EFFICIENT PRODUCT REPRESENTATIONS FOR AUTOMOTIVE LOGISTICS

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ABSTRACT

E-mobility and the increasing introduction of intelligent assistance systems that are based on embedded systems have led to a radical change in complexity of parts and variants in the automotive industry. To guarantee the availability of components and minimize obsolescence risks, dependencies between electronical and non-electronical components and the compatibility between hardware and software components have to be transparently documented in product representations. This is especially relevant for logistics, which acts as a cross-divisional function between technology development, procurement, production, sales and after-sales. This contribution presents a systematical analysis of the requirements on product representations in series production followed by a review of product representation approaches in scientific literature, focused on the automotive industry. Based on these findings, proven and innovative concepts for product representations are classified and rated against the requirements. Especially the advantages of semantic networks and graph structures seem to be promising.

Keywords: automotive product representation, automotive product structure, e-mobility, embedded systems

1. INTRODUCTION

Since mass production was introduced by Henry Ford in the early 19th century, the automotive industry has changed considerably (Holweg and Pil 2004). Nowadays, original equipment manufacturers (OEMs) offer their customers a huge variety of models - which can be individualised by several hundred options - to compete in international markets (Dörmer 2013). These options include design elements (i.e. colors), functional components (i.e. gear system) and recently more and more assistance systems (i.e. navigation and driver assistance systems). Besides, the OEMs constantly update their product range with increasing frequency (Schuberthan and Potrafke 2007).

Especially technological trends such as e-mobility and the increasing integration of intelligent assistance systems (based on embedded systems) have led to a radical increase in complexity of parts and variants (Kampker et al. 2016, Krumm et al. 2014). This digitization of the car has established new interrelations and dependencies among the car components. Here, the continuous compatibility of the various electronical and non-electronical components needs to be ensured. Prominent examples like the incident of the recall of the Takata airbags in 2015 (Sharon O'Malley 2016) show how easily the OEM's reputation is compromised by failures on supplier side. This challenge applies in particular to logistics: logistics has to guarantee material availability and quality under high demand uncertainty and acts as a cross-divisional function between technology developments, procurement, production, sales and after-sales.

In order to guarantee the availability of components and minimize obsolescence risks in parallel, it is essential for all logistics processes that the product representation depicts all dependencies between parts, components and car features and provides transparent holistic information for all involved departments. Especially, dependencies of components and the compatibility between hardware and software components have to be considered. Nevertheless, the current form of the product representation applied in logistics does not adequately document the new technical interrelations of components. Therefore, new forms of product representations or the enrichment of given product representations are required.

This contribution presents a systematical analysis of the requirements on product representations in series production followed by a respective rating of product representation approaches in scientific literature with focus on the automotive industry and the related field of mechanical engineering. Based on these findings, innovative concepts applicable for automotive logistics shall be identified.

The paper is structured as follows: all relevant terms and concepts will be defined in section 2, followed by a detailed discussion of challenges in the automotive industry. This leads to a deduction of requirements on product representations from different angles, but with focus on automotive logistics. Here, relevant characteristics are mapped and integrated in a holistic requirements catalogue. Subsequently, a systematic review of scientific literature on product representations in series production is given in section 3. The methodology pursued in this step is explained beforehand. In section 4, the state of research is classified and promising approaches and concepts are rated against the defined requirements. The contribution concludes with a summary of key insights and an outlook on further research.

2. CHALLENGES FOR THE AUTOMOTIVE INDUSTRY AND REQUIREMENTS ON PRODUCT REPRESENTATION

Before challenges for an efficient product representation for logistics in the field of automotive industry may be identified, a general understanding of the product car, its complexity and the logistics processes is necessary.

Nowadays, automotive customers have to deal with the rapid change of variants and options (Ebel and Hofer 2014). After the customer has chosen a car series and model, the model is typically further individualised by so-called options and option packages. These – sometimes – several hundred options include for example exterior, interior and security equipment, but also assistance systems like navigation systems or driving assistance systems (for example parking aid) (eVchain 2014). The high potential for individual configuration is an essential marketing factor for premium OEMs, but contributes significantly to the complexity of the product car.

A typical car consists of about 3000 to 6000 material items. If different variants and their parts are considered, it results in about 15000 to 20000 items per car (Klug 2010). This is a challenge in itself. But even worse, customers tend to expect that their vehicle orders can be recustomised, i.e. changed even shortly before actual production and that the produced car is rapidly delivered on the formerly planned date (Alford et al. 2000, Krog and Statkevich 2008).

Nowadays, among the items of a car are many simple parts, but automotive suppliers develop more and more complex modules (Trojan 2007). Moreover the proportion of the electric and electronic components increases within the car (eVchain 2014). This shift in the competence of the car manufacturer has been identified and analysed since many years. OEMs focus more and more just on the assembly of supplied parts and modules, the product marketing, the coordination of suppliers, and the distribution of the end product (Meissner 2009). In this context - as mentioned before - logistics plays a significant role as cross-divisional function between technology development, procurement, production, sales and after-sales.

The effective logistics management of the automotive supply chain requires that resource and component requirements resulting from anticipated or realised market demands are synchronised with resource capacities and restrictions of the production and supply chain. Therefore, the logistics planer needs a holistic set of information. Since relevant data is typically kept in a highly fragmented information landscape (Bockholt 2012, Meyr 2004, Stäblein 2008), this data has to be integrated into a transparent and efficient form of product representation.

