Lean product development 4.0 process determining factors

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

supervised by

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Preface

This master thesis was written as part of the educational program of the Professional MBA automotive industrie offered by the TU Vienna and the STU Bratislava, where my interest in industrie 4.0 and up to date automotive management methods encountered teachers which could satisfy my pretense of learning and understanding more about it.

That's why I would like to thank all of our teachers for sharing their knowledge and professional experience during the apprenticeship.

Especially I would like to thank Dr. Christoph Wecht for mentoring this thesis and his support during the writing process.

Since this program is extra-occupational I would like to thank my family for making it possible for me to attend the program and for their support and patience during the time necessary for learning and working on the educational subjects. That's why I would like to dedicate this thesis my partner Heidi and our daughter Helen.

September 2015 Christian Jursitzky

Affidavit

I, **Dipl.Ing. Christian Jursitzky**, hereby declare

1. that I am the sole author of the present Master's Thesis, "development 4.0", 86 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 this Master's Thesis as an examination paper in any form in Austria or abroad.

Vienna, 22.07.2015

Signature

Content

List of abbreviations

Computer aided engineering	CAE
Computer aided design	CAD
Concurrent engineering	CE
Computational Fluid Dynamics	CFD
Collaborative Product Commerce	CPC
Cyber-physical- system	CPS
Computer Aided Industrial Design systems	CAID
Digital Mock-up	DMU
Finite Element Analysis	FEA
Failure method and effect analysis	FMEA
Internet of Things	IoT
Internet of Humans	IoH
Lean product development system	LPDS
Module lifecycle management	MLM
Model based system engineering	MBSE
Module development team	MDT
Original equipment manufacturer	OEM
Product lifecycle management	PLM
Production engineer	PE
Product data management	PDM
Radio frequency identification	RFID
Simultaneous engineering	SE
Start of production	SOP
System lifecycle management	SysLM
Virtual Reality	VR

1. Abstract

“Management becomes necessary when an organization reaches a certain size and complexity.”

Peter Drucker [1]

1.1. Challenges of the automotive industry

The current automotive market introduces year in and year out an increasing number of model variants tailored to customer needs. Beside an increasing number of vehicle body types, the technological level is steep rising. Technologically highly affected areas are drive train, chassis and electronic assistance systems.

The target of development departments is to fulfill new technological requirements with the best possible quality and suitable technical solutions meeting customer expectations. The more products are customized the more flexibility in developing and producing these systems is necessary. Contrariwise the R&D capacities increase only slowly or are limited due to different reasons.

That is why efficient methods to deal with the high amount of vehicle types and technologies have to be implemented. The state of the art in developing vehicles today is characterized by keywords like lean product development, modularization, platform strategies, supplier integration, etc.

The question is if current development processes will be able to deal with the high complexity arising out of the number of variants and the dependencies between modules, platforms and subsystems? Which process factors are crucial for development departments to engineer products suitable to industrie 4.0 production possibilities?

Interestingly the production concept industrie 4.0 could provide some potential answers.
Industrie 4.0 encompasses methods for flexible, efficient production systems in extreme down to lot size one. This will be enabled e.g. by to the use of self-organizing cyber-physical systems, cluster intelligence and the availability to utilize other for production flexibility relevant data. Cyber-physical systems are characterized by the autonomous acquisition of data, networked machine to machine communication and machine learning.
Currently development processes can´t offer cars engineered as one individual item. But the production possibilities of industrie 4.0 especially the manufacturing of lot size one – would as a consequence necessitate to have an idea about a development process which could develop one specific product for one customer as well. This new high flexible development process will be called in this master thesis “development 4.0”.

The aim of this thesis is to analyze today`s vehicle development process structures and to identify critical process factors, having in mind the highest possible flexibility regarding product features. Furthermore it shall be checked if industrie 4.0 methods could be used in development to expand the possible range of complexity by using given capacities and minimizing development cost for vehicle variants in parallel. The development processes of lean product development will then be advanced to development 4.0.

1.2. Problem description

"I suppose it is tempting, if the only tool you have is a hammer, to treat everything as if it were a nail."

Abraham Maslow

Today's vehicle development systems are based on lean product development ideas (see case study Toyota) using the experience of lean production systems. Modularization and platform strategies in parallel with the shift of system technologies to Tier 1 suppliers are common methods which build the baseline for automotive development today.
Product complexity leads to high level processes. Most of these processes are done semi-automated and do need a lot of controlling effort – project management and timing are the main factors of meeting the given deadlines.

1.3. Delimitation

The subject of this master thesis is delimitated by the vehicle development process from initiating a new project to start of production - considering relevant sub processes which define the critical paths in terms of quality and value stream. This shall be also seen in the context of a product lifecycle management as defined in industrie 4.0. The role of the different development stages of a vehicle like the fuzzy front end and the influence of open innovation are considered as part of the product definition process.

Following subjects will be examined in detail:

- The nature of current automotive complexity (platforms, modularization, supplier integration, development trends) in the context of the product definition process.
- Definition of a lean product development process – using as a case study the processes of Toyota
- How to use the automotive relevant data which is available in the cloud of big data?
- The nature of industrie 4.0 methods and if these methods can be used to increase the flexibility of todays development processes.
- Which process parameters define the level of possible flexibility in a development 4.0 process?

1.4. State of the art development processes

State of the art vehicle development systems use lean product development methods.
This means they have analyzed and know their value streams and have developed efficient structures to manage the process concentrated on adding value.
Complexity is e.g. reduced by introducing modules like VWs MQB (Motorquerbaukasten – engine building kit) for engines which are used cross the existing vehicle platforms.
Cooperation's between system suppliers and OEMs become more and more important in the context of reduction development effort at the OEM and system engineering.
These methods shall reduce the development efforts for a single vehicle derivate in terms of manpower and costs – in parallel quality shall be increased as well. The

process is still the classic engineering sequence marked by the acquisition of prototypes and extensive testing to achieve a high quality in the field.

1.5. Approach to a solution

In the first step the future automotive product structure will be analyzed. Based on the thus determined product complexity the performance limits of current automotive development systems shall be identified – the Toyota lean product development system [5] will be used as a case study. In the next step the applicability of industrie 4.0 timing requirements in the product development process as part of the product lifecycle management (PLM) concept shall be questioned. Assuming that industrie 4.0 possibilities shall be supported by a synchronized development process (which then will be called development 4.0) it will be determined which processes are necessary to develop products down to in extreme lot size one.

Based on this analysis it will become obvious that a high amount of product flexibility leads to special methods in development and production – PLM (product lifecycle management) will integrate both into a high networked system using cyber-physical principles, cluster intelligence and other industrie 4.0 methods. The current state of the art development methods will be analyzed in regard to their applicability within the new framework manly influenced by product complexity and industrie 4.0 product lifecycle management. A concept for a development 4.0 method will be designed based on the identified sphere of activity, the focus will be on process determining factors.

Method: analysis & synthesis

The following steps will be performed to evaluate and conclude on the before mentioned scope.

STEP 1 – Product analysis: future automotive products analysis

Product definition process – what are future customer expectations?
Which level of complexity is possible?
How is complexity influenced by innovations and customer expectations?
Flexible development – limits of modularization and platforms

STEP 2 - Process analysis: lean product development– case study Toyota

What are the basic ideas of the Toyota product development system?
What are the key parameters of the Toyota product development system?
Which key factors determine the development process?

STEP 3 – industrie 4.0 potentials: new level of production flexibility

What are the advantages of industrie 4.0?
Which methods enable industrie 4.0?
What kind of processes are necessary?
What is the heartbeat (later called pulse 4.0) of industrie 4.0?
Which key data is necessary to operate the system – big data?

STEP 4 – synthesis: development 4.0 – methods and processes

Based on industrie 4.0 and big data timing the pulse of development 4.0 will be identified and used to analyze the PLM process and the process determining factors.

STEP 5 –conclusion: interpretation of process determining factors

1.6. Scope of the master thesis

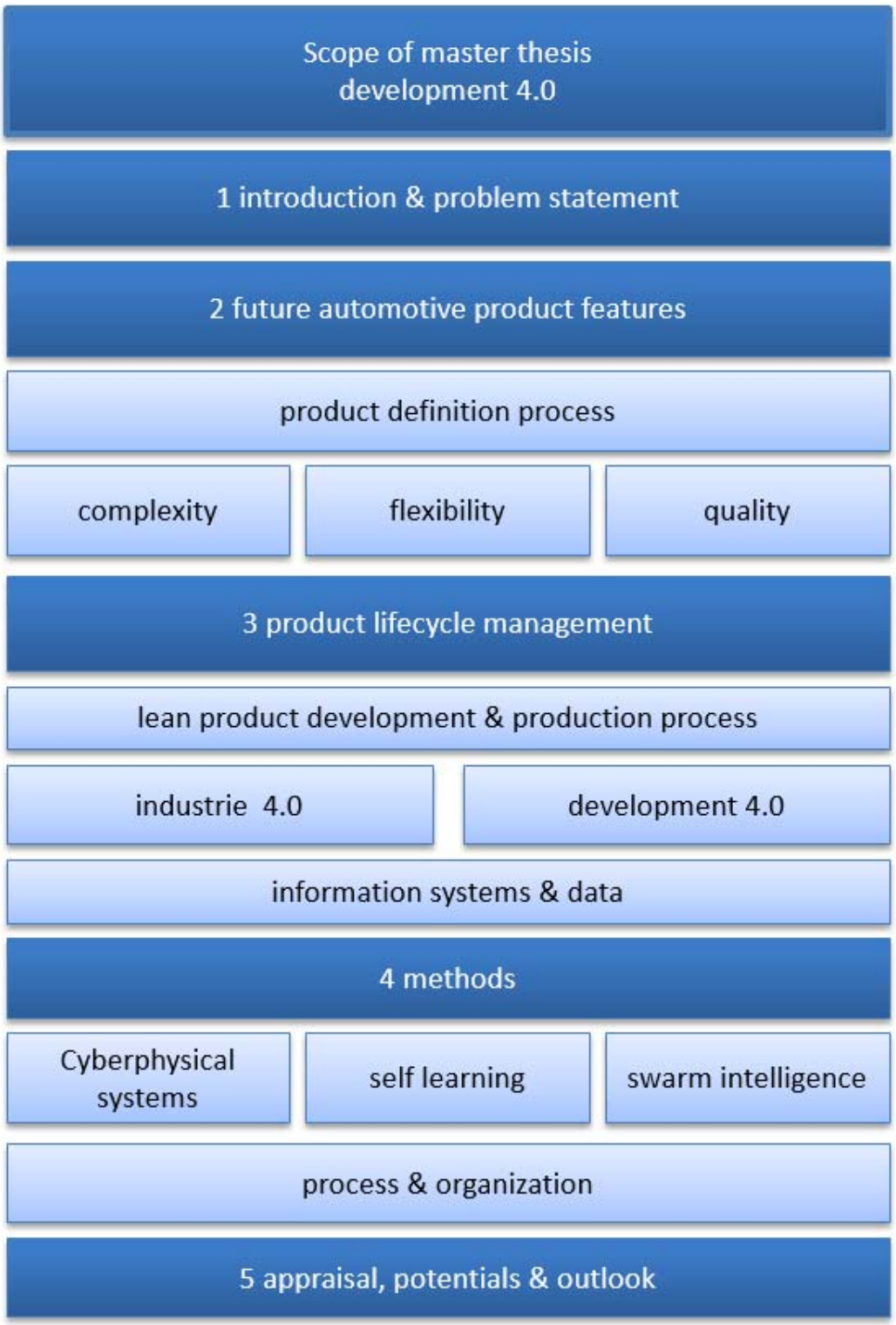

Figure 1: scope of the master thesis

2. Future automotive products

The new variety of vehicle versions in combination with high product complexity leads to the necessity of optimizing development efficiency. Industrie 4.0 offers ideas and tools to master the challenge in production and has an interesting concept of product lifecycle management (PLM).

2.1 Complexity

Automotive complexity has two aspects:
1.) Product complexity
2.) Industrie 4.0 PLM system complexity

Product complexity evolves from the number of different vehicle types and the level of technology used. Examples are driver assistance systems, emission control methods, comfort features, etc. In the future the complexity will increase e.g. due to autonomous driving technologies and the use of the internet in the vehicles. Product complexity is managed by industrie 4.0 production system and the integration of the whole lifecycle of a vehicle including the information created by the vehicles and their users. Thus a closed loop between customer usage and the vehicle creation process will be implemented.

