NordDesign 2018
August 14 – 17, 2018
Linköping, Sweden

Simulation of the system properties of a high-pressure storage depending on the degree of product maturity

Daniel Duschek (M.Eng.)[1], Prof. Dr.-Ing. Michael Vielhaber[2]

[1]*csi entwicklungstechnik GmbH, Sachsstr. 5, 85080 Gaimersheim, Germany*
daniel.duschek@csi-online.de
[2]*Institute of Engineering Design, Saarland University, 66123 Saarbruecken, Germany*
vielhaber@lkt.uni-saarland.de

Abstract

The constantly increasing customer requirements as well as the shortening of development and innovation cycles of future vehicle models presents the automotive industry with a great challenge. In order to continue to exist in established markets and to expand into new markets, agile, target-/user-oriented and economic product development is necessary. In addition to changes in global sales markets, compliance with new environmental regulations is another challenge for the automotive industry.

In particular, the introduction of electric drive technologies into existing module or modular strategies is a task to be solved. The variety of different vehicle models also increases the complexity of the product and development costs, too. One measure to reduce complexity in the automotive industry is the use of common parts. Through a platform, module and series strategy, the costs and development time of a vehicle model can be reduced. The common part strategy as well as the scalability of a component is discussed in more detail using a hydrogen pressure accumulator. Based on the approach for the design and evaluation of the hydrogen tanks, the system properties, such as volumetric or gravimetric density, can be derived and the influences of the assemblies can be taken into account. For a goal-oriented design of a pressure accumulator with application-specific innovative design (shape and hybrid structure), an analysis of the interrelationships of features is required. By means of a parameter study of different vehicle models, the influence of characteristics on the properties of the pressure accumulator and on the system properties of the chassis assembly can be derived.

However, in order to achieve the defined requirements for the component, a target-oriented adaptation in the course of vehicle development is necessary. The created approach serves for a quantitative evaluation of different scenarios in the course of the product development process under shows recommendations for action.

Keywords: Product Development Process, Product Engineering, Design automation, Simulation, High pressure storage

1 Introduction

The change in the automotive industry caused by autonomous driving, alternative drives and new services for customers, for example car sharing, confronted the automotive industry with a great challenge. In addition, the constantly rising customer demand and the reduction of the development and innovation cycles of future vehicle models require an effective and efficient product development process. An important challenge for the automobile industry is the change on global sales markets. The consideration of environmental aspects becomes more and more important during product development beside market requirements (development time and cost) and customer requirements (product quality and performance).
The result of the electro mobility trend, new competitors, such as Tesla, have positioned on the market, too. To survive in established markets and to expand into new markets, agile, sustainable, targeted and economic product development is necessary. As a result of increasing competition, premium car manufacturers are developing timely derivatives. The return is measured in terms of development costs and duration. A view onto energy storage systems shows that the acquisition costs for alternative powertrain vehicles are more expensive in comparison to conventional combustion architecture. Today's vehicle powertrain architectures can be differentiated into 3 types: conventional, electrical and hybrid as a mixture of both aforementioned. The challenge is to find the best solution for all powertrain types integrated in a platform strategy. The platform architecture provides the basis for further vehicle properties which define the main part of greenhouse gas emissions during driving (Edwards, R.2014)
One possible solution in the product development process of a vehicle model is the use of a platform or module strategy for a series. Another aspect is the use of common parts, see Figure 1. However, in order to achieve the defined requirements for the component, a target-oriented adaptation in the course of vehicle development is necessary. The created approach serves for a quantitative evaluation of different scenarios in the course of the product development process under shows recommendations for action. (Schneider, R. A. & Rieck K 2012). Therefore, the analysis and synthesis of characteristics and properties of a product at each phase of the product development process is essential. The developed simulation tool enables the evaluation of the product maturity and the effect on the assembly components. By visualising the effects of change preferences on the specific requirements, a recommendation for action can be derived. Therefore, a conclusion must be drawn on the resulting additional costs and the time delay. Of major importance is the identification of the greatest influences on system parameters, such as external boundary conditions (e.g. sales market, environmental regulations). This is necessary for efficient and effective development.