This product representation needs to bundle all information needed to capture the customer's anticipated or realised demand (e.g. model volumes, option quotas and dependencies among these). It has to allow to determine the required resources capacities and material items needed to satisfy the customer's or market demand.

The compatibility of car models and options for a respective car series is described by a highly complex set of technical rules, while the relationship between the fully-configured car and the corresponding material items is described by the bill of material (BOM) (Pawlikowski et al. 2016). But in particular, technological trends like e-mobility and the increase of embedded systems – which may be subsumed under the term “digitization of the car” – have changed the requirements on this product representation applied by logistics.

E-mobility causes a major challenge in the compatibility of the electronic components and the connection of the energy consuming components to the energy source(s) in the vehicle. Compared to vehicles with a combustion engine, electric vehicles differ in various components (e.g. the battery control system); the share of electronic components is much higher. Since this represents an important bottleneck in e-mobility, a holistic information base with all dependencies has to be considered to ensure the compatibility.

Vehicle functions are enriched by safety-, comfort-, environment friendly-, and drive technology functions. Of course, these functions have effects in the area of driver assistance, but also on chassis engineering, drive technology and electronics as well as body technology (Ebel and Hofer 2014). Due to the increasing number of electronic components, in particular the large number of embedded systems, new forms of dependencies and compatibility questions arise between non-electronical and electronic components, e.g. their software versions. An embedded system is an information processing system that is embedded into enclosing products (Marwedel 2011). For example, the navigation system communicates with driver’s mobile phone and simultaneously provides input for the driver assistance systems. All of these components are subject of continuous development cycles on hardware as well as on software side. Therefore, compatibility has always to be ensured.

Nevertheless, innovation life cycles in the electrical industry (semiconductors, control units, embedded systems) are significantly shorter than vehicle life cycles and corresponding technical component life cycles (Grimm 2003). While new versions of a car series are launched every three to eight years, the innovation cycles of the electrical industry are significantly shorter. The incentive for the OEM to upgrade electronical functions, components or parts (including new partners such as Apple or Google) in series production is rising. The effect is a continuous change in car models during their life cycle and electronical innovations in components must be constantly adapted to given structures. Consumer electronics (e.g. smartphones) innovation cycles are about one year. That is significantly shorter than the life cycle of vehicles (Kampker et al. 2016, Krumm et al. 2014).

Since new characteristics of electronical components like the compatibility of software versions are not (comprehensively) mapped in product representations, the complex dependencies between electronic and other components are not transparent for logistics. This poses a major challenge and in result, these processes are not always under full control (Nagel 2011). Sometimes the customer becomes an involuntary beta tester – as in the case of the Toyota recall of hybrid electronics software (Edmunds.com 2017). The related unplanned costs and the considerable loss of reputation has to be avoided.

Due to the tremendous influence, the serviceability of parts and modules must already be logistically secured in the early development phase. This requires, in addition to the problem of technical feasibility, that new technologies are to be tested for their compatibility with logistics series processes (Weinzierl 2006).

To guarantee an early insight into possible bottlenecks, the transparent access to relevant data is an important criteria. Lack of transparency is not necessarily a consequence of non-existent data. Rather, it is due to the fact that the data to be considered is often extremely comprehensive and at the same time distributed over different software systems, which often do not have interfaces with one another. On top of this, the type of data processing - from the perspective of variant management - is often inadequate (Kesper 2012).

These effects carry on into the after-sales and also spare-part business. After a few years of use, many electronical systems of a vehicle (e.g. navigation systems) are outdated and obsolete. These cars can only be sold with large discounts to second-hand customers. A way to counteract the massive loss in value is to update the components, e.g. by integration of Apple CarPlay in an end-of-life vehicle (Moynihan 2014). In order to handle the respective logistics, a complete insight into the vehicle structure is necessary to ensure interoperability with existing components, control devices, interfaces and connections to energy sources and energy consumers. The availability of components on hardware and software side needs to be guaranteed. But also obsolescence risks of spare part inventories have to be minimised.

Hence, it is necessary to provide transparency on the multiple new dependencies of innovative electronical vehicle components. But today, the challenges and opportunities introduced by embedded systems and e-mobility are not considered sufficiently in product structures, which are an integral part of the product representation, for logistics. The characteristics of these components have to be identified and integrated within the logistics-relevant product representation.

Nevertheless, the logistics strategy is strongly connected to the cost-efficient variant diversity (see for example Lechner et al. 2011), e.g. by preferring an early or late differentiation in the physical processes (variants of an electronic component are delivered to the assembly site or differentiation is postponed to a late configuration at the assembly site).

Thus, the new characteristics of electronic components are relevant for development as well as sales, planning, logistics, production, distribution and after-sales. The objective of the product representation for logistics is the efficient management of dependencies and interrelationships in automotive planning and order management processes, part procurement, production and part distribution processes (Romberg and Haas 2005). The ideal product representation of the future shall support all processes and stakeholders in every phase of the product life cycle. Only this allows to integrate new modules, components or software components safely and quickly into an existing vehicle structure and into the logistics process.

Nevertheless, it is necessary prerequisite to assure consistency and avoid redundancy in and between all data entities when integrating data into one information model. As it is easily understood, an integrated information base could reduce the complexity and increase transparency of the different processes immensely. The advantage of this integration is the faster and easier access to relevant data and its innermost dependencies, as well as the reduction of redundancies (Pawlikowski et al. 2016).