2.1.1 Product families, platforms and modules

Products which have to meet the targets of different markets in the world must be tailored according to the regional market requirements to be successful. The move to sustain product quality having vehicle variants and new technical features is to use as much as possible common parts, modular systems (modules) and vehicle platforms. Due to the eased production process of modular systems and the thus increased quality the number of current vehicle types can be handled. In the future efficient new development methods must be identified to extend the number of possible vehicle variants further.
On the other hand the costs for production and development must be kept under control. The key is the communalization of components which leads to modularity within the systems. The modularity is made allowance in the SysLM (System lifecycle management) process, which means that the SysLM methods are applied to modules which are linked via systems.
The idea of SysLM (system lifecycle management) will be cut down to the core cell – the module and is then called module lifecycle management (MLM). This industrie 4.0 principle will become obvious in the development 4.0 process as well.

As already mentioned, one basic principle of automotive products is that there are platforms and modular systems which are common structures within the different vehicle types. The difference between platforms and modules is that modules are used cross the platforms and body designs whereas platforms differ only within the vehicle categories – see figure 2.

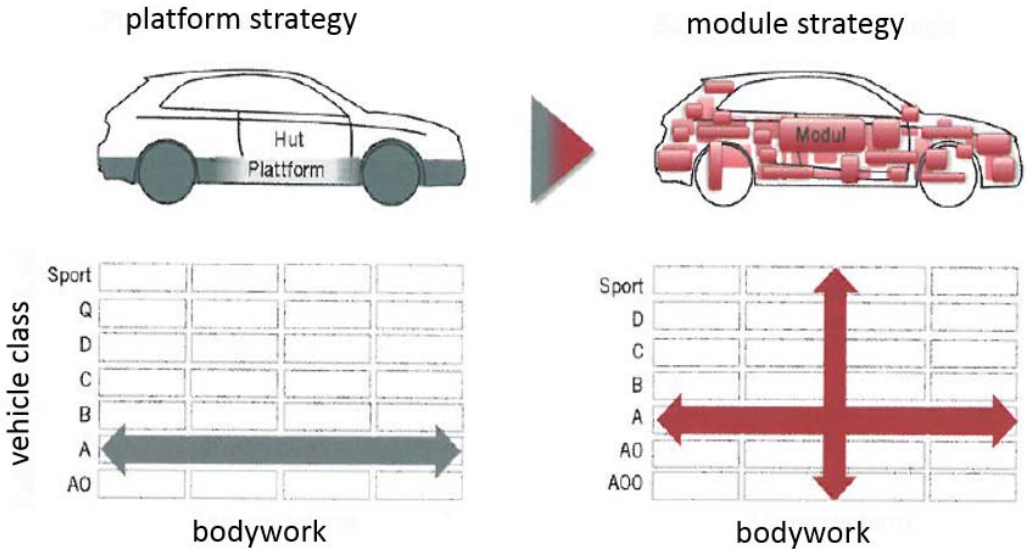

Figure 2: [28] modular platform MQB (Motorquerbaukasten) strategy Audi

A platform is a communal structure for a group of similar vehicles marked by a shared set of common design features. This features characterize the vehicle type and can be outer dimension or other limits like wheelbase, etc. The platform defines normally in which vehicle plant the car is assembled since the production lines are made for one or more platforms. Modules are components within a vehicle which can be used cross the platforms. Examples are engines, gear boxes, steering wheels, etc.

The term product families is an expression which categorizes vehicles due to their similarities – often the platform used, sometimes the size or the customer class. A product family is signified by the use of common modules, share components and similar product characteristics [33]. This means a product family can include also different platforms. The motivation to define product families is to reduce the possible variation within the vehicle categories. From development and production point of view the high variance and thus evolving complexity of products is a challenge. To reduce variance product families are defined considering the needs of specific customer groups. The sharing of components leads to economic advantages, less stock in production and reduced service complexity. Furthermore the quality level increases if more common modules are used. Communality means less complexity and thus a high level of qualification of the systems and used parts.

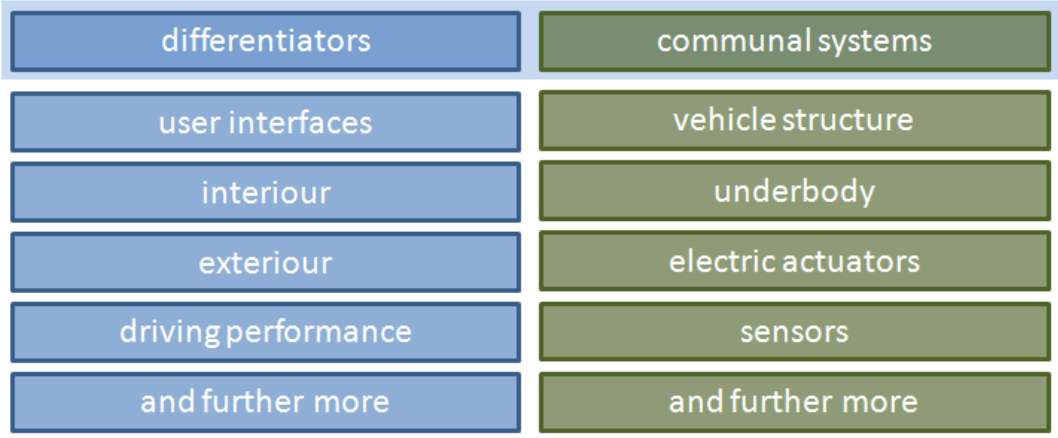

Figure 3: differentiators and communal systems – the perception of the customers

The downside of communality is the lack of vehicle distinctiveness. Since people are different and have different ideas on how a car should be - distinctiveness is necessary to meet the customer needs.
To understand which components and functions are affected by variability it is necessary to divide the vehicle components and functions into two groups. There are systems and functions which are differentiators – which means they are recognized by the customer as a value and systems which can be communalized over the platforms (communal systems), since they only need fulfill their function in best possible quality, which means no failure during the vehicle lifetime. Quality understood as “no failure” is a differentiator as well, as long as there are different level of qualities of vehicles available on the market. Figure 3 shows examples for differentiators and communalities.
[33] An article about “product family selection” demonstrates how product families are created under the criteria auf cost optimization - the subject of cost will later play a role when designing new product families for industrie 4.0.
The development of differentiators must be a core competency of OEMs – done in cooperation with suppliers. Communal systems can be developed by system suppliers on their own theoretically used by all OEMs as communal parts. Here it is important to avoid adoptions depending on the vehicle package in which they are used, which is especially at peripheral parts difficult.

Examples for **differentiators** are:

- Outer design of the vehicle
- Vehicle interior design
- Power train as source of driving experience
- Environmental aspects – CO2 consumption, sustainable materials, lightweight
- Additional functions for customers like internet connection in combination with special application to add value to the driving experience, driver assistance systems, etc.

Examples for **communal systems** are:

- Seat adjustment systems
- Suspension
- Body in white – assuming a vehicle category of a platform system
- Engine components like engine control units, actuators for subcomponents of an engine, etc.

Differentiators will play an important role within development 4.0 – they can be influenced by customer opinions about future driving needs – like autonomous driving or electrification of the powertrain. OEMs which are able to react on an evolving customer demand quickly will have a market advantage. This is proven by our current reality where simple subjects like the availability of USB connectors or the usability of coffee cup holders can influence the opinion of a customer. These differentiators are one factor amongst others that lead to product complexity [41]. The cost of complexity become relevant if the product portfolio exceeds a certain range – or the complexity within platforms gets too high. The correlation between complexity, influenced by our differentiators and costs is shown in the next picture – figure 4. The optimum regarding costs and customer value is an important factor. From a cost point of view it is necessary to check the level of the complexity and the related costs as well when development 4.0 tasks are defined – as will be described later.

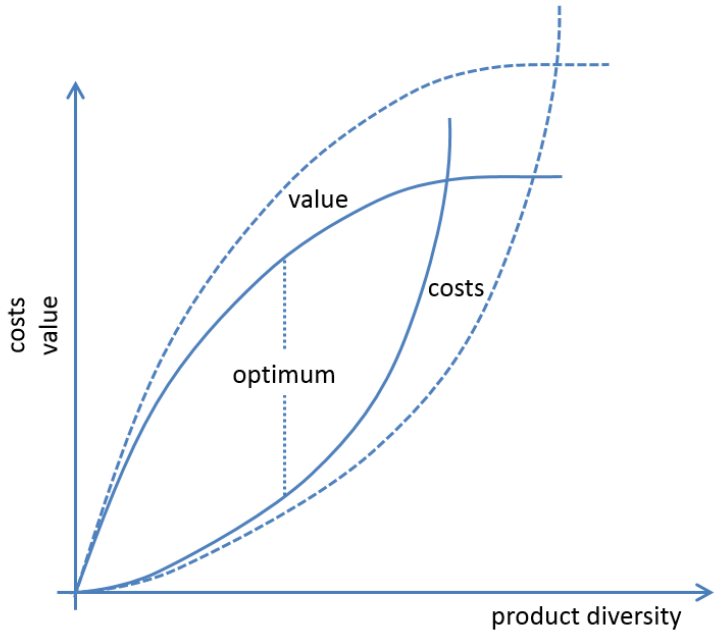

Figure 4: the costs of complexity [41] – according to Schuh &Schwenk 2001 p 24

2.1.2 Ilities & Ivities or customer value

To structure differentiators and rate them it is necessary at first to understand how to identify them. [35] Is a good example for the early stage of automotive data analysis - “big data” was used to identify trends. In this example the trends are long term trends, which could be handled by a conventional vehicle development process. The challenge of development 4.0 will be to evaluate quick arising trends (which are of customer value) regarding stability and sustainability – proper software tools and filters are necessary to detect real trends out of big data.
The fact if vehicle properties are of customer value and accepted by the broad range of customers[1] becomes obvious often after having put the product into series. The

[1] Normally the vehicle targets are created based e.g. on existing products, competition analysis and other trend predictions – vehicles in series confirm then if the assumptions made at the beginning of the development process where correct.

term used to describe these valuable properties is “ilities”[2] – another expression is “lifecycle properties”. To respond to the ilities it is necessary to design a vehicle in a way that the ilities are fulfilled. The more variation in the systems and modules can be avoided – the higher is the chance to fulfill the ilities, simply because the development capacities are limited. Not every aspect of customer needs can be realized immediately – due to time necessary for development or the availability of technology.

Based on 1.3 Million scientific article published between 1884 and 2010 ilities were analyzed [35] by counting how often the trigger word was mentioned in automotive relevant publications.

The results for the most frequent 22 ilities is shown in figure 5. The ilities are normally co-dependent – that means there a special group of properties which are often mentioned together in a text.

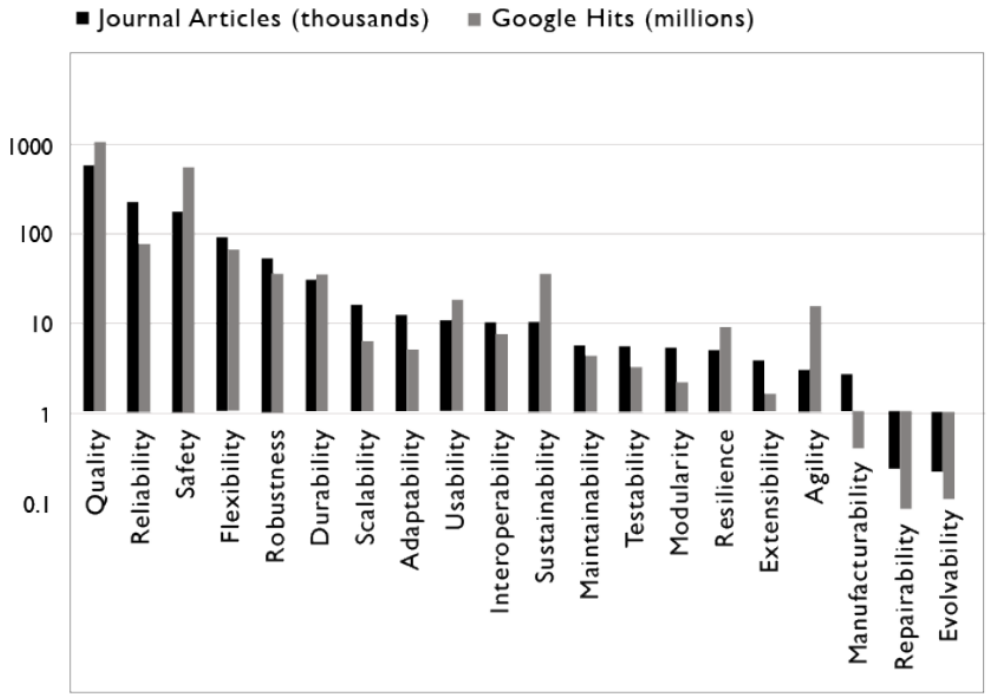

Figure 5: [35] – development of ilities between 1884 and 2010

The rating of ilities changes as social changes occur - the way the ilities change can be analyzed using big data methods.