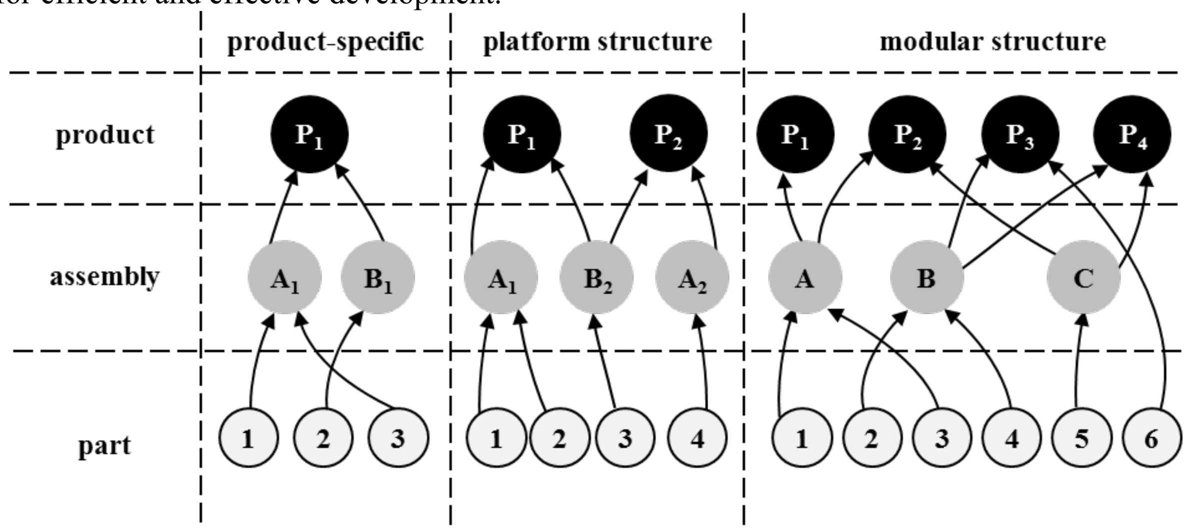


Figure 1. Schematic overview of product-specific, platform and modular structure (Schuh, G. 2013)

2 Target identification and research questions

In order to be able to record the changes of product properties, as a result of external influences on the system and to create instructions, it is necessary to establish a relationship matrix of characteristics and properties depending on the temporal product development process.

The research questions based on motivation and target identification, as follows:

- how can the technology of storages be integrated into the product development process of conventional module/assembly architectures and how can an evaluation of the system properties be derived?
- what influence does a change in the system properties of the chassis and the vehicle as a whole have on the characteristics of the storage system?

The simulation tool based on the Weber product development process approach. In this publication, the relations of characteristics and properties as well as the degree of maturity of high pressure storage are discussed and validated in more detail. A transfer of the approach is possible.

3 Product development process and product maturity

New development describes a product development started from the first scratch without any carry over or retention of existing components. An example for a new development is the Tesla Model S, because this car was the first product from Tesla. Adjusted design is a small modification of a product in order to satisfy the new boundary conditions, like new legal requirements. Parts and assemblies are varied within certain predefined limits in development for variants building in order to realize a high number of different products.
The product structure is nearly the same, whereas some individual components are varied. An example is the similar derivate development of a cabriolet version of a vehicle (Pahl, G., & Beitz W., 2013). The product development process of a car from the first draft to start of production (SOP) is a complex process (Ethiraj, S. K., 2007). On the base of external boundary conditions, for example the government adopt a new law to limit the permissible greenhouse emission, requires an agile adjustment of the product properties. Another important point is the dynamic of currently and new market from OEMs. For the development of new markets partly niche vehicles are being developed (Murray-Webster, R. & Pellegrinelli S., 2010). The variety of different vehicle models increases the complexity of the product and the development costs (Glynn, M.A. 2010) (Hobday, M. 2000) (Stoffels P., & Vielhaber, M. 2016). That means that the list of product requirements must be defined in dependence on the company strategy, like the COP strategy.

3.1 Definition of product maturity

The planning period is used to define requirements and properties for the vehicle. The company's future strategy must also be taken into account, such as the electric vehicle fleet offensive until 202X. The alignment is necessary because the corporate strategy may not be achieved with the currently available vehicle models, for example based on the combustion engine. As a consequence, an extension of the model range is required, which in turn affects the requirements and properties of the product (Pahl, G., & Beitz W., 2013). A challenge to be solved is the real-time evaluation of the degree of maturity. A comparison of the standard product development process of automobile manufacturers documents that the degree of maturity is defined in 6 steps, see Figure 2.