The resulting requirements on product representation based on the described challenges for the automotive industry can be summarised as follows:

- Besides already documented dependencies in BOMs and technical rules, the **integration of new dependencies** like the compatibility of software versions is required.
- It is necessary to **integrate cross-functional information** to support every phase of the product life cycle, i.e. all processes from development over series production to after-sales.
- As innovation cycles for new technology products accelerate, the continuous compatibility of parts and modules needs to be ensured because electronic systems and their software are developed faster as car types. In this context, **modularity** of the product representation allows to replace components more easily.
- The complexity of the product car is further increasing. The **management of comprehensive and complex information** is necessary.
- **Transparent data structures** are necessary to identify and manage possible bottlenecks to avoid intern expenditure and a deterioration of the delivery service to the customer.

Before approaches and concepts for product representations are evaluated against these requirements in section 4, the following section 3 gives a systematic overview over the state of the art.

3. STATE OF THE ART OF PRODUCT REPRESENTATIONS

Methodologically a content analysis has been pursued to provide a reproducible literature overview of the state of the art in product representations in the field of the automotive industry. Conducted in the English-speaking area, the digital databases ScienceDirect and Google Scholar have been searched with defined search terms and a period from 2006 to 2017. The core terms of the search were “product representation” and “automotive”. The term “product representation” was also modified by the synonyms “product architecture”, “product structure”, “product data”, “product graph” and “product tree”. “Embedded systems” as well as “e-mobility” have not been considered as search terms in the context of product representation because the authors did not want to limit the results more than necessary. Moreover, relevant findings from the related field of mechanical engineering also have been considered.

The 107 resulting scientific publications have been preselected based on the abstracts, keywords and titles. After a thorough analysis, 27 papers from the last decade have been identified as relevant and a limited number of types of product structures could be derived. Furthermore, eight older publications and also books and dissertations found while analysing the results have been included.

3.1. Literature Review

In general, product representations are product knowledge decomposed into its elementary components from a technical view (Deng et al. 2012). These components can be either a physical or a non-physical artefact (service and software components) (Kissel 2014). The next larger units are modules. A definition of modules is given by Klug (2010) as an assembly of several components or assembly units. The modules, which may comprise a variety of functions (Rapp 1999), shall generally be easier replaceable than each part of the module separately (e.g. door, seat, cockpit, power pack, roof). Modules are used within a so-called modularization to subdivide a system. Modularization may occur differently within the phases of the product life cycle such as development, procurement, production, distribution, utilization and disposal (Blees 2011, Gu and Sosale 1999, Krause et al. 2014).

According to Schuh (2014) a product structure as an elemental part of the product representation is typically a structured formation of the product and its components. Generally, structure levels are introduced to represent assemblies, which bundle components in the product structure. Product structures support the multiple use of assemblies and parts. Another important objective of product structures are the reduction of production information and the support of the information flow.

Figure 1 illustrates fundamental product structures. Modular systems are designed from a certain number of building blocks (basic body and attachment). The definition of modules has been given before. In contrast to modules, series comprise components of the same design but of different size. Packages combine components to realize a variety of functions.

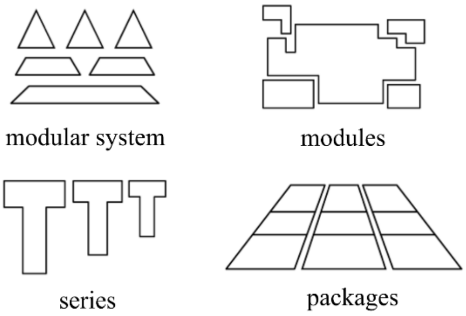

Figure 1: Fundamental product structures [based on (Schuh 1988)]

The most widespread form of product structure is the bill of material (BOM). Within a BOM, the components, i.e. parts and modules that constitute the product in the context of an assembly, subassembly or model are listed (Lee et al. 2012). BOMs are considered as an integral part of the product representation in the automotive industry. In BOMs, the information on components (e.g. compressor, cable, etc.) that are necessarily installed in a product to implement a function (e.g. climate control system) are documented (Wagenitz 2007). Brière-Côté et al. (2010) give a more detailed specification of BOMs: BOMs are described relationally as a list of subassemblies, components, parts, and raw materials which is applied to construct higher-level assemblies. To build a finished product, the BOM lets deduce the type and quantities of each material item used.

In the automotive industry, typically, the relevant data is complex and distributed over several systems in relational data structures. This not only holds true for BOM data, but also for other product information like model descriptions or technical rules. In particular, these different data fragments are not integrated in a common information base (Bockholt 2012).

In literature another common product structure is the tree structure. Literature differentiates between variant trees and feature trees, which differ in their representation and the integrated information (Kesper 2012). While variant trees represent the variety of semi-finished products arising during the assembly process, the feature tree illustrates the variety resulting from the combination of characteristics and their properties (Kesper 2012, Schuh 2014).

Variant trees form the basis for the reduction of variants by means of assembly sequence optimization or product structure optimization. The variant tree is often used to visualize component and product diversity that arises in assembly processes (Kesper 2012, Schuh 1988). Schuh (1988) identifies variant trees as an important instrument to design and evaluate product variants, where different components are symbolised by different boxes (see Figure 2) (Kesper 2012). According to Schuh (2014), variant trees are typically constructed in defined steps. The product characteristics and their properties are captured in a first step. Afterwards, constraints on combinations of properties as well as the prohibitions of combinations are defined and variants are generated. The assembly sequence is determined after the integration of part information and allocation of part usage. The variant tree may be depicted graphically in a last step (Kesper 2012).