[2] The word ilities comes from the ending of many analyzed and identified properties like flexib**ility**, maintainab**ility**, etc.

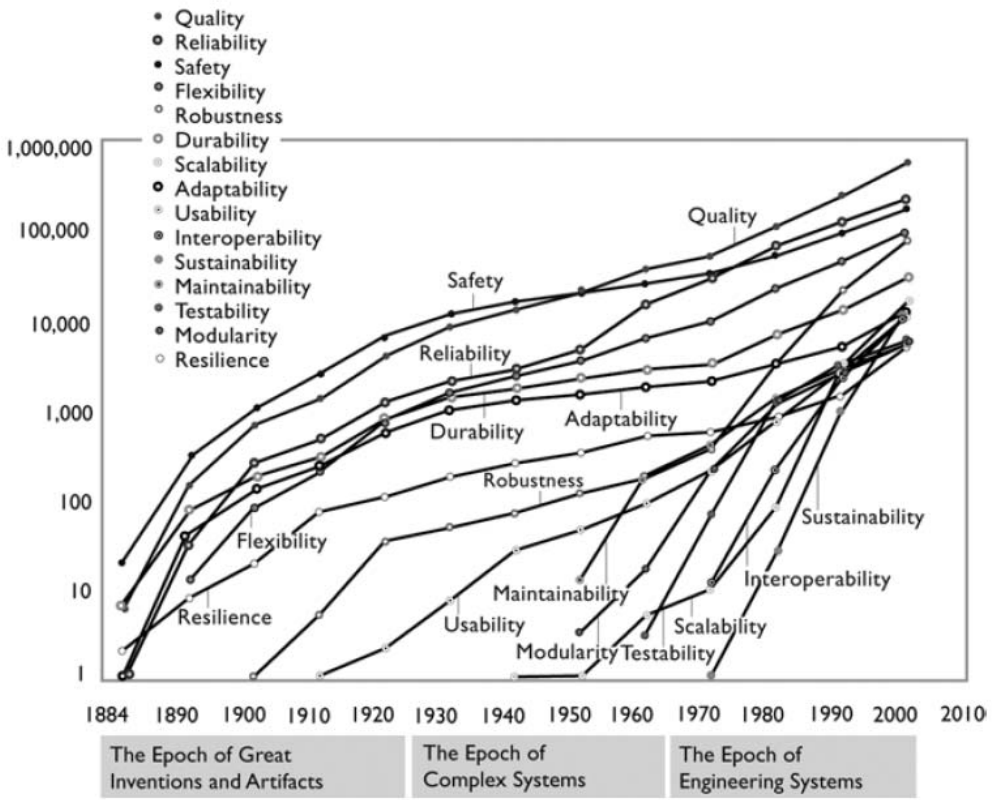

Figure 4.2
Cumulative number of journal articles in which an ility appears in the title or abstract of the paper (1884–2010). Source: Inspec and Compendex, accessed via Engineering Village (8 August 2010).

Figure 6: [35] – time dependent trends for ilities

Figure 6 illustrates how ilities vary and develop depending on time. The absolute increase of trigger wordings is caused by the amount of data available and thus not surprising. But the really interesting thing is when new requirements evolve in this case starting in 1950 like sustainability, scalability, modularity, etc.
Obviously these subjects are important to manifest the customer value of the vehicle – they are strong selling arguments especially if they can be used as an already described differentiation property.
As mentioned this is just an example – it will be important in the future if big data is analyzable to understand which of these properties have value for the customer and how the car system layout looks like which offers the ilites as a selling argument.
In recent times new terms of importance occurred – like connectivity and adaptivity – that's why I would like to introduce the word "Ivitiy"[3] additionally to "Ility".

2.1.3. Industrie 4.0 lifecycle management - product complexity

The development processes must implement quality moves (like FMEA, simulation, etc.) to ensure the product quality. The similarity of systems (due to modular concepts) can be used to adopt and optimize the tools within the production and development environment.
[14] Current product complexity is already enormous. For example a Ford Pickup F150 has today 16 possible vehicle equipment options which can be chosen by the

[3] "Ivity" as the suffix of e.g. connectivity

customer to obtain his personal model. This means that combinative number of 654 billion different F150 possible vehicle combinations. Audi, BMW and Mercedes offered in 2012 66 different vehicle models. VW has 280 vehicle types in his portfolio. The prediction is that in Germany in 2015 there shall be 415 new vehicle types introduced on the European market. In the 1970s the typical vehicle lifetime was 8- 10 years until a new model was introduced. Today the lifetime is 4-5 years. The development time for a vehicle was reduced in this time by one third. The product complexity is managed by flexible production systems and a high usage of platforms and modular systems.

2.2 Flexibility

2.2.1 The necessity of industry 4.0 for new product structures

The number of combinations of different vehicle equipment options leads to a high effort in production to plan and control the process. The control process is already highly automated but still vulnerable for disturbances since production plans often must be changes manually. Industrie 4.0 introduces the intelligent product.
The intelligent product enables 4.0 manufacturing concepts in the context of product lifecycle management. Products become independent from the centralized production planning – know which step is the next in their production process and when they have to be finalized. They decide which machine or assembly step can be done depend on the information created in the cybernetic production environment. The complexity is still there but can be handled by the use of intelligent components.

2.2.2 Industrie 4.0 product properties – smart products

[14] The product becomes an active element – with following core properties

- Clear identity - Product ID for each unit
- Can be geographically localized
- Is part of a cyber-physical system
- Knows how and when it was manufactured
- Documents its own history in terms of customer relevant data

Today`s products are more complex and there is a clear trend to individualization. Industrie 4.0 products are mediums to transport and create information relevant for the product during the creation process and the use by the customer. This information can be collected by big data objects and employed to continuously improve the product and its successor.
The product a **smart object** – produced in a smart factory as an improvement of the current lean production factory. Another key feature beside the properties mentioned above is that a smart product stays always in contact with the manufacturer. In the first step for service purposes – but the in the second step to understand how it is used to improve it within the running development process for the next product generation.

Development has in the process of information exchange with the customer and its product an important role.
The product reflects in the context of the usage by a customer how it is used and if the product properties need improvement. Thus the product can be tailor-made based on customer needs.
To realize the use of the data some core technologies are identified [14]:

1.) Mobile computing
2.) Social media
3.) Internet of Things
4.) Big data
5.) Analysis and prediction

Cars are by nature mobile systems which are already connected today with satellites for navigation. Todays navigation systems are options but in 2018 a mandatory emergency call system shall be introduced in new vehicles [46] in the

European Union. Thus every vehicle will be accessible via satellite for data exchange.

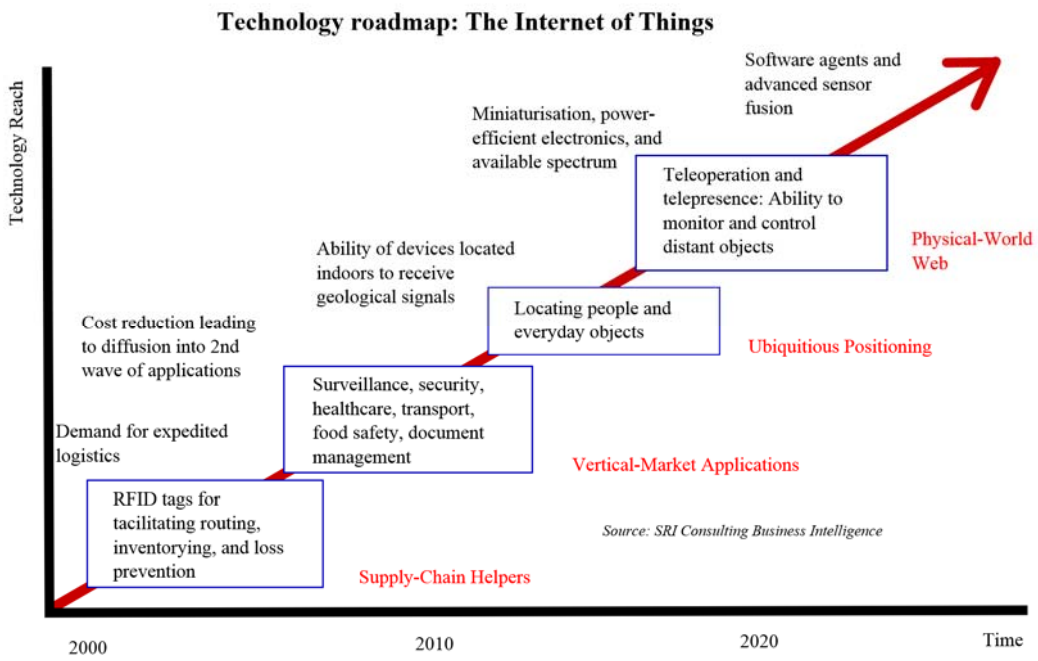

Figure 7: Internet of things [47]

The internet of things (IoT) introduces a new data structure (figure 7) which creates a huge amount of data called **big data**. Big data is by nature unstructured data which cannot be handled by conventional information processing technologies. The term big data is also used to describe new technologies capable to deal with enormous amount of complex information. Another aspect of big data will play an important role. This is the answer to the question who owns big data and how is the data confidentially secured? Current laws and regulations regarding the acquisition of data must be checked regarding the possible consequences if big data is used. In my opinion data should only be used if the customer of a vehicle allows the use of the data of his vehicle.
Privacy is an important factor when big data is created in a cloud. [45] For example since 1. October 2014 the electronic e-call system is mandatory for new vehicles. Due to this technology a continuous usage of data out of the vehicle will be possible. In principle the possibility to acquire data for the improvement of the vehicle by the OEM is positive – assuming that the customer allows this usage of data. The fields of usage can be extended to a large range of products – e.g. assurance companies could be interested in driving profiles to offer different rates.

Figure 8 shows examples of technologies how a vehicle and its environment can create mobility relevant information. The mentioned laser, radar and cameras in a vehicle describe only the part where a car interacts with the street. This is only a small section of sensors and systems in a vehicle which creates usage relevant data. Further examples are the use of features like internet, telephone, driver assistance systems as well as fuel consumptions and driving conditions which could be of interest to improve a vehicle.

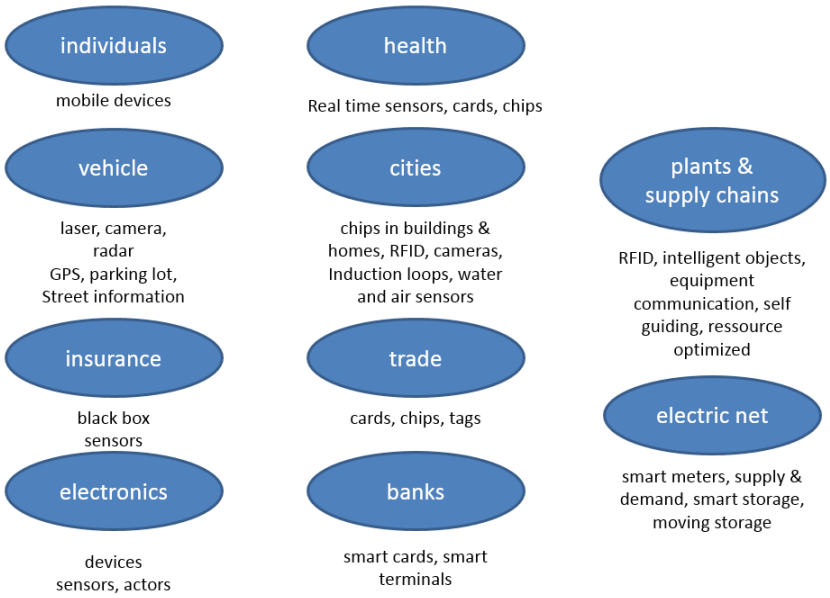

Figure 8: intelligent sensors which are used for the IoT. (Source IBM) picture 3.4 [14] – picture modified

2.3 Product quality

Quality is one of the most important subjects during the lifecycle of a product. The expectation of the customer is to have a car which has zero defects over lifetime. In parallel more and more features are offered in modern cars. The more systems and modules are available the higher are the qualification efforts to offer perfect quality. The key to optimize quality is to improve the development processes. The simulation of product properties on component, module and system base is very important and has as well a role in development 4.0. Theoretically if everything could be simulated the necessity of extensive functional and durability testing can be discussed. To reduce the range of this master thesis the potentials of CAE are investigated only as a potential in the context of process determining factors. The focus will be on the identification of these factors having in mind to create the best possible product quality due to optimized processes.