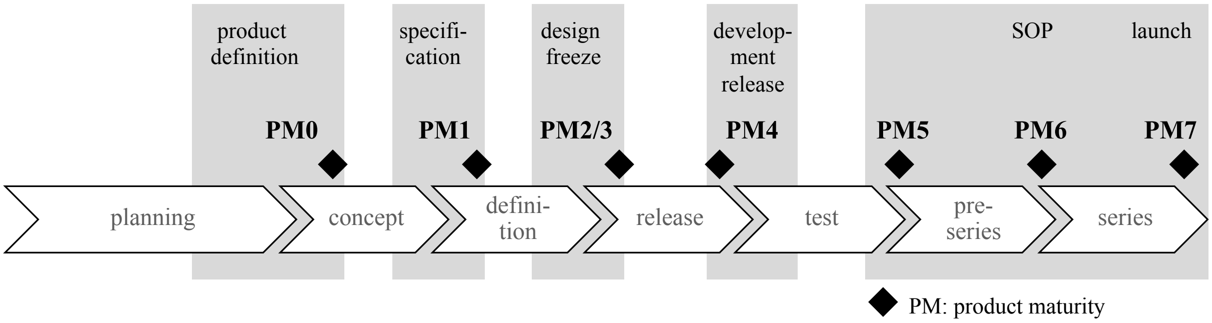


Figure 2. Product development process in automotive industry (Burr, H., 2008)

The following sections explain the approach to designing an electric vehicle with range extender in detail.

3.2 Definition of the modules of a fuel cell vehicle

A benchmark analysis of commercial electric vehicles or fuel cell vehicles shows that they can be categorized into a platform, for example like a skateboard, and a vehicle head, like a hat. Figure 3 shows the result of a preliminary investigation and the influence of the modules on the system properties of the energy storage module. For the approach, the external boundary conditions of the head are simplified, i.e. a variation of the weight or energy consumption is combined and considered holistically.

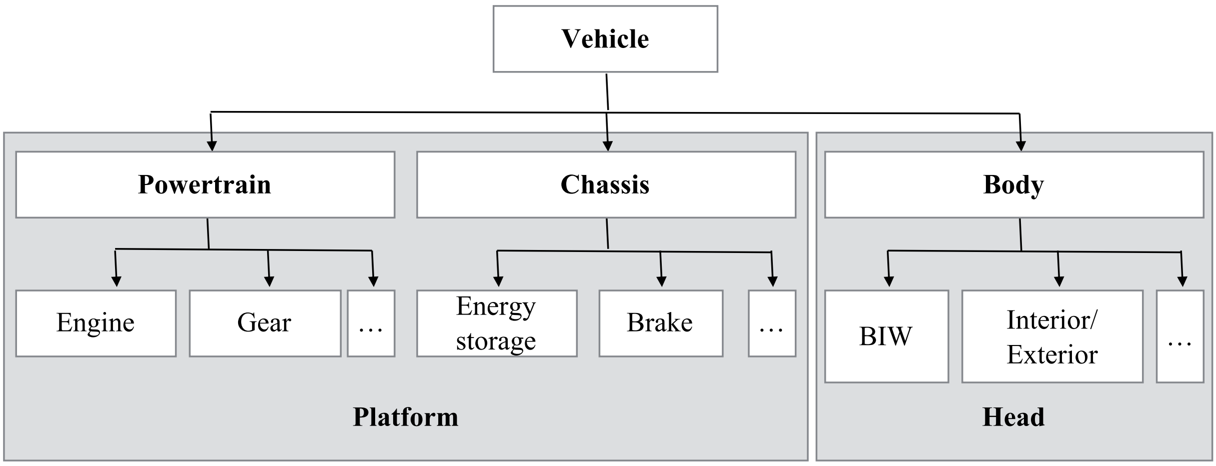


Figure 3. System overview and definition of the vehicle (Duschek, D., & Vielhaber, M.,2017).