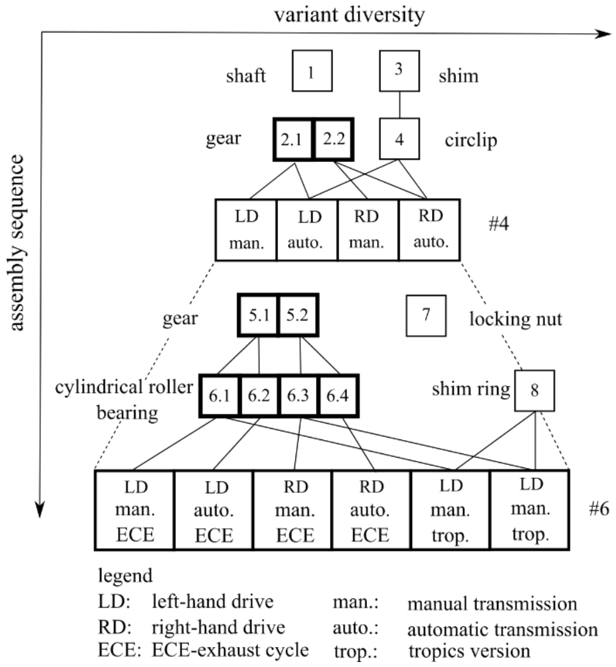

Figure 2: Variant tree [based on (Kesper 2012, Schuh 1988)]

The widely spread feature tree is often incorrectly also designated as a variant tree. It is an instrument to graphically depict variants or spectra with a focus on their characteristics and properties. The feature tree usually starts with a "root" node and then branched from left to right (see Figure 3).

A feature is presented by a vertical level. One variant is depicted by a branch of the tree, where the extent and shape of the feature tree depends on the order of features. A different order changes the total number of the feature expressions to be displayed (Kesper 2012). The visualization of the diversity, resulting from the combinations of characteristics and properties, is also depicted by this kind of tree. Nevertheless, to facilitate the interpretation of the representation, it is recommendable to list the categories of specifications in order of importance (Zagel 2006).

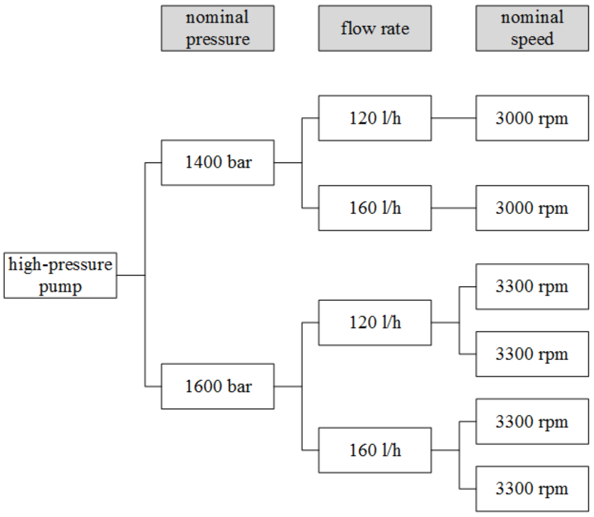

Figure 3: Feature tree [based on (Kesper 2012)]

A general formulation of tree structures is the hierarchical structuring. Ariyo et al. (2008) presents the hierarchical structuring as a technique to disassemble a (complex) product.

Within a product representation, not just the product structure as described has to be considered, but also dependencies and interrelations between a product, its components and the relevant assembly tasks. An extended product tree structure originally proposed by Zeng and Gu (1999) can describe these relationships. There are two types of nodes distinguished in an extended product tree. The assembly task node represents simplified assembly information included in the product structure while the component node represents a product or component. The connection between two component nodes is a parent-child relationship where a parent component (or assembly) consists of all its child components. A component is assembled by the appropriate assembly task that is signalled by the connection between the component and the assembly task. All nodes together form a recursive product structure tree (Deng et al. 2012). As long as functional requirements and cost-effectiveness persist, modules can be shared by different end products (Fujita 2002).

Another tree based approach for product representations has been realised in the tool suite OTD-NET (order-to-delivery and network simulator (cf. Wagenitz 2007). For different applications in logistics (e.g. process simulation, demand and capacity management or risk management) a hierarchical variant tree based on product descriptions with further enriched information is applied. Even sales information, technical rules and BOM rules are integrated into the hierarchy of product classes within the tree structure (Liebler 2013).

Another similar, but generalised form of product representations are graph structures, which – in contrast to tree structures – may be multidimensional. In mathematics, graphs are used to document pairwise relationships of features (Riggs and Hu 2013). In principle it is not necessary that a graph structure has just one “root” node. An illustration of relations between components can also be realised by liaison or connection graphs. Riggs and Hu (2013) used these graphs and developed a method to graphically illustrate the disassembly precedence relations among all components. Components or respectively parts are represented by nodes in liaison graphs, whereby the relation between those are depicted by edges (Hu et al. 2011). Within a precedence graph, the precedence order between components is documented instead of the physical connection (Riggs and Hu 2013). The disassembly precedence graph is a directed graph, illustrating the order of disassembly for the product in focus (see Figure 4).