2.4 Product complexity – summary

Future cars are high complex since demands of customers are getting more and more specific regarding vehicle types and features needed. The most important ability is to identify new customer needs quick using advanced computational methods based on big data raw information which identifies ilities and ivities of customer value. The industrie 4.0 production concept allows to product a high variability – which will be described later. The key of success is to implement new arising needs quickly and with highest possible quality in a PLM process, especially in a development 4.0 sub-process.

3. Product lifecycle management

The time to market for a new car or new features is characterized mainly by two factors.
The product development process is the first factor to bring new products within short time to maturity phase. The second factor is the production method, which means the used technologies to create components of a vehicle. Regarding production industrie 4.0 offers methods to create the highest possible flexibility within a production system. The development state of the art methods shall be analyzed regarding potentials to create high flexibility in the first step and then adopted based on industrie 4.0 knowledge to create a robust and short development process which then will be called 4.0. As starting point the Toyota lean product development process shall be used as case study for a current normal development process.

3.1 product development process

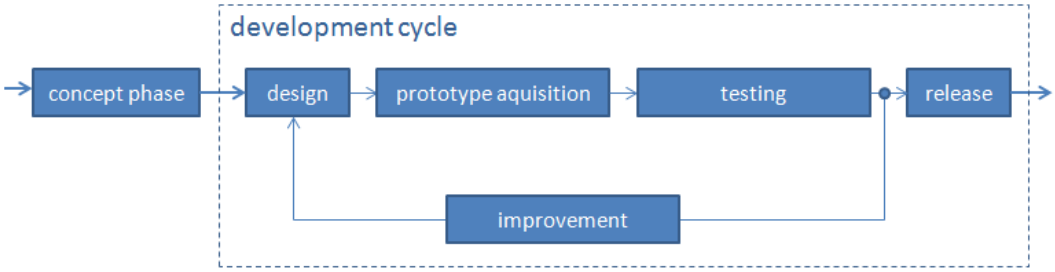

Figure 9: conventional development process

Today product development (figure 9) processes (e.g. at Toyota) are characterized by a closed loop structure which consists of a concept phase where the rough draft for a car like usage, principle size, performance, fuel consumption, etc. are defined. This is followed by a design an simulation phase where the layout of the platform and the modules are elaborated. After the acquisition of prototypes the testing of the vehicle and its modules starts. Based on the test results the components and systems are improved. In the last step the durability, function and quality of the vehicle is confirmed and the new car is released for production. The different fields of action are shown in figure 10.

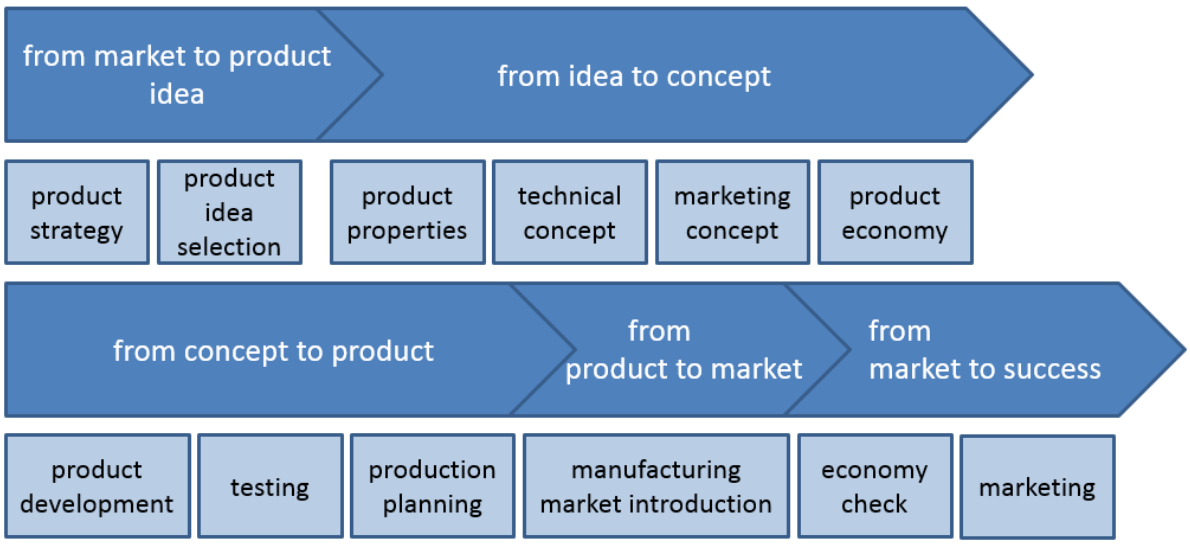

Figure 10: Source [12] page 30 – model of the integrated process chain

As part of the development process the possibilities to produce a product under the condition of series production in a vehicle of component plant are developed as well. The production requirements are an important factor during the design of the components.
Figure 11 shows a possible product development process in the automotive industry

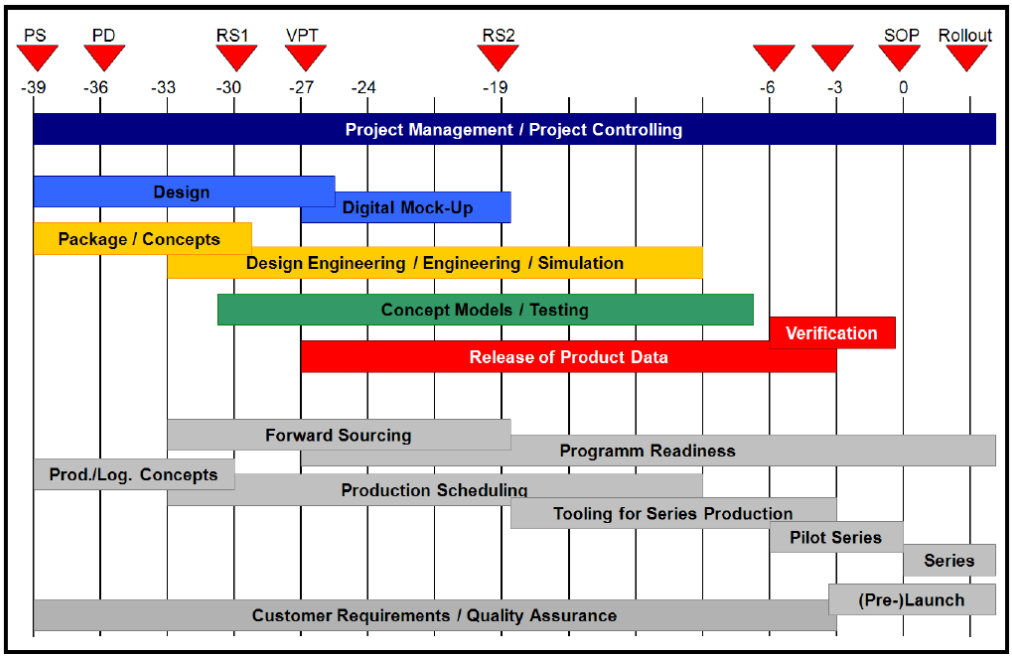

Figure 11: source [26] – development lead-time in automotive industry

Development and production of vehicles are core processes, surrounded by marketing and sales activities. These activities do create hardware but also an image of this hardware including the processes it a virtual reality. The totality of these factors and the way how they are handled is described by the term product lifecycle management – PLM or System lifecycle management SysLM (figure 12).

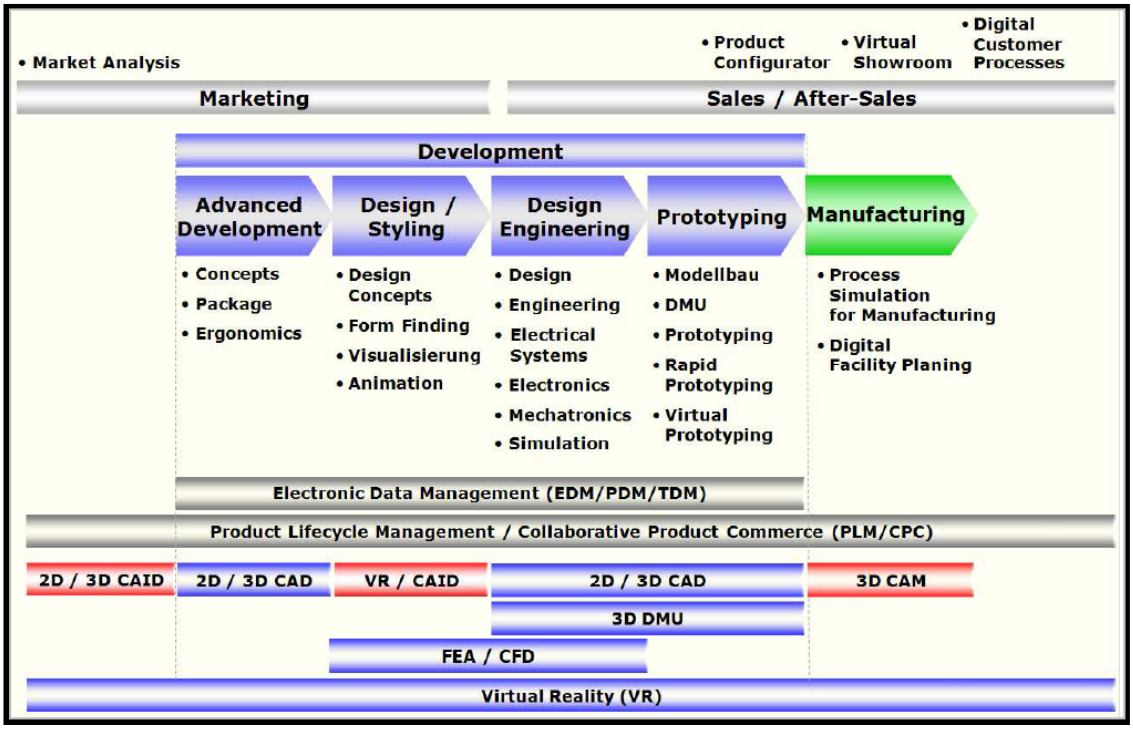

Figure 12: Source 26 – integrated virtual product development process

To ensure the product quality different guidelines are used in the world. German OEMs and suppliers use the guideline [13] – VDA (Verband der Automobilindustrie) Schriftenreihe to establish a consistent quality management systems within the whole supply chain – figure 13.