4 Energy storage based on hydrogen

The challenge is both the integration of new technologies, such as batteries or pressure accumulators, into existing installation spaces of conventional platform/module strategies and the design in the product development process (PDP). The dimensions of new energy storage system, like batteries stacks or high-pressure tanks (hydrogen), are much higher compared to state of the art fuel tanks. So, it is necessary to define new designed space without losing comfort for the customers or less range. In order to define the degree of maturity of the component (pressure storage) and the product, a continuous analysis and synthesis of the characteristics and properties (CPM approach according to Weber is required. Consequently, a simulation tool in the Product development process is of importance for a goal- or application-oriented design and definition of the maturity level. The approach is based on a large number of preliminary investigations and will be discussed in more detail in the following section. (Weber, C. 2005) (Lüdeke, T. 2016)

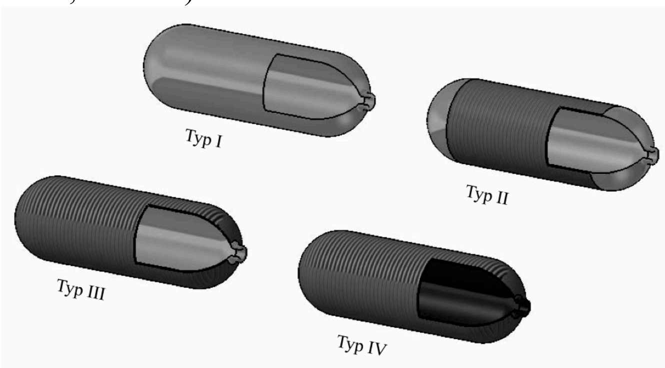


Figure 4. Classification of hydrogen storage systems (EC 79/2009), (Duschek, D., & Vielhaber, M.,2017).

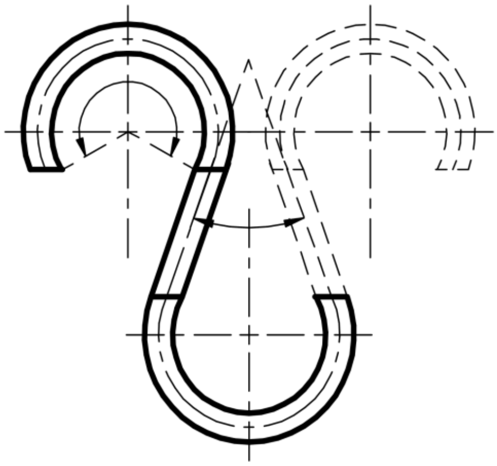
An analysis of commercially available types of pressure tanks according to EC 79/2009 shows that these can only be integrated into existing vehicle structures to a limited extent, see Figure 4. Commercial high pressure storage systems have a vessel shape with a specific inner diameter and length. The hydrogen pressure storage system types are defined as follows:

- Type I: Seamless metallic cylinder
- Type II: Hoop wrapped cylinder with a seamless metallic liner
- Type III: Fully wrapped cylinder with a seamless or welded metallic liner
- Type IV: Fully wrapped cylinder with a non-metallic liner

The structure based on a metal liner or assembled with composite material, like carbon, by wrapping, see Figure 4. The liner is used to barrier coat for hydrogen gas. By using composite fibre, the empty weight of type I tanks can reduce. The metal container is much heavier as a hybrid structure design. The weight aspect is very important for greenhouse emission, influence total mass, and driving performance of vehicle. Therefore, the ratio of metal and the fibre/matrix layers define the potential of lightweight strategy. Another aspect is the capacity of gaseous hydrogen storage system, because the constructed size is enormously. For example, if the trunk space is used as storage space, the customer losing convenience. The designer has the opportunity to reduce the tank dimension. This leads to a lower storage capacity and therefore a lower range. By rising up working pressure up the empty weight get higher. Furthermore, the storage capacity can only be scaled to a limited extent due to the tank structure. Based on the findings and an analytical consideration of different installation space dimensions (vehicle classes) new innovative designs for pressure tank were developed (Töpler, J. 2014). The following table shows the main necessary properties of high pressure storage systems:

- volumetric density [kg H_2 /dm^3]
- gravimetric density [kg H_2 /kg]
- volumetric energy density [kWh/kg]