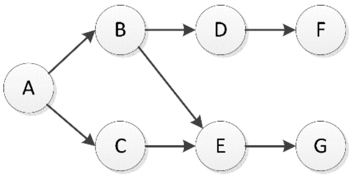

Figure 4: Example of a disassembly precedence graph (Riggs and Hu 2013)

Luo et al. (2016) describe another graph structure, the AND/OR graph, which is widely used in disassembly planning as product representation. These graphs consist of nodes and hyperarcs. Disassembly tasks are represented by hyperarcs, where nodes stand for components or subassemblies of a product (Viganò and Osorio Gómez 2013). A more complex subassembly can be formed by joining two or more components together (Li et al. 2002). Nodes in the graph are either AND or OR branches and form a hierarchical structure. AND relations are vertical links, where OR relations are nodes linked in the same level. In Homem de Mello and Sanderson (1990) the AND/OR graph has been applied to represent satellite equipment for an increased planning flexibility. A combination of weights and the AND/OR graph can be found in Min et al. (2010). This weighted AND/OR graph is used for disassembly planning and represents the product structure and element constraints. The adjacent graph is another type of graph-based methods, which is used to represent component relationships of products (Song et al. 2010). Components or subassemblies are represented by nodes. Directed or undirected lines represent the relationships between connected components or subassemblies. Compared to AND/OR graphs the adjacent graph can include more information of component constraints for product structures (Luo et al. 2016).

There are some more innovative approaches in literature to depict product representations. These are based on ontologies and semantic networks.

An ontology is defined as a uniform vocabulary with the objective to exchange information in a particular field. The focus of ontologies is the description of real or intended things, whereby a consistency check for partial descriptions can be performed (Bock et al. 2010). It allows inter alia reuse and analysis of knowledge (Noy and McGuinness 2001).

A semantic network is, in contrast, a graphical representation of knowledge. These networks are realised with the aid of nodes and arcs (López-Morales and López-Ortega 2005). Nodes are used to represent objects, concepts or situations. The dependencies between the nodes can be deduced from the arcs (Yang et al. 2012). A simple example of a car as a semantic network has been illustrated in Figure 5, where, e.g. the relationship that a car is a (“ISa”) vehicle with specific parts and components is expressed.

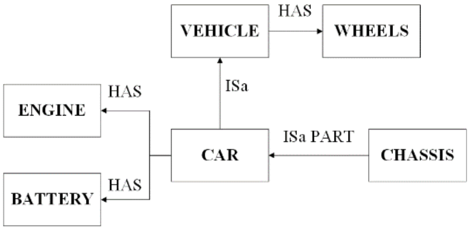

Figure 5: Example of car as a semantic network

Vegetti et al. (2011) present an example of an ontology-based semantic network where two hierarchies are applied to handle product variants from different angles. To efficiently deal with a high number of variants, the abstraction hierarchy allows to represent product data on various granularity levels. The organization of knowledge related to structural product information and to the BOM is obtained by the structural hierarchy.

“Design Structure Matrices” (DSMs) denote a compact representation of product element contexts, mainly used for a development perspective (Deng et al. 2012). This structures are suitable for models with many variant features as they allow a comprehensive presentation of information (elements of any type, i.e. components or process steps). To map the relationships of parameters between components the DSM is illustrated as a square matrix with the same columns and rows (see Figure 6) (Danilovic and Browning 2007). Only one type of connection (e.g. “…is linked to…”) per DSM can be defined.

	element A	element B	element C	element D
element A	▨	X		
element B		▨	X	
element C		X	▨	
element D	X			▨

Figure 6: Example of a DSM (Deng et al. 2012)

Nevertheless, it is difficult to keep an overview and ensure the manageability of the matrix representations for larger systems with several hundred elements (Kissel 2014).

Summarizing, relational databases, tree structures, (generalised) graph structures, ontologies, semantic networks and design structure matrices are the types of product representations which may be identified in literature. Based on the defined requirements, the next section rates these forms of product representations in order to manage the challenges related to digitization in form of e-mobility and embedded systems.

4. FRAMEWORK FOR FUTURE PRODUCT REPRESENTATION – AN EVALUATION

The different concepts and approaches are now analysed in order to decide to what extent they match the requirements identified in section 2. The results are summed up in Table 1. The applied rating is:

- X : requirement fully met,
- O : requirement limitedly met,
- – : requirement not met.

The first requirement identified has been the **integration of new dependencies** like the compatibility of software versions. Relational data structures of course allow to integrate a multiplicity of dependencies by extension of the relational data schema (rating "X"), but at the expense of transparency. In contrast, tree structures, graph structures and ontologies allow to integrate new dependencies in a more structured way by adding new types of edges. By limiting the view on a different aspect, a transparent access to data can be guaranteed, thus leading to the rating "X". Different forms of dependencies can be deduced directly from the arcs in semantic networks, this also leads to the rating "X" here. The DSM in contrast (rating "-/O") depicts only information of one type of relationship. Thus, to depict another kind of dependency, another matrix needs to be generated. This would lead to a multiplicity of matrices which is not feasible in practice.

The second requirement, the **integration of cross-functional information**, is also fully (rating "X") met by all structures except the DSM (rating "–"). Similar to the integration of new dependencies, cross-functional information can be added in the same way.

Table 1 – Framework of rated product representations

Criteria / Approach	Integration of new Dependencies	Integration of cross-functional Information	Modularity	Management of Comprehensive Data	Transparency
Relational Data Structure	X	X	X	O	-
Tree Structure	X	X	O/X	O/X	O
Graph Structure	X	X	X	X	X
Semantic Network	X	X	X	O	-/O
Ontology	X	X	X	O/X	O/X
DSM	-/O	-	X	-/O	O

The cross-functional characteristic of the new information can be explicitly documented. A DSM as presented e.g. by Deng et al. (2012) or Kashkoush and ElMaraghy (2016) on the other hand only allows to illustrate simple one-dimensional relationships and not to append additional cross-functional data.

