/RH.

4.7.4 Calculation model of variety-induced complexity cost for the inventory by zero variant and variant V

Inventory is another logistical resource being occupied and consumed during the transformation of logistics objects (product variants) in processes. The inventory equations developed by Lechner enable the assignment of individual inventory levels to each variant depending on the inventory strategy and product variety. The results of calculated zero-base inventory level and it's cost for the different components of the rear bumper system are demonstrated in Figure 36. Like the logistical resource floor space, the required inventory level and the cost for the different variant scenarios (for v = 1 to 150) are calculated as well. Figure 36 represents the static model condition for two and five variants (v = 2;5) as an example. An important aspect of the capacity equations (i.e., floor space, inventory and process time equations) is that they are not interdependent and not interact with each other. Inventory at the OEM is distinguished in warehouse stock and in-process inventory. The latter is to be determined according to process time equations, which is not a part of this calculation.

As the increase of the product variety leads to higher warehouse stock at the OEM which in turn increases the stock keeping costs; the following inference can be drawn: The more product variants, the higher volatility in demand is, which in turn triggers a higher risk for stock-outs. In order to prevent shortages in delivery due to running out of stock and in order to maintain the requested service level z, the OEM keeps a higher safety-stock. In the demonstrated calculation the parameter z is chosen from statistic tables to make sure the probability of this variants stock out is above a certain service level.

The graphic illustrations provided in Figures 37-39 indicate the modeled inventory development as a mathematical function of product variety on the example of middle bracket. The breakeven for the JIS delivery principal, represented by the 12th product variant, is triggered by changes necessary in the logistics system. These changes cause a reduction of the step-fix cost as no warehouse stock is required to be held at the OEM. The inventory cost which are saved by the sequencing of the delivery parts directly at the assembly line is shifted to the supplier in the form of an increased product purchasing price. The calculation of the variety-induced warehouse stock demand and the complexity cost have been conducted for the other components of the bumper system in a similar manner.

VARIANT-INDUCED INVENTORY CONSUMPTION AND COST EQUATIONS AND THEIR VARIABLES						
DIVISION	**VARIABLE / EQUATION**	**DATA INPUT / CALCULATED VALUE**				**DESCRIPTION**
Part name		Lateral bracket LH/RH	Corner bracket LH/RH	Middle bracket	Rear bumper	
Number of variants **V**		2	2	2	5	
Inventory	$B^V = BL^V + BU^V$	**3594**	**3594**	**1911**	**1853**	Inventory by variety V
	BU^V	**0**	**0**	**0**	**0**	In-process inventory by variety V
	$BL^V = \mu^0_0 + z * \Sigma^n_{i=1} \sigma^V_i$	**3594**	**3594**	**1911**	**1853**	Warehouse inventory level by variety V **(Standard delivery; SuMa)**
	$BL^V = \mu^0_0 + z * \Sigma^n_{i=1} \sigma^V_i$	**1725**	**1725**	**875**	**856**	Warehouse inventory level by variety V **(JIS)**
	B^0	**3440**	**3440**	**1728**	**1710**	Inventory by zero variety
	$BL^0 = \mu^0_0 + z * \sigma^0_0 = \mu^0_0$	**3440**	**3440**	**1728**	**1710**	Warehouse inventory by zero variety
	$BL^1 = \mu^1_0 + \mu^1_1 + z * (\sigma^1_0 + \sigma^1_1)$	-	-	-	-	Warehouse inventory by variety 1
	$BL^V = \mu^0_0 + z * \sigma^V_i$	-	-	-	-	Warehouse inventory by variety V
	$BK^V = BLK^V + BUK^V = BL^V + BU^V - BL^0 - BU^0$	**154**	**154**	**183**	**143**	Additional, variety-induced inventory by variety V
	BUK^V	**0**	**0**	**0**	**0**	Additional, variety-induced in-process inventory by variety V
	BLK^V	**154**	**154**	**183**	**143**	Additional, variety-induced warehouse inventory by variety V
Warehouse stock	μ^V_v	**1200**	**1200**	**640**	**310**	Average demand of the variant v per unit time by V
	σ^V_v	**54**	**54**	**64**	**25**	Standard deviation of the variant v per unit time by V
	z	**0,95**	**0,95**	**0,95**	**0,95**	Service level factor
Inventory cost	e^V_v	**4,35 €**	**2,53 €**	**4,95 €**	**93,15 €**	Purchase price of the variant v by the variety V
	e^0_0	**4,22 €**	**2,46 €**	**4,81 €**	**81,00 €**	Purchase price of the zero variant
	z_K	**12%**	**12%**	**12%**	**12%**	Imputed interest rate
	$K^0_{BL} = \mu^0_0 * e^0_0 * z_k$	**16.259 €**	**9.478 €**	**9.309 €**	**155.131 €**	Cost of warehouse inventory by zero variety
	$K^V_{BL,v}$	-	-	-	-	Variety-induced complexity cost of the warehouse inventory by variety V
	$KK^V_B = K^V_B - K^0_B = KK^V_{BL} + KK^V_{BU}$	**1.237 €**	**721 €**	**1.295 €**	**38.189 €**	Variety-induced complexity cost of the inventory by variety V (Difference between cost of inventory by V and zero variety)
	KK^V_{BL}	**1.237 €**	**721 €**	**1.295 €**	**38.189 €**	Variety-induced complexity cost of the warehouse inventory by variety V
	KK^V_{BU}	**0**	**0**	**0**	**0**	Variety-induced complexity cost of the in-process inventory by variety V
	$K^1_{BL} = K^1_{BL,0} + K^1_{BL,1} = \mu^0_0 * e^1_0 * z_k + [e^1_1 * (\mu^1_1 + z * \sigma^1_1) + e^1_0 * (z * \sigma^1_0 - \mu^1_1)] * z_k$	-	-	-	-	Inventory cost by variety 1
	$K^V_{BL} = \mu^0_0 * e^1_0 * z_k + z_k * [\Sigma^n_{i=1} \; \Sigma^{nV}_{V=1} e^V_i * (\mu^V_i + z * \sigma^V_i) + \Sigma^n_{i=1} \; \Sigma^{nV}_{V=1} e^V_0 * (z * \sigma^V_0 - \mu^V_i)]$	**17.496 €**	**10.199 €**	**10.604 €**	**193.320 €**	Inventory cost by variety V