The innovative design of the pressure storage systems is specifically adapted to the application and use, see Figure 5. As a result, the complexity in the design of the system properties increases. By analysing the interrelationships of parameters, it is possible to evaluate the characteristics and derive the influence on the system properties. The challenge is also the development of platform strategies and that the design of a new hydrogen tank can be individually scaled. In the following chapter, the method, based on Weber's approach, is discussed in more detail.



parameter	notation
d_i	inner pipe diameter
k_{rb}	bending factor
r_b	radius of curvature
α	angle
l_g	length of straight pipe
l_b	length of bended pipe
l_{ges}	total length
t_{ges}	wall thickness
p_i	Internal pipe pressure (operational pressure)

Figure 5. Innovative hydrogen storage system, parameter (Duschek, D., & csi entwicklungstechnik 2015)

5 Approach to identify the properties depending on the degree of maturity

5.1 Characteristics-Properties Modelling (CPM)

The Characteristics-Properties Modelling (CPM) approach based on the strict distinction between characteristics and properties of a product as follows (Weber, C. 2000) (Weber, C. 2012):

- Characteristics (Characteristics Ci) describe the structure, shape and quality of a product. and can directly modified.
- Properties (Properties P_j) describe the behaviour of a product and cannot be directly influenced by the developer. They can only be determined by the developer indirectly via the characteristics. Examples of properties include weight, safety, aesthetics, manufacturing and assembly reliability as well as the cost of a product.

In order to define the modelling approach of products, each property requires a relation which links them to the corresponding characteristics. In CPM, there exist two directions of the relations (Relations R_j, R_j^{-1}) between characteristics and properties, see Figure 6.

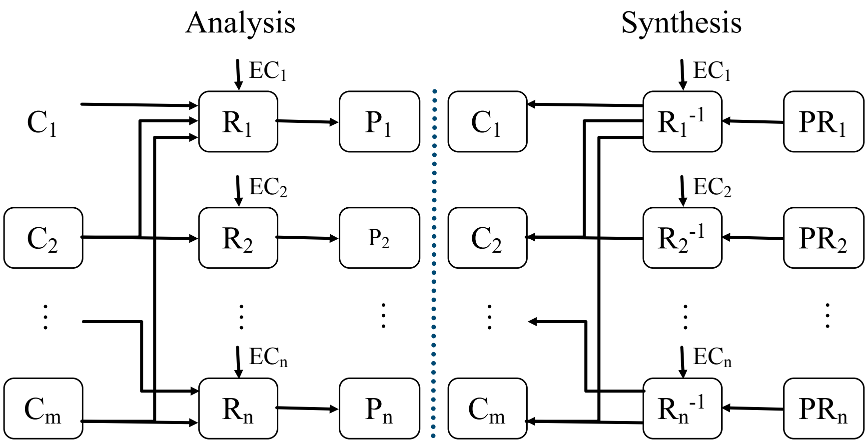


Figure 6. Analysis and synthesis (Weber approach) (Lüdeke, T. 2016)

The analysis (R_j) based on already known a clearly determined characteristics or give prognoses for non-existing product. The analysis can be done by estimates, experience, calculations, tables/diagrams, simulations or experiments. In the synthesis (R_j^{-1}), the characteristics of a product are defined. As the main target of synthesis at the product development is to find the best possible combination of characteristics. The CPM-approach will be discussed in detail to the assembly ”powertrain” for the part ”energy storage”.

5.2 Simulation

The simulation tool and developed tables, results from previous studies, enable a pre-design without considerable computing power and an evaluation according to existing development goals of pressure storage tanks, see DOE 2020 (DOE 2019) (Edwards, R., 2014). The visualized designs can be imported into CAD software programs such as Catia V5 and then optimised. A "tolerance range" for the parameters is defined on the basis of the knowledge obtained. However, it should be noted that the specific deviation of a parameter decreases over time in the product development process. After a product maturity level X, an adjustment of the pressure tank design can only be realized with considerable development effort or production costs.
Analysing of hydrogen storage systems show three main facts for the system parameter as follows:

- empty weight of high pressure storage system
- stress caused by internal pressure
- design, material and manufacturing costs

Based on a parameter study and the analysis of the axial and tangential stress, caused by internal pressure, the pipe diameter and length of the cylinder have an enormous influence on the system performance of storage systems.