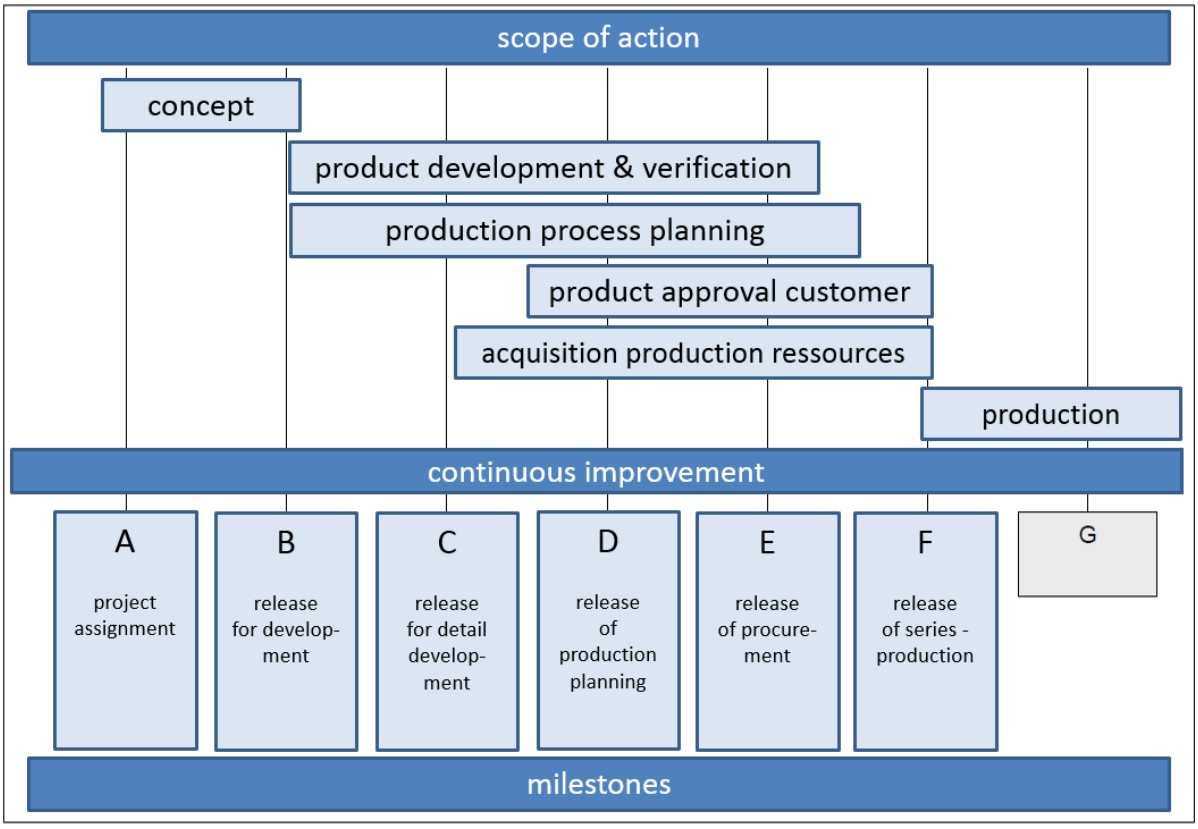

Figure 13: [12] page 64, [13] scope of action during development

During the development process different grades of maturity are checked when the milestones A to G are reached. Milestone A initiates the strategic phase, by defining the framework and targets of a vehicle project. Within the strategic phase decisions regarding product portfolio, technical and economical boundary conditions are made. If the strategic orientation is done the concept phase starts - Milestone B is reached. Milestone C is the end of the concept phase where product concepts and business cases are evaluated – the project is ready to be decided or confirmed. At this point of time still many details are unknown, but the main concepts regarding targets of the vehicle, like fuel consumption, driving performance, design concepts, innovations to come are clear, as well as the profitability of the vehicle project. If the achievability of the targets is confirmed the development of the details is initiated. Within this phase the iterative design and testing process of the parts to be brought into series is managed. The production process must be developed in parallel to (or as part of) the product development – milestone D.
At the end of milestone E the product, all necessary machinery and facilities are released for acquisition. The testing has to be finished between milestone E and F. At milestone F the product is released for series production, which means the suppliers get the permission to produce their components corresponding to the OEM orders.
To develop a vehicle a time of approximately 5 years must be considered (figure 14). The strategic phase is a continuous process within a car company. The concept phase starts approximately 50 month before SOP, series development 36 month before SOP. The processes to assemble components of a car are developed in parallel.

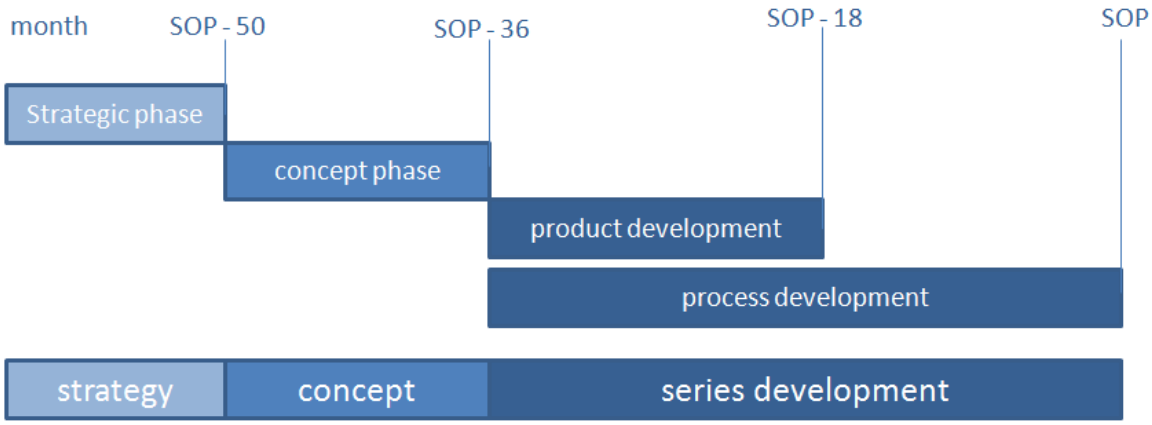

Figure 14: development time source [23]

The time for development of a component is determined by VDA maturity grades A-D. These grades are to be reached within the development process. Timing in the context of quality is very important as will be shown later when the term pulse 4.0 is introduced.
The grades from A-D are

A-sample

- Package sample
- Emulated systems
- Restricted function and use

B-sample

- Restricted function
- Not all functions implemented

C-sample

- Corresponding functions in regard to a series part
- Already out of small series tooling

D-sample

- First series parts

To achieve all those quality levels different timings for components and systems are necessary. If systems use parts which are already in series they can be reworked in shorter time than components which are totally new.

3.2 Lean product development a case study

3.2.1 The Toyota lean development system

„Plan carefully and execute exactly“

[5] Toyota adopted its development process based on “lean” principles starting in the early 1990´s. The target was to eliminate late product design changes – which lead to variation and poor quality. To realize the better quality Toyota emphasized front loading and concept work. Front loading means to spend at the beginning of the development process as much brainwork as possible to create stable design concepts.
Another motivation of the front loading process and the introduction of platforms is to reduce vehicle development costs and development times drastically.

Toyota tried to minimize variation early by

- standardizing systems and
- creating an early share – involve all team members early

One of the first ideas Toyota introduced was the vehicle platform system. The platform is seen as the base for different vehicles (hats). It contains power pack (engine and transmissions) front, center pan, rear end structures, front and rear axles with suspensions, frames and sub-frames, brake and electrical systems, bumper beams and fuel tanks.
These components define drivability and basic quality structure. Common front end structures contribute to similar crash properties, reduce iterative testing requirements and enable a standardized package situation in the front end. The platform can be stretched or enlarged to enable a better variety of vehicle variants. Due to the use of platforms less prototype tools are needed und thus the development costs are reduced.

All these components are invisible for the customer. Advanced technologies are also enabled within platforms as far as they can be foreseen in form of allowances. New technologies are reviewed regular and checked if and how they can be incorporated in the new product platforms. The suppliers participate at these reviews and support new technologies – this is a prerequisite to be and stay a primary supplier for Toyota. New concepts are only brought into series after having tested them on a broad base of simulation and prototypes – Toyota is conservative regarding the introduction of new technologies. Short vehicle cycles are necessary to incorporate new technologies in time. Certain lead models are selected to introduce advanced technologies to lead customers before they are brought into mass production.

Some facts about platforms at Toyota

- ➔ They are seen as a source of quality
- ➔ At Toyota platforms are used up to 15 years.
- ➔ On average 7 vehicles are produced based on one platform
- ➔ Too much product communality can lead to poor product differentiation.

Another key process at Toyota is the set based concurrent engineering (CE) process. Within this activity alternatives are evaluated in an early stage. This is done e.g. for the design of a new vehicle.

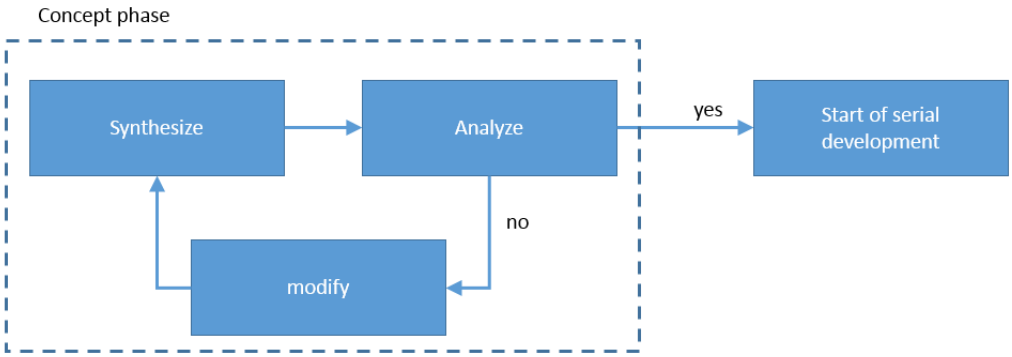

Figure 15: process of a concept phase

During the iterative selection process of design alternatives – the best ideas are traced in parallel, having in mind the set given for concurrent engineering. A “set” is an amount of boundary conditions which often leads to target conflicts. This set with its implicit target conflict has to be resolved, which is done by narrowing down the alternatives to one product solution. The decisions made within this parallel process of tracing different solutions are always targeted to optimize all of them in small steps. Thus the concept is continuously improved. The final decision is made at the end of the process based on the different repeated optimized options. During the process the focus on the vehicle system is important. Subsystems are seen as part of a vehicle system and decisions are made based on their valence for the vehicle as a whole.

All concerned departments are involved in the decision finding process. Subsystems are called modules – the departments participate in form of cross functional module development teams (MDT). These teams cooperate with the vehicle designers from the beginning of a project. The approach at Toyota was different to other OEMs in the past – design and functional module concepts are evaluated in parallel instead of making a design and then evaluating if the modules can be incorporated. The SE Team spends also time in the production plant to understand the manufacturing requirements of the plant operators and engineers. The target of these meetings is “mizen boushi” which can be interpreted as prevention of mistakes.

The members of these module teams come from development, led by a senior engineer and from production departments. Thus the product functionality and also the manufacturability can be evaluated at once. Priorities are set based on both aspects – a product should have superior functionality but must be able to be manufactured in a lean production environment as well. Part of the MDT is the SE (simultaneous engineering) Team – the SE Team consists of different engineers in the development department combining the disciplines of design and testing. The SE team leader is responsible for the component the SE team designs. Responsibility is understood as being in charge of function, quality and costs.

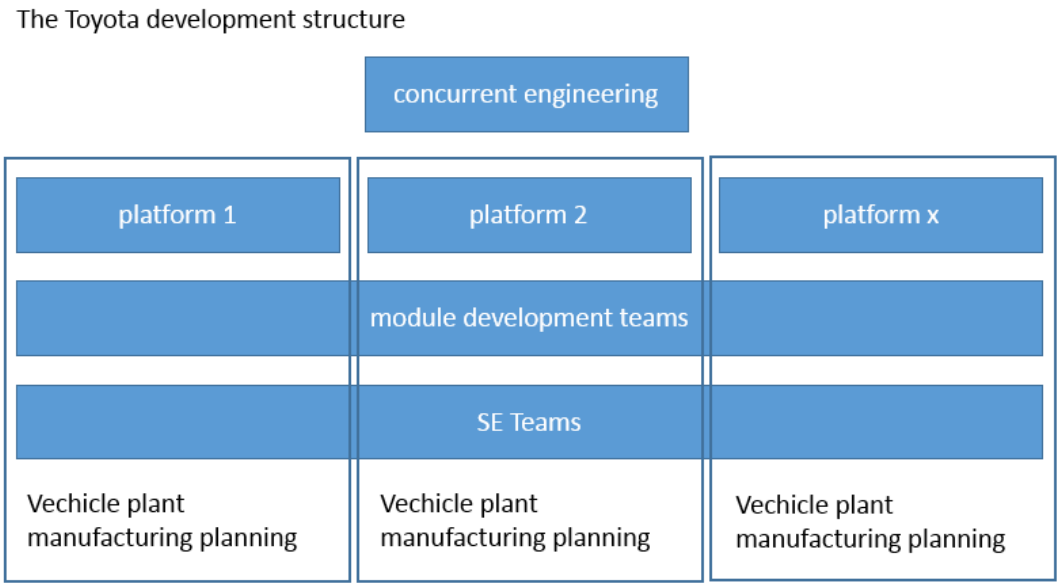

Figure 16: [5] Toyota development process structure

Lower level activities are standardized - e.g. if a new component is designed the manufacturability has to be evaluated – this is in the case of Toyota an example for a lower level activity. To standardize the evaluation process different tools are used. The PE (production engineer) measures the manufacturability based on common architecture standards and design rules. A component quality matrix is used to check if the quality pretense is fulfilled – the lessons learned regarding continuous quality improvements are also incorporated in the quality matrix. Based on standardized knowledge the evaluation if a part can be manufactured at an acceptable price can be done with a good decision stability.

Furthermore common architecture features and the principle of reuse is applied. If this concept is executed consequently the development costs are reduced and the vehicle quality is improved. Carry over parts (modules) within different platforms are standard - see also section product structure.
The process is reviewed continuously and the concepts are evaluated based on vehicle targets and their reachability. The targets are set based on the “customer first” mentality which puts the customer interest into the focus when targets being set.