Regarding the third requirement **modularity**, the tree structure approach is rated "O/X". The tree structures of Kesper (2012) and Schuh (1988, 2014) do not support modularity natively, but ElMaraghy et al. (2013) introduced an approach with evolving part/product families. Within the more general graph structures, two or more components or subassemblies can be joined together and form a more complicated (sub-) assembly (Luo et al. 2016). Therefore and in accordance with the ability to integrate a multiplicity of dependencies, modularity as described in section 3 is supported (rating "X"). Ontologies and semantic networks behave in a similar way as graph structures (rating "X"). By managing information over different data sources, relational data structures also fulfil the criteria of modularity (rating "X"). But it should be noted that it is difficult to remain transparency if the amount of data increases. DSMs with their simple direct connections between two components allow to replace components including their dependencies one by one. Though the level of information granularity is limited in DSMs they fulfil the requirements of this category in full (rating "X").

The next criteria to be evaluated is **the management of comprehensive and complex information**. Product representations based on tree structures and graph structures meet this requirement as the examples in section 3 show. But it should be noted that tree structures may become very complex in terms of system size (rating "O/X") (Kesper 2012). Graph structures fulfil this criteria better, because of their more general layout, which allows to structure the graph more flexibly according in dynamically changing environments (rating "X"). Especially the multidimensionality and the integration of several "root" nodes if need support this argument. In general, ontology based approaches have an average ability to manage complex systems (Lim et al. 2010). However, the approach of Vegetti et al. (2011) with its hierarchical concept shows a promising development and leads to a rating of "O/X". A DSM does not allow to illustrate complex multidimensional and cross-functional automotive data (rating "–/O"). Its tabular structure very quickly becomes intransparent (Kissel 2014). Semantic networks and relational data structures meet this requirement limitedly (rating "O"). Both approaches allow to manage complex and comprehensive automotive product data but transparency decreases and typically redundancies increase steadily with increasing data complexity.

The last requirement is **transparency**. The rating "–" is given to relational data structures due to the arguments already given above. The huge variety of distributed automotive data within the given relational data structures quickly leads to poor transparency and redundancies (Bockholt 2012). As stated before, the DSM can only depict one-to-one connections and is strictly limited in the size of the model. Under this limitation of data the transparency is high, but it requires multiple matrices for more complex cross-functional data sets. This results in the overall rating "O". In the case of semantic networks only similar relationships between two components are mapped, i.e. natively there is no kind of hierarchy or overall view in a semantic network (Yang et al. 2012), which limits the transparency radically in complex data environments leading to the rating "–/O". Graph structures limit the transparency eventually when being multidimensional, but allow to generate limited views on the structure (rating "X"). An especially enhanced graph structure is given by Riggs and Hu (2013) by presenting a disassembly precedence graph. The evaluated approaches based on ontologies are in their form similar to the hierarchical tree or graph structures, thus resulting in a rating "O/X".

All discussed ratings are summed up in Table 1 forming a framework of rated product representations.

5. KEY INSIGHTS AND OUTLOOK

In order to guarantee the availability of components and minimize obsolescence risks, it is essential that the product representation applied in logistics depicts dependencies and provides transparent holistic information. Especially, dependencies of technical and electronical components and the compatibility between hardware and software components have to be considered.

The research presented here is an important starting point, as it specified the five essential requirements on the automotive product representation originating from e-mobility and the integration of more embedded systems. A systematic literature research led only to a total of 27 relevant papers from the last decade which indicates the research necessary in this field.

The identified papers have been analysed thoroughly and the core types of product structures have been identified in result. Based on the beforehand deduced requirements, the state of research has been rated and promising approaches have been identified.

This structured discussion showed that DSMs are a valuable tool in development, but are not suited for complex cross-functional information as required by logistics. Regarding the complexity within the automotive industry, especially semantic networks, tree structures and generalised graph structures have proven to be promising candidates for a new generation of product representations. Especially, graph structures fulfil nearly all of the new requirements and may give answers to the challenges of parallel component development within the automotive industry.

To conclude, a variety of types of product representations is available today, but due to the findings of the literature review, an approach based on graph structures should be elaborated for logistics in the near future. Nevertheless, ontologies and semantic networks offer a new and different perspective on the integration of additional especially cross-functional information. Consequently, the combination of approaches may hold additional value and should not be neglected.

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REFERENCES

Alford, D., Sackett, P. and Nelder, G., 2000. Mass customisation — an automotive perspective. International Journal of Production Economics vol. 65, pp. 99–110.

Ariyo, O. O., Eckert, C. M. and Clarkson, P. J., 2008. Hierarchical decompositions for complex product representation. 10th International Design Conference Design, pp. 737–744, May 19 - 22. Dubrovnik - Croatia.

Blees, C., 2011. Eine Methode zur Entwicklung modularer Produktfamilien. Thesis (PhD). Hamburg University of Technology.

Bock, C., Zha, X., Suh, H.-w. and Lee, J.-H., 2010. Ontological product modeling for collaborative design. Advanced Engineering Informatics vol. 24, pp. 510–524.

Bockholt, F., 2012. Operatives Störungsmanagement für globale Logistiknetzwerke: Ökonomie- und ökologieorientiertes Referenzmodell für den Einsatz in der Automobilindustrie. Thesis (PhD). TU Dortmund University.