Figure 36: Calculation model of variety-induced complexity cost for the **inventory** by variant zero and V.

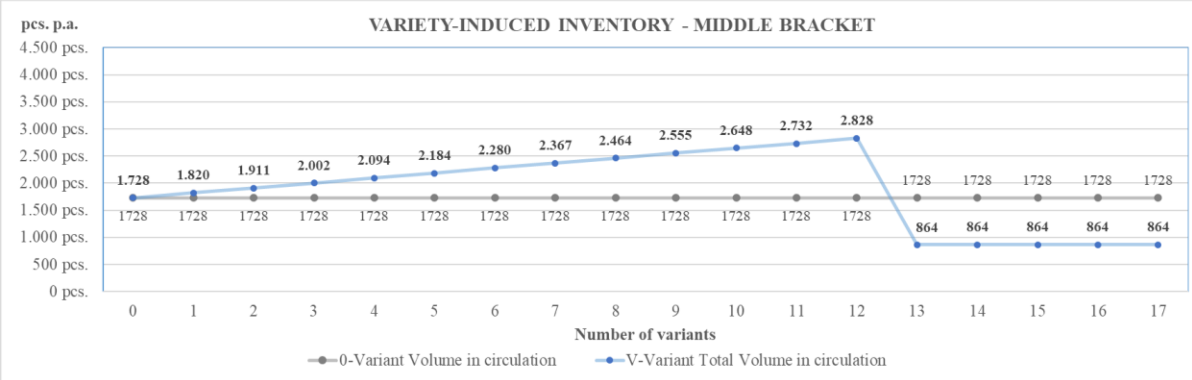

Figure 37: Comparison of zero-base and variety-induced inventory level calculated for the middle bracket.

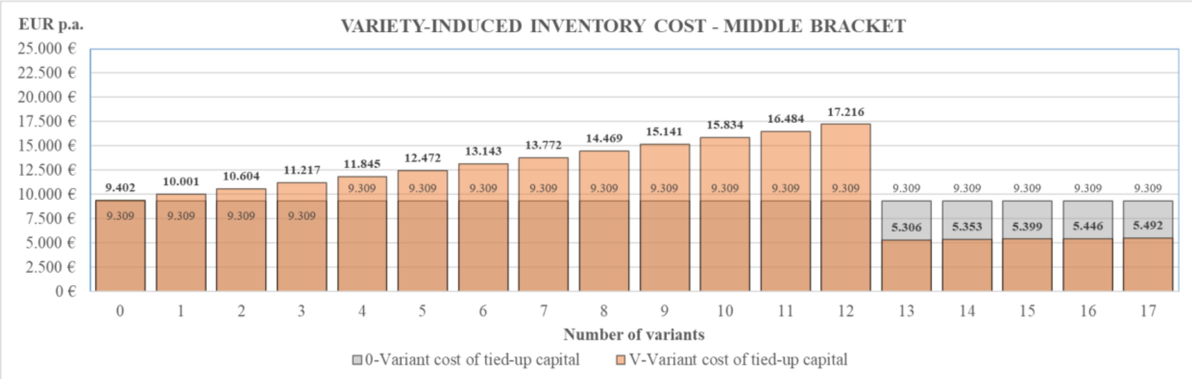

Figure 38: Comparison of zero-base and variety-induced cost calculated for the inventory of the middle bracket.