3.2.2 The Toyota meeting culture – and the pull principle

All information necessary to attend at a meeting is provided to the participants before the meeting. The team members have time to prepare before they attend the meeting. Often they try to reach consensus between the participants before the meeting – thus an efficient meeting culture is created.
All processes at Toyota are linked by physical flow and information flow. Within a “flow” process the pull principle is leading, thus overproduction and jam of material is avoided. In production this means in the optimal version that a one piece flow is achieved. The creation of stores for material and is minimized. The flow principle affects also the suppliers on Tier 1 level – this is called levelled flow which is one of the main principles of Toyota lean production system.

These principles are transferred into the development department which is seen as a “knowledge work job shop” characterized by multiple simultaneous developed vehicles like different car are produced in the vehicle production plant. In contrary to

production units where the flow of material is optimized in development information flow is the main principle. The other difference between lean manufacturing and lean product development is the cycle time. The cycle time of a development department is defined by times for concept work, design, acquisition of prototypes, testing and verification and the lead time for industrialization of a component. In development the cycle time is much longer than in a manufacturing facility.

3.2.3 Value stream mapping & seven wastes

To understand and optimize the information flow principle the value stream mapping method is applied. Like in production the flow of information is documented – single steps are linked within the timeframe. The target is to identify and eliminate waste. Action plans are derived and thus the process is optimized.

The value stream consists in principle of all tasks which are necessary to qualify a product – the emphasis is on design work and functional integration of systems, components and modules.

As in production theory - seven wastes are known in development.

- Overproduction (more done than necessary for the next process step)
- Waiting (for missing material and or information)
- Conveyance of material an information (moving from one place to another or speed of information transfer)
- Processing (not necessary process steps)
- Inventory (information or material not being used)
- Motion (unnecessary meetings or reviews, long travel distances)
- Correction (it is better to prevent errors than to correct them)

The motivation for value stream mapping is to find barriers which prevent a continuous flow. If those barriers are identified waste can be eliminated.
Typical problems are for example working in large batches (which can be vulnerable to disturbance) or different centers of competence which have cycles that don't fit to the cycles of their process partners. Different cycles lead to waiting times, one of the seven wastes. Overburden could be a reason for different cycles in creating results. Another problem is unexpected work, which has as consequence delays due to the "double" usage of capacities that are planned for the normal workflow.

Important findings out of the lean product development concept which was examined by using value stream methods at Toyota are

1. Product development is done in large batches – defined by milestones or stage gates. The development cycle time is proportional to the cycle time of the development of the components. The component with the longest cycle time defines the cycle of the vehicle development process.
2. The capacity level of development departments must be balanced, the processes should be in "Tact"
3. Unexpected workload is assigned to special projects to not disturb the normal development process
4. Discipline at task execution and project management (timing is essential any deviation leads to uncontrollable variation)
5. The law of utilization says that if the usage of capacities is increased the average cycle time will increase in significant nonlinear way – if no changes on a different level are made.

6. Variability has a similar effect, the average cycle time increases and the work in progress gets more. Typical variabilities are – missing or fault information, missing basic data, etc.

These laws are valid for production as well as for engineering. Process logic and stability are very important. Instability in the process like unstable design data, unknown functional data leads to decisions which will create variability.

3.2.4 Planning and synchronization

Another main subject is the levelling of workload. The process begins with the portfolio planning procedure. The start of productions (SOPs) are normally staggered regarding timing. Within the portfolio planning process the current portfolio of a company is analyzed and optimized under the criteria of business economics. The change of market forces can be fast. The ability to react to these forces can be an important business advantage – the more reactive development is – the more business and portfolio optimization is possible during the development process.
To implement successful procedures it is important that every participant in the cross functional team understands the roles of his process partners. Activities are sequenced, coordinated and linked. The stage of cooperation is reviewed frequently at design reviews. The target of these efforts is to create a predictable product development process which is necessary for the planning of capacities. The staffing is flexible – more people are cooperating in the industrialization phase.
Tasks are standardized in regard to create predictable results which enables the necessary development flexibility.
The prototype shops have to be integrated in the development process flow. The prototypes needed must be predictable in regards to the necessary machines.
The management checks the status of the work progress on a daily base by walking through the shops and discussing current issues directly in the departments. Information is made visible by “andon” boards. The andon board is normally used in production to show up the status of the lines, e.g. how many vehicles are produced, the number of workers, etc.
The “pull principle” is also executed consequently in product development. Like in production the product is pulled to the customer – which is the partner of the next development process step. That means an intellectual production step is only initiated if there is a demand. In product development the system known out of the lean production process is implemented for information flow. Here the right information is created at the right time and submitted to the person who needs it. All activities are linked by the flow principle. The idea is to create a continuous information and result flow without waste.
The pull principle is implemented in product development by using the cross functional team as an equivalent to the production cell which realizes the “one piece flow” in vehicle production. Production cells are arranged in way that buffers are avoided. Thus the continuous flow of material is achieved. The analogy to material flow in production is information flow in development.

3.2.5 Reduction of variation, flexibility and predictable processes

For Toyota it is important to reduce variation also in the development process – thus queuing in tasks shall be prevented. The repeated use of platforms is a good example for the standardization used in product development.

Three field of standardization are identified

1.) The use of standard designs – modularity & platforms
2.) Standardized processes – like task sequences in the development process
3.) Standardized engineering skills – all teams should have the same level of engineering performance

The tools used are checklists which are updated based on the growing knowledge base of the engineers. This shall prevent that important facts are not considered during the development process. From a content point of view they can contain interface descriptions, manufacturing requirements, etc. Checklists are reviewed using the Plan-Do-Check-Act cycle (PDCA).
Another important point is that the cross functional team owns the authority to fulfill the requirements of the checklist of their product.
The standardized process is necessary to understand who needs what and when in the development chain. The fulfillment of this process requirement must be reviewed on a regular base – processes that are out of the development "Tact" are then synchronized.
Sometimes there is a necessity to outsource work to suppliers – the synchronization of these parallel process must as well be ensured.
To optimize the flow also in the prototyping process products are classified e.g. for die parts from A to D - to differentiate by criterions – here e.g. the size of the die necessary and also the time necessary to produce the hardware. This is respected in the program planning – here the releases of the parts are timed to achieve an optimal flow in hardware allocation. The parts with the longest lead times define most of the times the total time for development – the critical path must be monitored very carefully – this will be also an important process factor for development 4.0.
Thus the cooperation of people within the process and the use of tools and technologies is aligned. The four subsystems people, process, tools and technology are in the focus of Toyotas product development strategy.

3.2.5 People

People are guided by the spirit of teamwork, continuous learning and improvement. It is a special social culture marked by the same values and beliefs supported by the management of Toyota.
Although Toyota has as matrix organization where a program boss has its role as well as the leader of function, which means every engineer hast two bosses - the role of the chief engineer makes a significant difference. The chief engineer has the overall responsibility – thus conflicts of interest are avoided. The chief engineer has no formal authority over the developers – that means normally a group of only about 6 people is reporting to the chief engineer – he has the responsibility but in fact no direct authority over the people. His focus is to deliver value to the customer. The different departments are led by general engineering managers – which keep track of the different projects and the capacities in their groups.

The basic tasks are managed within the teams (SE-Teams) by the "bureaucratic manager" which operates based on standardized checklists as described before.
The "group facilitator" integrates the work of the different SE Teams and their "bureaucratic managers" he or she brings in the ability to review and change technical concepts and coordinates people with often different opinions. The system designer has the overall system in the focus, checks the specifications and prepares them for detailing in the SE teams. The group facilitator and the system designer report to the chief engineer, who follows a concept and leads the integration. In difference to other companies Toyota seemed to be able to avoid compromises and

a time intensive organizational structures through its cross functional organization. The organization is in principle product focused and chimneys as a platform orientations are avoided. The spirit of cross-functional thinking across different platforms is one main characteristic of chief engineers working at Toyota. Meanwhile other companies have already set up similar organizations as shown by the example of the Toyota LPDS.

Product planning	Functional departments				
	Design	Body	Chassis	Engine	Test
Camry	▲	▲	▲	▲	▲
Corolla	▲	▲	▲	▲	▲
Celica	▲	▲	▲	▲	▲
Etc.	▲	▲	▲	▲	▲

● chief engineer ■ functional general manager ▲ PD engineer

Figure 17: [5] Toyota Matrix organization

Figure 17 shows how the chief engineers for different vehicle platforms cooperate with the functional departments. A double reporting to CE and general manager of the department is avoided since the development engineers of each department report only to their own general manager and not to the chief engineer structure. A direct report to the chief engineer is in special cases in principle possible but not the daily business reporting procedure.

During a time when it was necessary due to competition and labor costs a new idea was developed. To improve the cooperation between production engineering and product engineering the module development team (MDT) was created.
The intention was to modularize systems across the platforms to save capacities. The advantage is the integration across the platforms, beginning in an early stage of the development. Thus the coordination across different platforms and functions could be improved and the effort reduced.

3.2.6 Integration of suppliers

In the late 1990 most of the automotive companies began to outsource more and more engineering and development tasks to their suppliers – which became then responsible for the system engineering. The OEMs reduced their in house engineering effort on components to concentrate on the integration of systems. The target was to lower the development costs and to get the cheapest supply of systems due to the competition of the system suppliers. In the first step the idea seemed to work, since suppliers were able to use cheaper workforce in low cost countries. Another main argument was that suppliers could develop more specialized expertise on their subcomponents than OEMs could.
The costs of the OEMs where reduced, and they became quicker in their own processes due to this outsourcing strategy. The systems suppliers operated independently from the OEMs – the interfaces where just the integration tasks of the vehicle. The efforts to sustain system quality of the vehicle became more and more due to the increase of the system complexity. Now the OEM engineers had to integrate often new systems, which where to them a black box developed by their suppliers, into their vehicle.
Toyota has a different understanding of partnering. They train every supplier to be an extended workbench of Toyota. The cooperation style of Toyota was very

efficient so that they were rated as a favorite business partner of their suppliers compared to other companies. In 2003 a JD – Power survey revealed that in North America Nissan, Toyota and BMW where the best OEMs which promoted supplier innovation. Honda and Mercedes where also mentioned as good or being above average.
The difference is that Toyota takes care of struggling suppliers to get them again on track, commitments and promises are held. Contracts are binding and not reneged, Toyota does not negotiate on costs reductions after the contract is signed. Price targets are tried to reach with mutual efforts. Contracts are valid for the lifetime of a vehicle.

3.2.7 Toyota lean development process – summary

1.) LPDS starts at the front of the product development “front loading”
2.) Cross functional teams are in the center of the working structure
3.) The process is led by the concurrent engineering department – which is responsible for the development of platforms – module development teams make sure to introduce standardized systems cross the platforms. The SE Team is responsible for the component development.
4.) Quality, manufacturability, functional optimization and costs are in the center of the considerations of the cross functional teams.
5.) Standardization and the reuse of modules and platforms characterizes the design process at Toyota.
6.) Organizational – Chief engineers lead the development on a customer orientated base – platforms, MDTs and SE-Teams are answerable to the chief engineers
7.) Suppliers are integrated based on Toyota working principles as extended workbenches.

The main problem of the current process is that standardization does not allow to implement quick nonstandard changes during the development phase – as soon as a product development process is initiated it has to go through the scheduled milestones. On the other hand all described methods and organizational standards have as principal goal product quality. The Toyota processes are made to create highest possible quality by avoiding late changes. Late changes are changes which can only with difficulties be implemented using conventional production and testing methods. The key is to reduce times for prototype production and testing systems – based on industrie 4.0 ideas these process determining factors will be identified in the chapter “development 4.0”. The base for the identification will be an analysis of industrie 4.0 processes and methods.
In general the idea of platforms and modules as well as the cooperation strategy with suppliers in combination with the Toyota cross platform organization is very efficient. This should be used as a base for development 4.0. The main weakness in the context of industrie 4.0 or batch size one - is the inflexibility due to stable, standardized processes. The challenge now is to solve the target conflict between stable processes (quality) and changes during the ongoing development process.

3.3 Industrie 4.0

3.3.1 Definition of industrie 4.0

Sources [14], [24]

Industrie 4.0 is a synonym the fourth industrial revolution. The term industrial revolution was created mid of the 18th century when especially in Europe the step from an agricultural to an industrial society took place. The second industrial revolution happened at the beginning of the 20th century characterized through the automation and the broad range use of electricity (Ford, Taylor). The milestone for the third industrial revolution was the use of computers – at first mainly used in automation control systems.