Brière-Côté, A., Rivest, L. and Desrochers, A., 2010. Adaptive generic product structure modelling for design reuse in engineer-to-order products. Computers in Industry vol. 61, pp. 53–65.

Danilovic, M. and Browning, T. R., 2007. Managing complex product development projects with design structure matrices and domain mapping matrices. International Journal of Project Management vol. 25, pp. 300–314.

Deng, X., Huet, G., Tan, S. and Fortin, C., 2012. Product decomposition using design structure matrix for intellectual property protection in supply chain outsourcing. Computers in Industry vol. 63, pp. 632–641.

Dörmer, J., ed., 2013. Produktionsprogrammplanung bei variantenreicher Fließproduktion. Wiesbaden: Springer Fachmedien.

Ebel, B. and Hofer, M. B., eds., 2014. Automotive Management. Berlin: Springer.

Edmunds.com, 2017. Toyota Recalls - Toyota Safety & Defect Recall News[Online]. Available at: https://www.edmunds.com/recalls/toyota.html (Accessed 12 April 2017).

ElMaraghy, H., Schuh, G., ElMaraghy, W., Piller, F., Schönsleben, P., Tseng, M. and Bernard, A., 2013. Product variety management. CIRP Annals - Manufacturing Technology vol. 62, pp. 629–652.

eVchain, 2014. Modellierung der zukünftigen elektromobilen Wertschöpfungskette und Ableitung von Handlungsempfehlungen zur Stärkung des Elektromobilitätsstandortes NRW: (EM1006 – eVchain.NRW).

Fujita, K., 2002. Product variety optimization under modular architecture. Computer-Aided Design vol. 34, pp. 953–965.

Grimm, K., 2003. Software technology in an automotive company - major challenges. 25th International Conference on Software Engineering, pp. 498–503. Portland, OR, USA.

Gu, P. and Sosale, S., 1999. Product modularization for life cycle engineering. Robotics and Computer-Integrated Manufacturing vol. 15, pp. 387–401.

Holweg, M. and Pil, F. K., 2004. The second century: Reconnecting customer and value chain through build-to-order: moving beyond mass and lean production in the auto industry. Cambridge, Mass: MIT Press.

Homem de Mello, L. S. and Sanderson, A. C., 1990. AND/OR graph representation of assembly plans. IEEE Transactions on Robotics and Automation vol. 6, pp. 188–199.

Hu, S. J., Ko, J., Weyand, L., ElMaraghy, H. A., Lien, T. K., Koren, Y., Bley, H., Chryssolouris, G., Nasr, N. and Shpitalni, M., 2011. Assembly system design and operations for product variety. CIRP Annals - Manufacturing Technology vol. 60, pp. 715–733.

Kampker, A., Deutskens, C., Heimes, H., Ordung, M. and Haunreiter, A., 2016. Using E-mobility as an Enabler for a Fast and Lean Product Development to Optimize the Return of Engineering with the Example of Lithium-ion Battery. Procedia CIRP vol. 50, pp. 166–172.

Kashkoush, M. and ElMaraghy, H., 2016. Optimum Overall Product Modularity. Procedia CIRP vol. 44, pp. 55–60.

Kesper, H., 2012. Gestaltung von Produktvariantenspektren mittels matrixbasierter Methoden. Thesis (PhD). Technical University of Munich.

Kissel, M., 2014. Mustererkennung in komplexen Produktportfolios. Thesis (PhD). Technical University of Munich.

Klug, F., 2010. Logistikmanagement in der Automobilindustrie. Berlin: Springer.

Krause, D., Beckmann, G., Eilmus, S., Gebhardt, N., Jonas, H. and Rettberg, R., 2014. Integrated Development of Modular Product Families: A Methods Toolkit. In: Simpson, T. W., Jiao, J., Siddique, Z. and Hölttä-Otto, K., eds. Advances in Product Family and Product Platform DesignMethods & Applications. New York: Springer, pp. 245–269.

Krog, E.-H. and Statkevich, K., 2008. Kundenorientierung und Integrationsfunktion der Logistik in der Supply Chain der Automobilindustrie. In: Baumgarten, H., ed. Das Beste der Logistik. Berlin, Heidelberg: Springer, pp. 185–195.

Krumm, S., Schopf, K. D. and Rennekamp, M., 2014. Komplexitätsmanagement in der Automobilindustrie – optimaler Fit von Vielfalt am Markt, Produktstruktur, Wertstrom und Ressourcen. In: Ebel, B. and Hofer, M. B., eds. Automotive Management. Berlin: Springer, pp. 189–205.

Lechner, A., Klingebiel, K. and Wagenitz, A., 2011. Evaluation of product variant-driven complexity costs and performance impacts in the automotive logistics with Variety-driven Activity-based Costing. International MultiConference of Engineers and Computer Scientists, pp. 1088–1096. Hong Kong.

Lee, J. H., Kim, S. H. and Lee, K., 2012. Integration of evolutional BOMs for design of ship outfitting equipment. Computer-Aided Design vol. 44, pp. 253–273.

Li, J. R., Khoo, L. P. and Tor, S. B., 2002. A Novel Representation Scheme for Disassembly Sequence Planning. The International Journal of Advanced Manufacturing Technology vol. 20, pp. 621–630.

Liebler, K. M., 2013. Eine prozess- und IT-gestützte Methode für die Produktionsplanung in der Automobilindustrie. Thesis (Phd). TU Dortmund University.

Lim, S. C. J., Liu, Y. and Lee, W. B., 2010. A methodology for building a semantically annotated multi-faceted ontology for product family modelling. Advanced Engineering Informatics vol. 25, pp. 147–161.