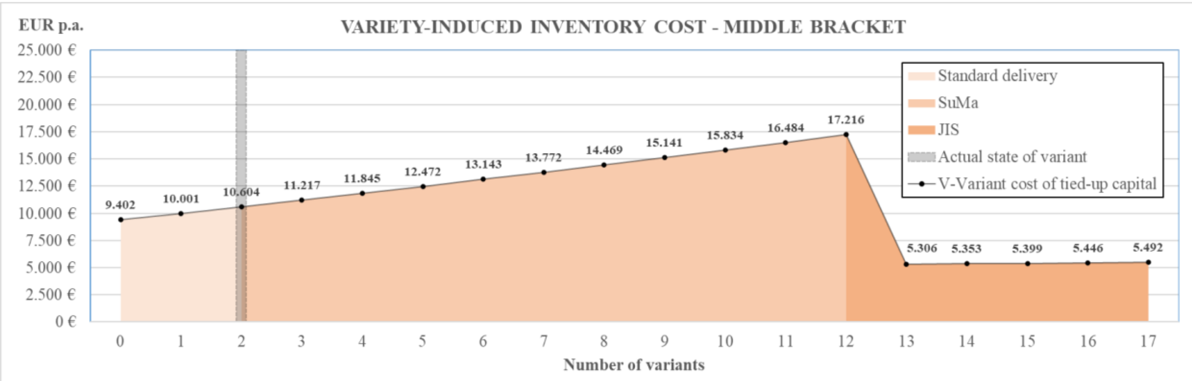

Figure 39: Variety-induced inventory cost calculated for the middle bracket.

4.7.5 Calculation model of variety-induced complexity cost for the transport process by zero variant and variant V

Transport is one of the several logistical processes being consumed by the logistical resources during the transformation of logistics objects. The existing process time equations had been modeled for the transport process and assign to each sub-process an individual time depending on product variety. The transport process equations account for the demand in logistics resources, i.e., personnel and all types of equipment as their consumption is dependent on time. The first step of the cost calculation involves the determination of sub-processes p_T, of which the (main) transport process P_T consist of. The transport process time T_P is then defined as the sum of all sub-process times t_P. The main transport process comprises generally the following sub-processes:

- Loading of full containers on the truck at supplier
- Driving of full containers to the OEM
- Unloading of full containers from the truck at OEM
- Loading of empties on the truck at OEM
- Driving of empties to the supplier
- Unloading of empties from the truck at supplier.

The times of the sub-process and the capacity cost rates of the consumed logistics resources are calculated in the next step. The results of the calculated zero-base transport process time and the cost for each different component of the rear bumper system are demonstrated in Figure 40. It had been ascertained that the increase of product variants can affect the transport process in three different ways: transport process content, transport process type and the number of transport process. Finally, the required transport process times and costs for the different variant scenarios (for v = 1 to 150) are calculated. Figure 40 represents exemplary the static model condition for two and ten variants (v = 2;10). Additional transport costs triggered by the increase of product variants materialize due to loading and unloading transport processes becoming more and more laborious and because of the increase in the number of required transports. The demand in time and the

VARIANT-INDUCED PROCESS TIME CONSUMPTION AND COST EQUATIONS AND THEIR VARIABLES						
DIVISION	**VARIABLE / EQUATION**	**DATA INPUT / CALCULATED VALUE**				**DESCRIPTION**
Part name		Lateral bracket LH/RH	Corner bracket LH/RH	Middle bracket	ASS rear bumper	
Number of variants **V**		2	2	2	10	
Time equation	**t^0_0 (min)**	120,00	120,00	73,49	56,74	Transport time by 0 variety
	$t^0_{0,F}$ (min)	20,00	20,00	20,00	20,00	Driving time by 0 variety
	$t^0_{0,L}$ (min)	20,00	20,00	8,37	4,19	Loading time by 0 variety
	$t^0_{0,E}$ (min)	20,00	20,00	8,37	4,19	Unloading time by 0 variety
	T^0_P (min)	36.120	36.120	22.120	119.560	Process time of the transport by 0 variety
	t^v_v (min)	123,72	123,72	77,21	56,74	Transport time by V variety
	$t^v_{v,F}$ (min)	20,00	20,00	20,00	20,00	Driving time by V variety
	$t^v_{v,L}$ (min)	20,93	20,93	9,30	4,19	Loading time by V variety
	$t^v_{v,E}$ (min)	20,93	20,93	9,30	4,19	Unloading time by V variety
	T^V_P (min)	37.240	37.240	23.240	136.640	Process time of the transport by V variety (**Standard delivery, SuMa**)
	t^v_v (min)	146,05	162,79	105,12	53,02	Transport time by V variety
	$t^v_{v,F,JIS}$ (min)	20,00	20,00	20,00	20,00	Driving time by V variety **(JIS)**
	$t^v_{v,L,JIS}$ (min)	26,51	30,70	16,28	3,26	Loading time by V variety **(JIS)**
	$t^v_{v,E,JIS}$ (min)	26,51	30,70	16,28	3,26	Unloading time by V variety **(JIS)**
	$T^V_{P,JIS}$ (min)	58.857	57.302	31.640	244.808	Process time of the transport by V variety **(JIS)**
	$CR_{R(L-E)}$ (min)	0,47 €	0,47 €	0,47 €	0,47 €	Unit cost of resource consumption for un-/loading
	$CR^0_{R(D)}$ (min)	1,34 €	1,16 €	0,50 €	2,18 €	Unit cost of resource consumption for driving by 0 variety
	$CR^V_{R(D)}$ (min)	1,39 €	1,22 €	0,56 €	2,18 €	Unit cost of resource consumption for driving by V variety
	$CR^V_{R(D),JIS}$ (min)	1,86 €	1,87 €	0,95 €	1,83 €	Unit cost of resource consumption for driving by V variety JIS
	$M^0_{F,AW}$	6	6	6	42	Number of drives per working week (ww) by zero variety
	$M^V_{F,AW}$	6	6	6	48	Number of drives per ww by variety V (**Standard delivery, SuMa**)
	$M^V_{F,AW,JIS}$	12	12	6	96	Number of drives per ww by variety V **(JIS)**
	x^0_0	301	301	301	2.107	Number of drives p.a. by zero variety
	x^V_v	301	301	301	2.408	Number of drives p.a. by variety V (**Standard delivery, SuMa**)
	$x^V_{v,JIS}$	403	352	301	4.617	Number of drives p.a. by variety V **(JIS)**
	$M_{B,VT}$	73	83	83	9	Number of containers per full transport (**Standard delivery, SuMa**)
	$M_{B,VT,JIS}$	57	66	66	7	Number of containers per full transport **(JIS)**
	TV_{VT} (m^3)	100,88	100,00	100,00	92,40	Transport volume per full transport (**Standard delivery, SuMa**)
	$TV_{VT,JIS}$ (m^3)	78,77	79,52	79,52	77,68	Transport volume per full transport **(JIS)**
	TV_{max} (m3/truck)	101,18	101,18	101,18	101,18	Max. transport volume per truck (**Standard delivery, SuMa**)
	$TV_{max,JIS}$ (m3/truck)	80	80	80	80	Max. transport volume per truck **(JIS)**
	TK^v_P (min/p.a.)	560	560	560	0	Incremental time increase by the additional variety V
	$TK^V_P = \Sigma^n_{i=1} t^V_i * y^V_i * (x^V_i - \Sigma^{nV}_{V=0} x_0^V)$ (min/p.a.)	1120	1120	1120	125248	Variety-induced process time for the process by variety V
	$KK^V_R = TK^V_R * CR_R$ $(R \in \{M,A,H,O\})$	1.127 €	1.181 €	1.200 €	166.316 €	Complexity costs of resources