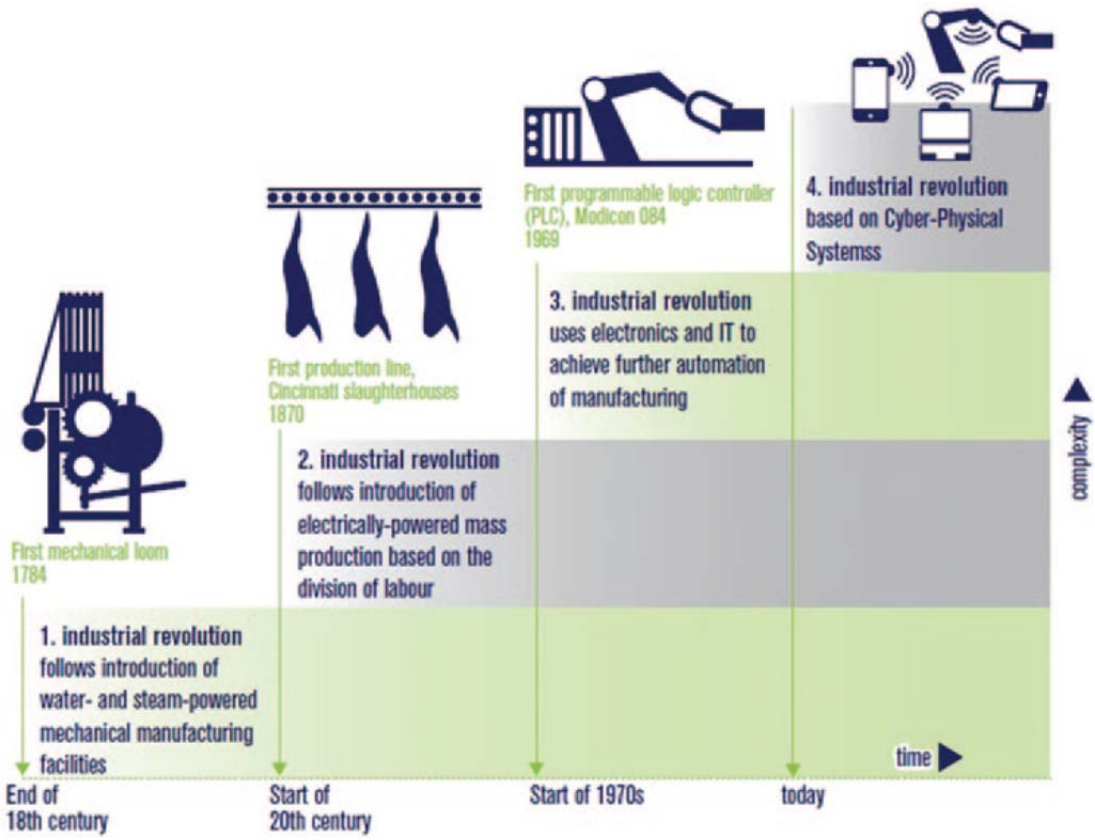

Figure 18: industrial revolution by the industrie 4.0 commodity team (source DFKI – Deutsches Forschungszentrum für künstliche Intelligenz) [62]

The fourth industrial revolution means the connection of products and environment via the internet – product and environment become interdependent. The process of data exchange will modify the products or lead to new product ideas – on the other hands the thus created products will have an influence on their environment as well. A revolution means often a quick change of something where the differences before and after are significant. Time will tell if industrie 4.0 will become a revolution or will take more time to be implemented which then is an evolution. In my opinion the ideas have the potential to change our understanding of products in the context of their environment and usage. We will potentially know how and when products are used. The technology to integrate this knowledge into a production system is already partly prepared – or under development – the efforts of the industry are getting more and more progress is visible.

The target of industrie 4.0 is to secure the production industry location Germany for the future. The program for industrie 4.0 was initiated by the German federal government in 2012. The idea is to connect products and services via software with the automated production facility. Automation makes sense in industry locations where the wages are high compared to other countries. The use of less manpower leads to cost optimization and secures facilities in Europe. The second factor is to maintain quality and reliability of automotive products in this high automated environment. The main factors are high reliable development and production processes capable to adopt the increasing product complexity or able to be adopted by the products and therefore necessary processes.
To answer the questions evolving from the key factors it is necessary to obtain a holistic view on the whole lifecycle of the product.

The key elements of industrie 4.0 are [24]

- Production network
- Product lifecycle management (PLM)
- Cyber-physical systems (CPS) including cluster intelligence and other methods

The targets are to

- Control and optimize value chains in production in real time
- Improve the visibility of information within the production process
- Realize autonomous decision process (machine learning)
- Integrate customers and suppliers in the OEM PLM process

These main components shall be evaluated regarding the possibility to integrate elements and methods of industrie 4.0 into a development process – this new process using core elements of industrie 4.0 will be called development 4.0.

3.3.2. Production network

Within the production network of industrie 4.0 all elements, like product, machines, transport units, tools, etc. communicate with each other. Important enablers to create a holistic network consisting of the mentioned elements will be sensors and RFID (radio frequency identification). The difference to existing production systems is that the product itself becomes an active element which controls partly the production system. That means it initiates a system process which decides when and where the next production step will happen, depending on current machine capacities.

3.3.3. Product lifecycle management

[14]
The methods and actions necessary to create a control loop between a product and its development process are called product lifecycle management. All data connected with the product must be managed during the lifecycle of the product – thus the data out of usage of the product is fed back into the development process. The higher the flexibility of the production lines will be – the easier it will be to incorporate changes on the product – if the product structure is capable to adopt such changes.

System architecture is in the first step the main focus for product lifecycle management – it is the split of the system in subsystems which have to fulfill the subsystem requirements (functions, quality) as well as requirements of the system architecture. Subsystems are linked by interfaces, which must be considered when

designing software tools to operate the system. Subsystems are “intelligent” – that means they exchange data and communicate with each other.

Current situation product lifecycle:

- innovation cycles are determining the product lifecycle
- the level of individualization is low – high costs for tools and development avoid a production based on the batch size one idea
- economies of scale are in the center of economic decisions

Future situation product lifecycle – industrie 4.0 – development 4.0:

- continuous innovation / or reduced innovation cycles
- high level of individualization
- economies of scope (band of products)

To realize product lifecycle management in the context of “working on the model” it is necessary to integrate the different programs and systems into a standardized common virtual reality. Figure 19 shows different software systems which are linked by interfaces to create a holistic view on the product. Product lifecycle management (PLM) and enterprise resource planning (ERP) create the outer shell followed by the inner shell of production relevant data like computer aided manufacturing (CAM). The core of the systems are more development relevant like finite element analysis (FEM) or computational fluid dynamics (CFD).

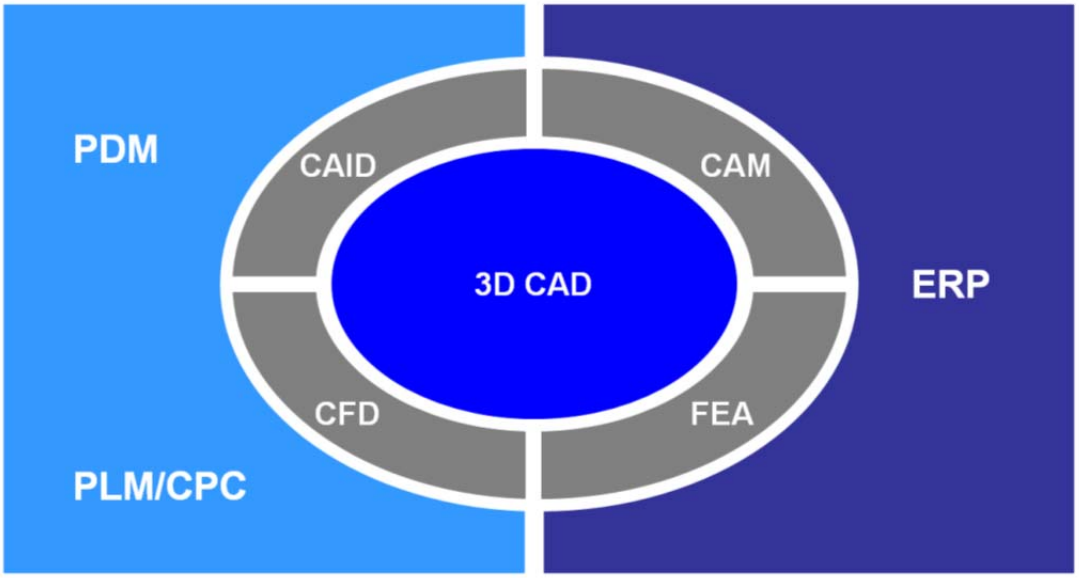

Figure 19: [26] – different software systems cooperation within a product lifecycle management system

Example of PLM software where integrates systems were used

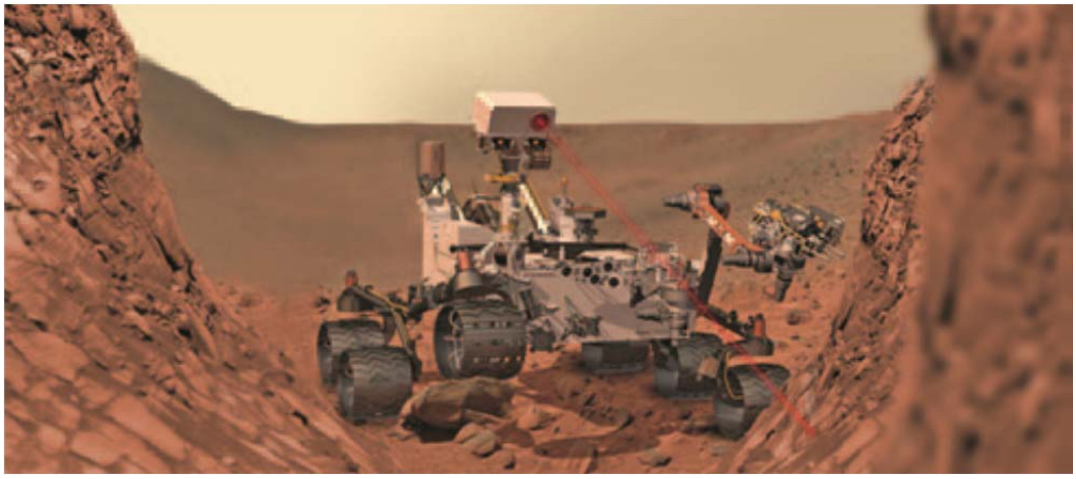

Figure 20: [63] Mars Rover Curiosity (Copyright NASA/JPL-Caltech)

During the development of the mars rover curiosity PLM software was used to analyze different designs virtually. The possibility to check designs without intensive testing is one of the key features of development 4.0. The less testing is necessary the quicker a new design can be released for the market and the less costs evolve out of hardware testing. Furthermore in this case the rover is relatively complex that means to test all possible variations would have taken much too long. The rover was developed by the Jet Propulsion Laboratory using PLM Software NX by Siemens [48]. With this software the CAD design (solid edge) is linked with a system to test the interfaces of the parts. In the second step a simulation of the mechanical behavior – motion control - of the assembly as well as the manufacturability is possible.
The application is also utilized by Daimler for the development of passenger and commercial vehicles. The PLM software NX is enlarged by compatible subsystems at suppliers to ensure an integrated data usage and transfer. Also VW is using the software to optimize manufacturing. Siemens NX offers currently three linked components. They are design, simulation and manufacturing. Another suppliers for PLM software is Dassault systems ([49] Transcat) and there are other suppliers available as well.

All those software packages include the three above mentioned components (production network, PLM, CPS). The systems have the target to speed up the development process by the possibility to virtually check design alternatives from quality and manufacturability point of view – without testing, just by working on the model.

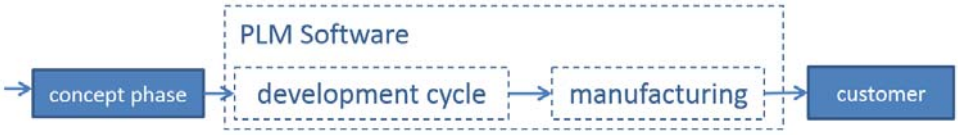

Figure 21: current use of PLM Software

Figure 21 describes the current field of application of PLM software. The information created by customers like usage and automotive trends is fed back using conventional opinion survey methods into the concept phase. The usage of PLM software is constricted by the OEMs and their suppliers. Some OEMs use integrated software packages as described before other use the three main components – design, simulation and manufacturability from different software suppliers which are semi-integrated using interfaces. All those systems have in common that the interface between customer data and PLM system does not exist – information must be processed manually to be used in the concept phase. The system is capable to deal with conventional data packages the influence of big data is currently not considered.