By modelling the relations of characteristics and the influence of system properties, based on CPM, the optimum of all parameter can calculated. For example, during the product development process of vehicle the total mass increase about 10 percent. The powertrain has to optimize to get the same driving performance as defined. The result of the action is that the engine need more energy and the range get lower. By using a tank with more energy capacity, the defined range can be reached. But the empty weight of the hydrogen storage system is higher and therefore the total mass of the car. Another very important point is the defined construction space for storage systems. On a later point of the PDP of a new model it is not always possible to change the size. The development process of high pressure storage system is a long term and cost a lot of money. The platform and modular strategy is used to reduce the costs and integrate the new technologies for more different car models. Therefor the variation of system properties has an influence for all vehicles. This is considered in the approach, Figure 7.

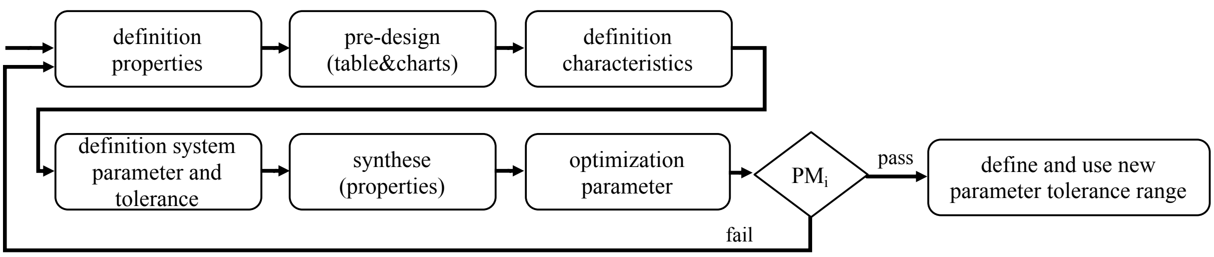


Figure 7. Approach simulation tool process

5.3 Example of application

The customer defined in the early PDP (PM0) the necessary properties as follows:

- construction space dimension: 1000 x 800 x 120 mm
- mass of hydrogen: 2,5 kg (70 MPa)
- weight of the car: 1500 kg
- hydrogen consumption: 0,8 kg / 100 km

The result of the predesign, based on the tables, shows that the new tank design reaches the development goals. The parameter d = 46 mm with a tolerance range ± 10% by PM0. After the milestone "design freeze" the designer has identified a rising mass of the head from 120 kg.
In order to continue to achieve the required performance characteristics, the electric motor power must be adjusted by 5%. The deviation is within the defined tolerances and the pipe diameter is increased by 2 mm. This is necessary to compensate for the 8% increase in storage capacity.
In the concept phase, the total mass of the vehicle is increased by another 200 kg. Only by using a high-power electric machine can the driving characteristics be achieved. This action leads to a hydrogen consumption of 1kg / 100km. The significant deviation in the temporal phase (PM 3) is, according to the simulation tool, outside the permissible deviations for the first defined parameter "pipe diameter". An alternative solution is to reduce the pipe diameter by 4 mm. However, this results in a higher tank weight, which can be ignored. However, the number of bends (per layer) increases by four. As a result, additional production costs of 20% are generated. The additional product costs can be compensated by reducing the range.
By using the developed simulation tool, changes in product properties due to external influences depending on the degree of maturity, can be calculated. The permissible deviations of the parameters are only possible in the early phase (>PM 3) without major changes. By evaluating and pointing out possible recommendations for action, a user-oriented tank design is also guaranteed according to PM 3.

6 Conclusion

Based on the tables of the previous studies of different construction spaces, an innovative new tank structure can be pre-designed. The characteristics can be defined by aligning the system properties with the development goals, such as the DOE guidelines. The developed simulation tool enables a multitude of possible tank architectures for every phase of the product development process. By adapting the characteristics within the defined tolerances, an optimization of the system properties is possible.

Another function is the definition of the deviation of the actual from the target value. The permissible deviation depends on the time development progress, i.e. which degree of maturity of the overall product has been reached. In the next development step, a weighting of the module influences and the extension by a platform approach (family model) is of immense significance.

The parameter studies show that both the pipe diameter and the length have the greatest influence on the properties of the tank. Therefore, an optimization of these parameters, the tolerable variation, is expedient in the development phase. In addition to the direct influence on the characteristics of the system, such as storage capacity, these define the production costs. As the application example shows, the storage capacity can be reached due to the higher mass of the head. However, several bends have to be produced and this results in higher production costs.