Figure 40: Calculation model of variety-induced complexity cost for the **transport process** by variant zero and V.

costs for other processes being occupied by the logistics resources during the transformation of logistics objects can be calculated in a similar manner. However, such calculation shall not be encompassed by this case study as this would overstretch the scope of this master thesis. The author of this scientific paper considers the demonstrated exemplary application of the process time equations as sufficient in order to evaluate their practicability for the purpose of complexity cost calculation in the automotive inbound logistics.

The modeled development of transport process as a function of product variety is graphically illustrated in Figures 41-43. The example of the assembly rear bumper shows the breakeven for the SuMa delivery principal already at one variant (v=1) and

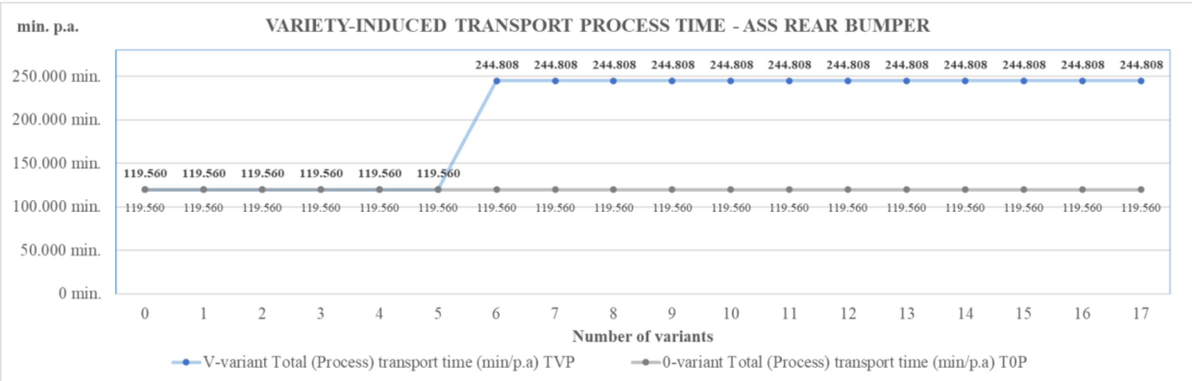

Figure 41: Comparison of zero-base and variety-induced transport process time calculated for the rear bumper.