López-Morales, V. and López-Ortega, O., 2005. A distributed semantic network model for a collaborative intelligent system. Journal of Intelligent Manufacturing vol. 16, pp. 515–525.

Luo, Y., Peng, Q. and Gu, P., 2016. Integrated multi-layer representation and ant colony search for product selective disassembly planning. Computers in Industry vol. 75, pp. 13–26.

Marwedel, P., 2011. Embedded system design: Embedded systems foundations of cyber-physical systems. New York: Springer.

Meissner, S., 2009. Logistische Stabilität in der automobilen Variantenfließfertigung. Thesis (PhD). Technical University of Munich.

Meyr, H., 2004. Supply chain planning in the German automotive industry. OR Spectrum vol. 26, pp. 447–470.

Min, S.-s., Zhu, X.-j. and Zhu, X., 2010. Mechanical Product Disassembly and/or Graph Construction. International Conference on Measuring Technology and Mechatronics Automation, pp. 627–631. Changsha City, China.

Moynihan, T., 2014. Apple's New Car System Turns Your Dashboard Into an iPhone Accessory[Online]. Wired. Available at: https://www.wired.com/2014/03/apple-carplay-system/ (Accessed 5 April 2017).

Nagel, J., 2011. Risikoorientiertes Anlaufmanagement. Thesis (PhD). Brandenburg University of Technology.

Noy, N. and McGuinness, D. L., 2001. Ontology Development 101: A Guide to Creating Your First Ontology. Knowledge Systems Laboratory, Stanford University.

Pawlikowski, K., Fruhner, D., Klingebiel, K., Toth, M. and Wagenitz, A., 2016. Benefits of an Integrated Hierarchical Data Structure for Automotive Demand and Capacity Management. The Eleventh International Multi-Conference on Computing in the Global Information Technology, pp. 20–25. Barcelona, Spain.

Rapp, T., 1999. Produktstrukturierung: Komplexitätsmanagement durch modulare Produktstrukturen und -plattformen. Thesis (PhD). University of St.Gallen.

Riggs, R. J. and Hu, S. J., 2013. Disassembly Liaison Graphs Inspired by Word Clouds. Procedia CIRP vol. 7, pp. 521–526.

Romberg, A. and Haas, M., 2005. Der Anlaufmanager: Effizient arbeiten mit Führungssystem und Workflow - von der Produktionsidee bis zur Serie. Stuttgart: LOG X.

Schuberthan, J. and Potrafke, S., 2007. Die Anforderungen des Kunden… In: Gehr, F. and Hellingrath, B., eds. Logistik in der Automobilindustrie: Innovatives Supply Chain Management für wettbewerbsfähige Zulieferstrukturen. Berlin: Springer, pp. 8–18.

Schuh, G., 1988. Gestaltung und Bewertung von Produktvarianten: Ein Beitrag zur systematischen Planung von Serienprodukten. Thesis (PhD). RWTH Aachen University.

Schuh, G., 2014. Produktkomplexität managen: Strategien - Methoden - Tools. München: Carl Hanser Fachbuchverlag.

Sharon O'Malley, 2016. Product Rrecalls. In: SAGE Business Researcher: SAGE Publishing.

Song, S., Hu, D., Gao, Y., Yang, M. and Zhang, L., 2010. Product disassembly sequence planning based on constraint satisfaction problems. China Mechanical Engineering vol. 17, pp. 2058–2062.

Stäblein, T., 2008. Integrierte Planung des Materialbedarfs bei kundenauftragsorientierter Fertigung von komplexen und variantenreichen Serienprodukten. Aachen: Shaker.

Trojan, A., 2007. …und die Auswirkungen auf den 1st-Tier-Lieferanten. In: Gehr, F. and Hellingrath, B., eds. Logistik in der Automobilindustrie: Innovatives Supply Chain Management für wettbewerbsfähige Zulieferstrukturen. Berlin: Springer, pp. 12–16.

Vegetti, M., Leone, H. and Henning, G., 2011. PRONTO: An ontology for comprehensive and consistent representation of product information. Engineering Applications of Artificial Intelligence vol. 24, pp. 1305–1327.

Viganò, R. and Osorio Gómez, G., 2013. Automatic assembly sequence exploration without precedence definition. International Journal on Interactive Design and Manufacturing (IJIDeM) vol. 7, pp. 79–89.

Wagenitz, A., 2007. Modellierungsmethode zur Auftragsabwicklung in der Automobilindustrie. Thesis (PhD). TU Dortmund University.

Weinzierl, J., 2006. Produktreifegrad-Management in unternehmensübergreifenden Entwicklungsnetzwerken: Ein ganzheitlicher Ansatz zur Entscheidungsunterstützung im strategischen Anlaufmanagement. Thesis (PhD). TU Dortmund University.

Yang, Q., Pan, X., Wei, D. and Wu, K., 2012. Research on Individualized Product Requirement Expression Based on Semantic Network. Physics Procedia vol. 25, pp. 1926–1933.

Zagel, M., 2006. Übergreifendes Konzept zur Strukturierung variantenreicher Produkte und Vorgehensweise zur iterativen Produktstruktur-Optimierung. Thesis (PhD). University of Kaiserslautern.

Zeng, Y. and Gu, P., 1999. A science-based approach to product design theory Part II: Formulation of design requirements and products. Robotics and Computer-Integrated Manufacturing vol. 15, pp. 341–352.