The sustainable approach is very important future aspect, because the total mass of a vehicle defines the energy consumption. At the moment the energy production based on fossil fuels. Therefore, the greenhouse emission is steadily rising. The negative trend can reduce by using renewable energy source. To guaranty a comprehensive power supply new energy storage systems and infrastructure are necessary.

Citations and References

Burr, H. (2008). Informationsmanagement an der Schnittstelle zwischen Entwicklung und Produktionsplanung im Karosserierohbau, Dissertation, Saarbrücken.

DOE (2009). US Department of Energy - Office of Energy Efficiency and Renewable Energy, Targets for Onboard. Hydrogen Storage Systems for Light - Duty Vehicles, report revision.

Duschek, D., & csi entwicklungstechnik (2015). Speicherbehälter. Anmeldung 31.07.2015. DE, Patentschrift DE102016110171 A1, WO2017021267 A1.

Duschek, D., & Vielhaber, M. (2017). Approach to an Agile Development of a Sustainable, Customer-specific Mobility Concept. EVS30 Symposium, Stuttgart, October 9-11.

Edwards, R. (2014) Well-to-wheel Analysis of Future Automotive Fuels and Powertrains in the European Context, report.

Ethiraj. S. K. (2007). Allocation of inventive effort in complex product systems, Strategic Management Journal 2.

Glynn, M.A. (2010). Fostering Innovation in Complex Product Development Settings: The Role of Team Member Identity and Interteam Interdependence, Journal of Product Innovation Management 27.

Hobday, M. (2000). The project-based organisation: an ideal form for managing complex products and systems, Research Policy 2.

Lüdeke, T. (2016). Beitrag zur gewichtsoptimierten Entwicklung mechatronischer Produkte, Universität des Saarlandes, Dissertation.

Murray-Webster, R. & Pellegrinelli S. (2010). Risk management reconceived: reconciling economic rationality with behavioural tendencies, Journal of Project, Program & Portfolio Management.

Pahl, G., & Beitz W. (2013) Konstruktionslehre: Grundlagen erfolgreicher Produkt-entwicklung. Methoden und Anwendung, Berlin, Springer Vieweg Heidelberg, 2013.

Schneider, R. A. & Rieck K. (2012). Komplexität in der Automobilindustrie am Beispiel Baukastenstrategie, 42. Jahrestagung der Gesellschaft für Informatik e.V. (GI), Braunschweig, Deutschland.

Schuh, G. (2013) Lean Innovation, Wiesbaden, Springer Berlin Heidelberg, 2013.

Stoffels P., & Vielhaber, M. (2016). Integrated Development Process of Products and Production Systems, Proceedings of the 11th NordDesign 2016, vol. 1, pp. 370-380.

Töpler, J. (2014). Wasserstoff und Brennstoffzelle - Technologien und Marktperspektiven, Berlin, Springer Vieweg.

VERORDNUNG (EG) Nr. 79/2009 DES EUROPÄISCHEN PARLAMENTS UND DES RATES, Über die Typgenehmigung von wasserstoffbetriebenen Kraftfahrzeugen, Änderung Richtlinie2007/46/EG, 14. January 2009.

Weber, C. (2000). Klassifizierung von CAx-Werkzeugen für die Produktentwicklung auf der Basis eines neuartigen Produkt- und Prozessmodells., In: Meerkamm, H. (Hrsg.): Beiträge zum 11. DfX-Symposium. Erlangen, Lehrstuhl für Konstruktionstechnik.

Weber, C. (2012). Looking at ”DFX” and ”Product Maturity” from the Perspective of a New Approach to Modelling Product and Product Development Processes, In: Krause, D.; Paetzold, K.; Wartzack, S. (Hrsg.): Beiträge zum 23. DfX-Symposium. Hamburg, TUtech.

Weber, C. (2005). CPM/PDD - An Extended Theoretical Approach to Modelling Products and Product Development Processes. In: Bley, H.; Jansen, H.; Krause, F.; Shpitalni, M. (Hrsg.): Proceedings of the 2nd German-Israeli Symposium on Advances in Methods and Systems for Development of Products and Processes. Stuttgart, Fraunhofer.