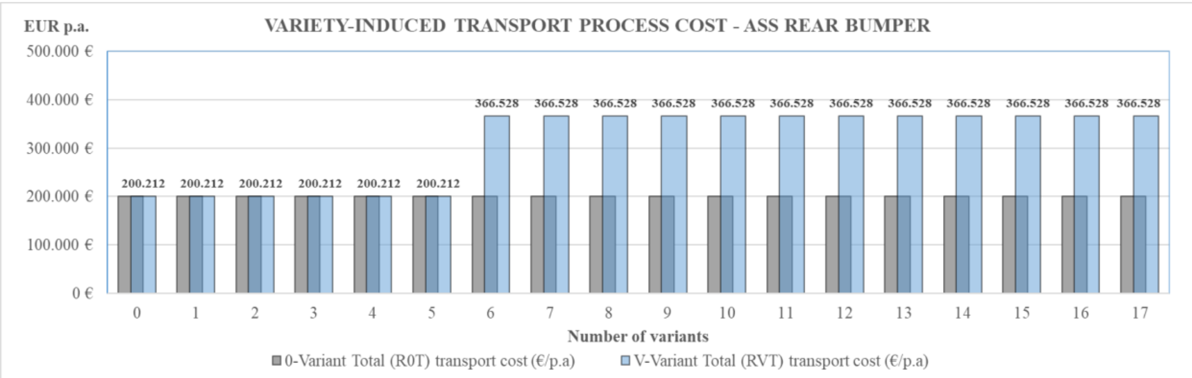

Figure 42: Comparison of zero-base and variety-induced cost calculated for the transport process of the rear bumper.

that – because of bulky geometry – the assembly rear bumper demands a significant size of a floor space in the assembly line.

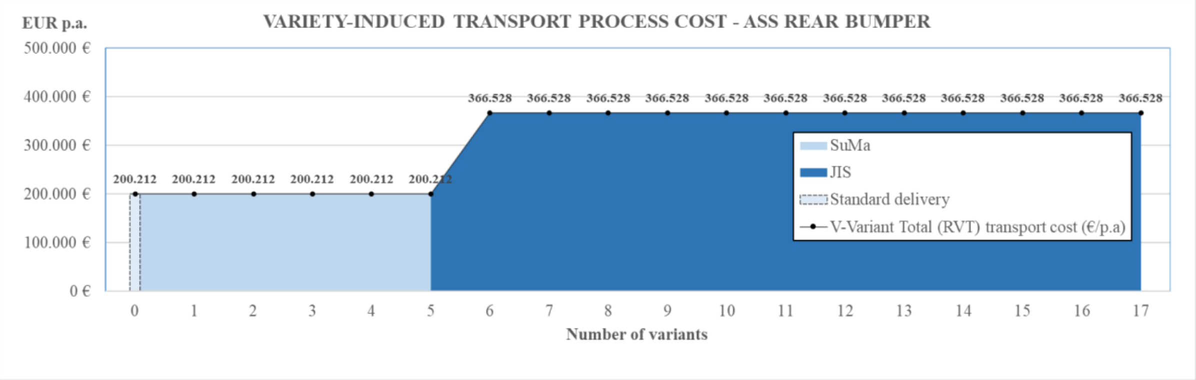

Figure 43: Variety-induced transport process cost calculated for the rear bumper.

Because of the similarity of product variants in terms of logistics handling, the differences in the transport process of each individual variant are marginal. A variant of five (v=5) present the breakeven for the JIS delivery principle, causing the discrete increase of step-fix costs. The calculation of variety-induced transport process time demand and of the complexity costs has been applied for the other components of the bumper system in a similar manner.

4.7.6 Summary of calculated logistical complexity costs and validation of calculation model´s behavior

The design and the basic functions of the developed calculation model for the evaluation of complexity costs in the automotive inbound logistics has been introduced in the Chapter 4.7. This static model, following the VD-ABC approach, enables the determination of variety induced logistical complexity in dependency of product variety. Both product-related and system-related components of logistics complexity are being encompassed by the calculation model also capturing logistics costs and performance.

The capacity equations, i.e., floor space equations, inventory equations and process time equations have been applied for the defined components of the rear bumper system and the resource demands of each different level of product variety have been captured by the designed calculation model. The model provides transparency over variety-induced complexity costs for the selected resources of inbound logistics. The knowledge reached by the application of calculation method is necessary for strategic decisions, e.g., the determination of an optimal order penetration point at an early stage in the product development phase. Normally, a graphical chart demonstrating the development of the **total variety-induced cost** per product family, dependent on product variety, would be generated as an output of the calculation model. But for the reason depicted in chapter 4.7.5 just one logistical process, i.e., transport process, has been considered in the cost calculation and therefore the informative value of the total variety-induced cost would only be of limited extent.

The model´s behavior has been validated several times, during and after its development. Errors that arose during calculation have been solved sufficiently. The outputs of the calculation model have been examined for different levels of product variety and improved accordingly. The designed Excel model provides plausible results based on the actual data input.

4.7.7 Integration of uncertainties in the developed calculation model

The in the previous chapters illustrated static spreadsheet calculation model, built in a meaningful way allows an integration of simulation modeling into the spreadsheet in order to support logistical decisions involving risk. The simulation software @Risk is as an Add-in for Microsoft Excel one of several tools providing a support for decision-making under risk. The main focus of @Risk is on use of Monte Carlo simulation involving a quantitative assessment of the uncertainties and key risk drivers. The presence of uncertainty means that there are probabilities attached to different potential outcomes.

The uncertainties in the product development caused by increasing product variety represent an essential challenge for the automotive inbound logistics. The logistical planning has only limited information needed for evaluating of variety-induced logistics complexity at the time of decision making available. The aim of this chapter is therefore to demonstrate, how the uncertainties resulting from product demand fluctuations and thus the dynamic logistical complexity can be captured by the developed calculation spreadsheet model.

One of the uncertainties relating to product variety is change in product variant quantity affecting the amount of daily built vehicles and therefore the peak quantity of built vehicles per day (see Figure 44) is chosen as an uncertain parameter. The next step in integrating of simulation modeling into the calculation model comprises the choice of probability distribution, using the uncertain parameter as an input. Probability distribution can be described as a set of possible outcomes, each with its associated probability of occurring. The asked experts may believe that the uncertain input parameter (daily peak of built vehicles) ranges from 726 to 983 with 854 being the most likely value. The author assumes that this uncertain variable is distributed according to a **Pert distribution** illustrated graphically in Figure 45. The Pert distribution was developed and is frequently used for modeling expert opinion.

MODEL DATA INPUT AND PRE-CALCULATIONS		
DIVISION	**DATA INPUT / CALCULATED VALUE**	**MEASURING UNIT**
Total quantity	1.249.074	vehicles
Peak quantity per day	854	vehicles
Take rate	33,33333	%
Part name	**Lateral bracket LH/RH**	**-**
Number of parts per car	2	**-**
Number of variants V	**2**	-

Figure 44: Selection of peak quantity of built vehicles per day as an uncertainty parameter.

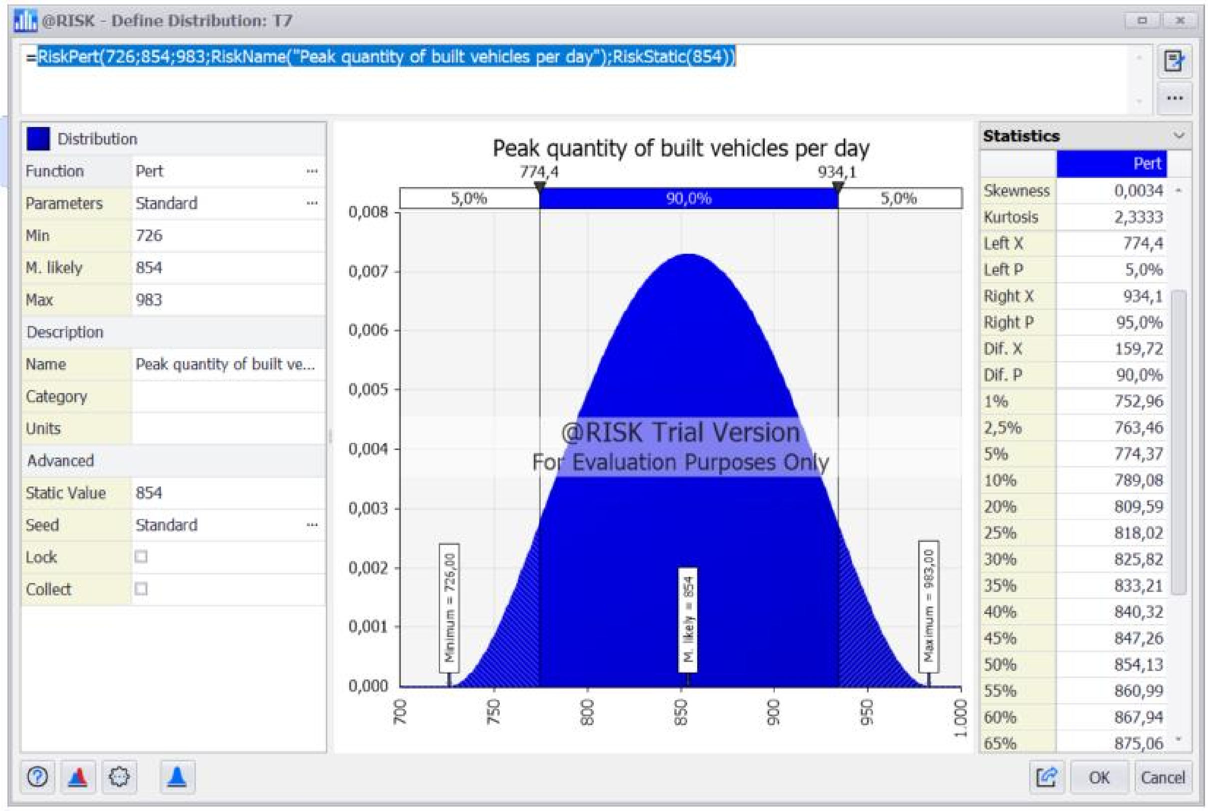

Figure 45: Selected Pert distribution with the range for the input parameter.

Before conducting the Monte Carlo simulation, the outputs of the simulation are to set up (see Figure 46). In this case, the adjustment costs associated to the logistical resources, processes and structures – as a result of fluctuations in demands for quantity of daily built vehicles – are to allocate based on the causation principal to

LATERAL BRACKET LH/RH		
V-Variant floor space cost	**Number of variants**	**V-Variant floor space cost**
=RiskOutput(;$D$2;1)+'4.Complexity cost calculation'!$O$42*F3	0	290.285 €
=RiskOutput(;$D$2;2)+'4.Complexity cost calculation'!$O$42*F4	1	311.745 €
=RiskOutput(;$D$2;3)+'4.Complexity cost calculation'!$O$42*F5	2	333.206 €
=RiskOutput(;$D$2;4)+'4.Complexity cost calculation'!$O$42*F6	3	369.727 €
=RiskOutput(;$D$2;5)+'4.Complexity cost calculation'!$O$42*F7	4	391.188 €
=RiskOutput(;$D$2;6)+'4.Complexity cost calculation'!$O$42*F8	5	412.649 €
=RiskOutput(;$D$2;7)+'4.Complexity cost calculation'!$O$42*F9	6	434.109 €
=RiskOutput(;$D$2;8)+'4.Complexity cost calculation'!$O$42*F10	7	455.570 €
=RiskOutput(;$D$2;9)+'4.Complexity cost calculation'!$O$42*F11	8	477.031 €
=RiskOutput(;$D$2;10)+'4.Complexity cost calculation'!$O$42*F12	9	498.492 €
=RiskOutput(;$D$2;11)+'4.Complexity cost calculation'!$O$42*F13	10	519.952 €
=RiskOutput(;$D$2;12)+'4.Complexity cost calculation'!$O$42*F14	11	541.413 €
=RiskOutput(;$D$2;13)+'4.Complexity cost calculation'!$O$42*F15	12	33.509 €
=RiskOutput(;$D$2;14)+'4.Complexity cost calculation'!$O$42*F16	13	33.509 €
=RiskOutput(;$D$2;15)+'4.Complexity cost calculation'!$O$42*F17	14	33.509 €
=RiskOutput(;$D$2;16)+'4.Complexity cost calculation'!$O$42*F18	15	33.509 €
=RiskOutput(;$D$2;17)+'4.Complexity cost calculation'!$O$42*F19	16	33.509 €
=RiskOutput(;$D$2;18)+'4.Complexity cost calculation'!$O$42*F20	17	33.509 €

Figure 46: The floor space cost of variants v by variety V selected as the simulation outputs.

the individual variants and therefore, the costs of variants v by variety V are selected as the simulation outputs.

Conducting the Monte Carlo simulation then depends on taking random samples from the selected Pert distribution for the uncertain input parameter (daily peak of built vehicles), computing the outcome for cost of variants v by variety V, repeating these ten thousand times, and aggregating the results of all ten thousand of trials. The results of 10,000 simulations for the actual state of variant number v=2 is shown in Figure 47 as an example. The illustrated histogram with sliders shows a 90% interval around mean of complexity cost for number of variants v=2, ranging from 307.604€ to 358.809€. There is almost 15% probability for the complexity cost of 333.206€. The panel on the right side shows a number of statistical summaries of examination which can support the OEM´s logistics planning with risk analysis. The other outputs are to examine in a similar manner. Finally, the adjustment costs as a result of uncertainty in demands for quantity of daily built vehicles are to be allocated to the individual variants.

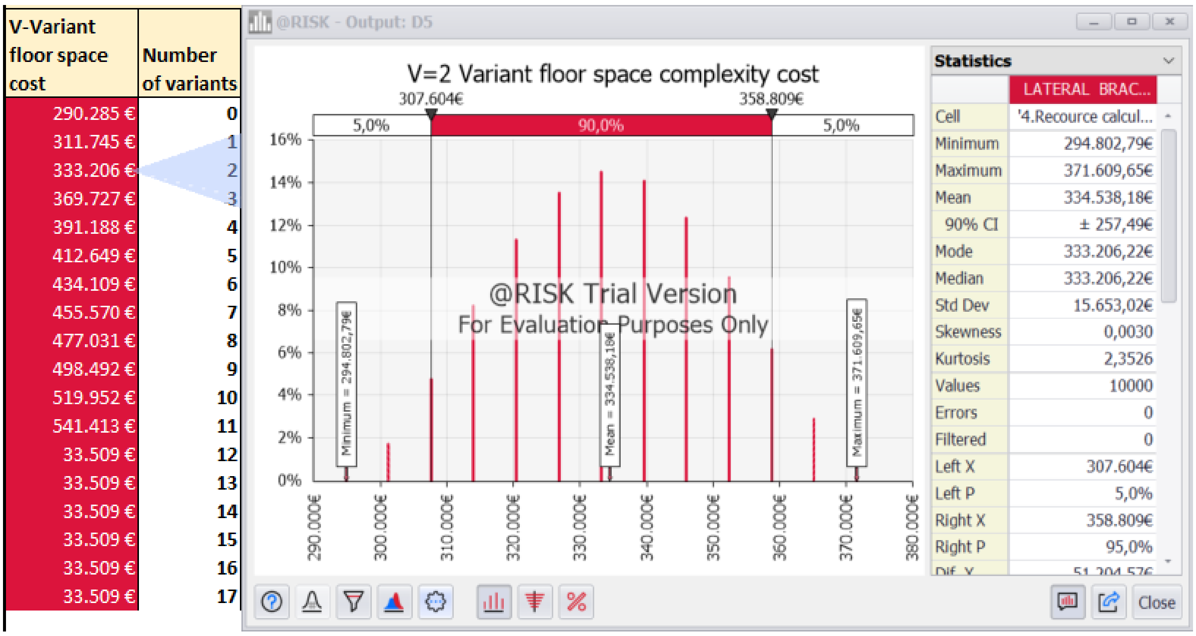

Figure 47: The result of Monte Carlo simulation representing the complexity cost for number of variants v=2.

4.8 Evaluation of model´s practicability and answer the second part of the research question

The knowledge and insights acquired by the application of the selected VD-ABC approach, demonstrated in a case study for the components of rear bumper system at OEM within the chapter 4, facilitated the finding of the answer to second part of the author´ research question:

Research question: *(i) Does an evaluation approach already exist, which allows the quantification of inbound logistics cost and performance impacts dependent on the level of product variety according to the actual input involved and* ***(ii) is this method applicable in the praxis at an OEM?***

Taking the key criteria (for the selected costing approach) defined in the chapter 2.4 into consideration, the author concludes that the costing method applied herein meets the following expectations:

- The developed spreadsheet calculation model provides a detailed graphical **illustration** of product variety impacts on the logistical processes, resources and structures and their interdependencies for the selected scope of automotive components.
- The design of the model allows the decision-making under risk supported by the simulation software @Risk as an Add-in for Excel. The main focus of this software is on use of Monte Carlo simulation providing a quantitative assessment of the **uncertainties** and key risk drivers.
- The straightforward **adaptability** of the model to different product families, and product groups is given not only within the OEM´s inbound logistics sector, but the model can be also easily adjusted to other fields of logistics (e.g., distribution).
- The **scalability** of the model on ongoing basis is realizable regardless of plant and its location, but the feasibility of the approach´s roll out in the different departments at an OEM has not been examined here and should

therefore be assessed in subsequent research conducted by an OEM or should be utilized in a prototypal implementation at OEM.

- Though the **creation** of the model is considered by the author as a **time-consuming** activity and therefore requires higher resource capacities, once the calculation model is finally designed, the demand in time required for maintenance and update of such decreases significantly.
- The model can be **easily updated** based on the actual data input. Different input scenarios have been validated by the author several times, during and after the model development.

The case study at the OEM demonstrated in this thesis shows, that the proposed design of evaluation model is **applicable in praxis**, and thus the second part of the research question has been answered.

5 Conclusion

The global automotive industry is and will be in the future constantly under competitive pressure arising from increasing customer demands, changes in customer behavior and market saturation. Consequently, OEMs continuously extend their product portfolios in order to differentiate themselves from their competitors. Not only the number of vehicle models, but especially the variety of assembly groups and individual parts show a strong upward trend. The increasing uncertainties and fluctuations in demand relating to the product variants are considered as one of the biggest challenges during the planning phase and operation at OEMs. In particular, the processes, resources and structures of automotive logistics are impacted by the increase in product variety.

Because the large portion of total vehicle costs in the automotive industry are determined already during the product development process and the increasing product variety affects predominantly the logistics sector, the knowledge regarding impacts of product variety is decisive to support strategic decisions at an early stage. Therefore, the aim of this research was to provide transparency over product variety-induced complexity, individual product variants, product variety and their impacts on logistics costs and the performance of inbound logistics at an OEM by selection and application of an appropriate evaluation approach.

The existing scientific literature provides several approaches for evaluation of complexity costs, which are fully or at least partially applicable to the automotive industry, but less expedient in the logistics sector. The selected VD-ABC approach applies a cost allocation based on the causation principle and captures impacts on logistical processes, resources and structures as well as addresses their interdependencies. The quantification of variety-induced logistics complexity costs is a noteworthy advantage of the VD-ABC.

The author chose to demonstrate the practicability of the VD-ABC in a case study for a defined assembly group at a particular OEM. By the adapting the calculation model to the fit the peculiarities of product variety-induced complexity, the author was able to capture significant criteria, such adaptability, scalability, updatability and maintenance and for which the presented calculation model provided reliable results based on actual data input. Though the author admits that the initial creation of the calculation model is a laborious process, once the method has been finally designed and implemented, updating such is easily feasible and the demand in time for the maintenance of such decreases significantly.

Based on the knowledge and insights the author of this thesis had gained during his analysis, selection and application of the most suitable cost calculation method, the author concluded that the VD-ABC has the greatest potential to surmount the missing link between the product variety-induced complexity and logistics costs and thus enabling the quantification of the impact of product variety in the automotive inbound logistics at OEM-level. However, the author recommends the application of the VD-ABC approach only for critical components with regard to product variety at OEM in order to avoid a higher demand in resources triggered by the necessity for the re-creation of the calculation model.

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