3.3.4. Cyber-physical systems

The term cyber-physical system emerged in 2006 (Helen Gill, US National science foundation) – the background idea for the expression was the term "cybernetics", a word which was created[4] by Norbert Wiener (US, mathematician) when he wrote his book (*Cybernetics or Control and Communication in the Animal and the Machine* (1948))
Cybernetics is the science of the control of systems – these systems can be physical, social, biological etc. and characterized by a closed loop information transfer where the information is controlled and fed again into the system.

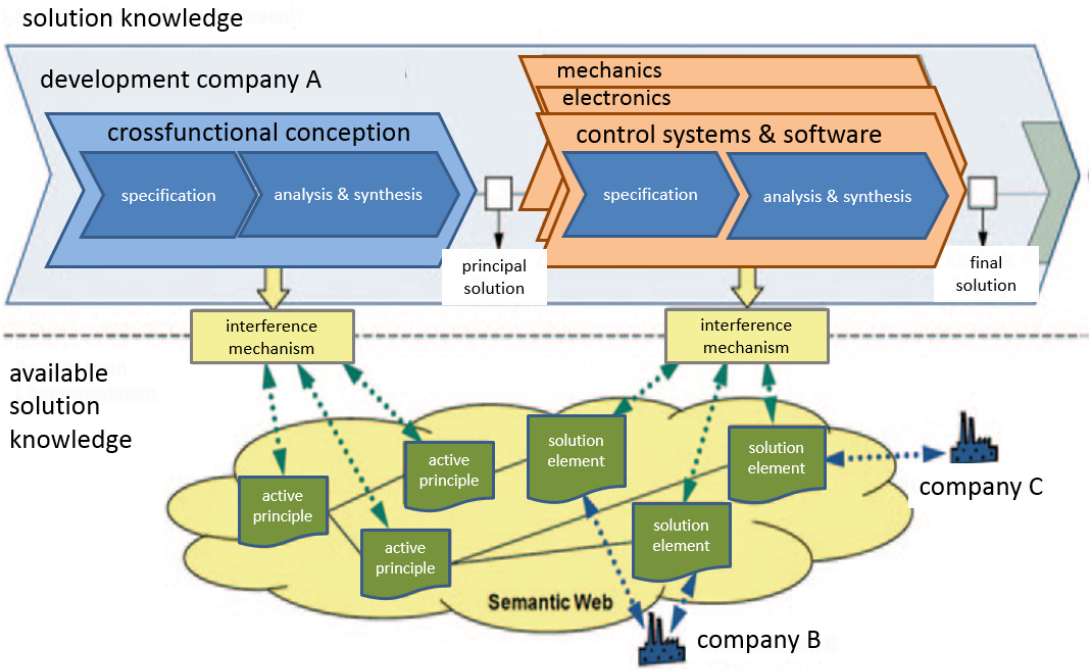

Figure 22: source [14] design principle of intelligent mechatronic systems. (Universität Paderborn, Heinz Nixdorf)

A CPS combines the physical world with the cyber world and is part of the cybernetic science [15]. Physical products, processes and or machines are connected via computational models. The cyber world thus created is in a continuous exchange of information with the physical world. The areas of the system where physical world and cyber world get in direct contact is normally called the

[4] André-Marie Ampère published already in 1834 the idea of a science called "*cybernétique" Source*: Hans Joachim Flechtner: Grundbegriffe der Kybernetik. 1970, S. 9.

CPS – the point of interest is the system of interactions between physical and cyber elements. Through understanding the interface area where the interaction takes please it is possible to create a cyber-physical system.
Cyber-physical system where historically developed step by step the main factor was the development of computer systems and software. The more capable the computational power of data processing systems became the more system integration was possible.

The evolution of cyber-physical systems [14]:

- Embedded systems
- Intelligent embedded systems
- Intelligent and cooperative systems
- System of systems
- Cyber-physical systems

The architecture of CPS for industrie 4.0 [14] includes three main factors:

1.) Product/system architecture – in our case vehicle architecture
2.) Architecture of value adding and company structure
3.) IT structure

The target of a domain model is the integration of these three levels – the base structure for all other structures is the product structure. The product structure determines company structure, value adding possibilities and IT structure. The challenge will be to integrate or exchange legacy structures.

The acatech Study [17] on the subject CPS shows that future products will have embedded electronics with software to supply the component with

- Adaptivity
- Autonomy and
- Context sensitivity – the way or context in which they are used

This information is used within a feedback loop between machines and virtual reality. The cyber-physical system is an intersection between these two worlds and does not unite physical and virtual reality. The important value when designing a CPS is to understand the interaction between physical and virtual world. [15]

A main criterion of industrie 4.0 is the use of cyber-physical systems, which means that a product owns all the information necessary to produce it. It is part of the cyber-physical production system – documents its history and can be physically localized. The production process is optimized automatically – since a holistic model of the production process checks continuous the status of products and machines – and modifies the production plan and production process to obtain an overall optimum.

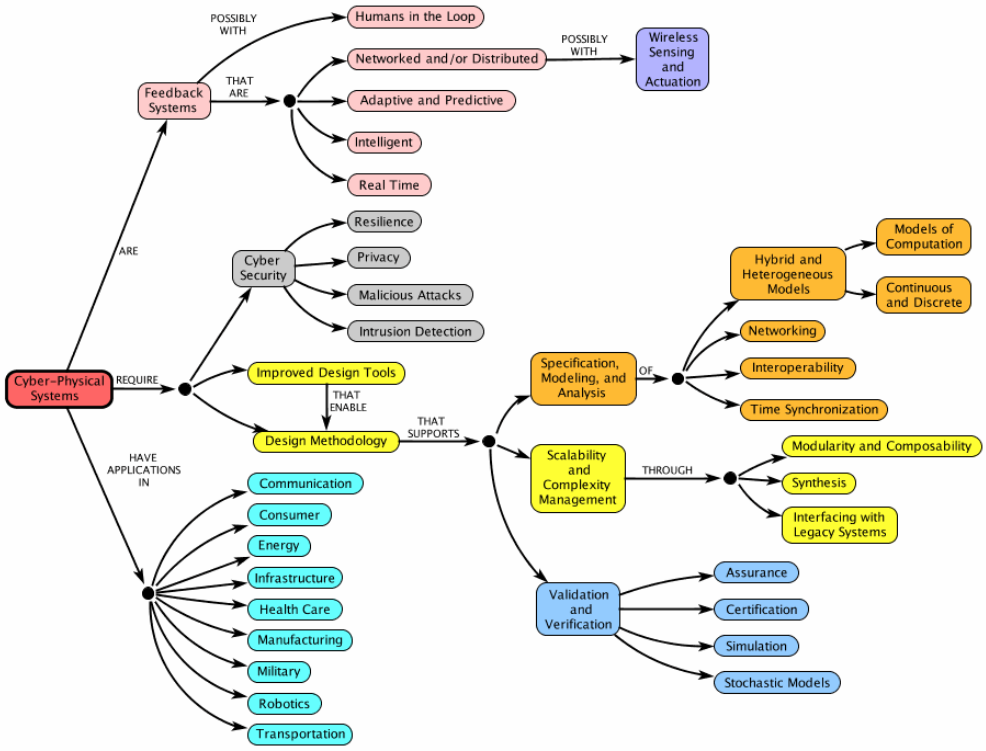

Figure 23: [14] – cyber-physical system

The cyber-physical production system of industrie 4.0 combines production facilities with products which are connected via “implicit intelligence”. The CPS has parts which are strongly related to the production process and parts which focus more on development system. Figure 22 explains how the real physical production facilities are transformed in a virtual environment. The virtual reality contains all data created during the development and industrialization process. To create a real time image of the production process in the virtual world embedded systems are used. Embedded systems are computer systems which cooperate with a large mechanical system often in real time. Figure 24 shows a cyber-physical production system where all necessary information exists virtual in parallel to the real world.

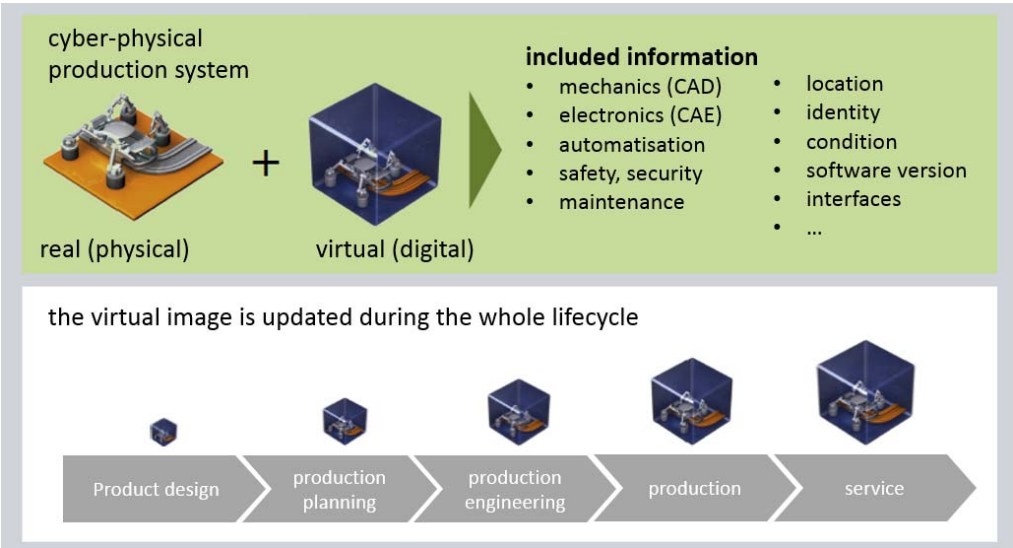

Figure 24: cyber-physical systems in the production process [25] - Siemens

3.3.5 Information structure and cycle time

Intelligent products will create a continuous information flow. Cars used by customers will have the information on how and where they were used.
The thus created data can be structured using four categories

1.) Usage of features (i-technologies)
2.) Driving behavior
3.) Environmental data
4.) Location of usage

If we concentrate on environmental sustainability the following information is of special interest.

- Fleet fuel consumption (actual customer consumption)
- Emission balance
- Driving cycle composition & customer driving style

Fleet fuel consumption can be used to optimize vehicle calibration based on the statistics of the routes that customers drive in daily life. The trend to real time emission measurement is supported by new emission laws – the first step regarding emission targets based on open cycles is already done – real driving emission regulations will be relevant in the 2017 [29].

The emission balance helps to understand how environmental friendly vehicles in real life are, based on absolute data created by customers. With the emission data of all vehicles in the field the optimization of applications can be done.

The combination of route and driving stile will give information about the actual real time loads. The future driving behavior will change significantly – the way people live [30] could cause a shift in typical driving cycles. Predicted are megacities, car sharing and also a shift in where the future markets will be (China, Africa, etc.). Today there is no “world car” and there won`t be a world car in the future. It is important to understand regional needs and to be able to tailor cars to typical customer needs. Industrie 4.0 will be one enabler to manufacture and deliver such cars.
The customer specific driving data can be used to adopt durability testing programs based on a possible shift in driving behavior, or to offer drivetrains optimized for the real driving behavior in a certain region of the world. The motivation is to achieve the best quality possible for each specific customer.

3.3.6 Big Data

Sources [14, 43, 44, 50]
Big data is defined by the fact that the amount of data or the speed of change of information can currently not be handled using conventional computational methods. The data relevant to develop a product will be created in the future by analysis of big data and will be the base information for the whole development and production process which is called lifecycle management.
The idea of Big Data is to unite analog data sources with the data extracted out of the IoT (Internet of Things) and the IoH (Internet of humans). It is called big data since the amount of data daily created in digital form is enormous. Each source of data can be used as long as it can be digitized and interpreted by a simulation

routine – here often neuronal nets are used – as an artificial intelligence for interpretation.

The knowledge how to filter and extract the data which is relevant for development will be one of the key abilities in the future.
[14] The processing of this data will be not possible with current information technology and software routines. New technologies have to be developed, which can filter and structure big data based on different information levels. Pattern and trend analysis as well as the influence of correlations will be considered to find relevant information.

The reason for that is based on three facts.

1.) Data will be available in more detail (the more powerful a computer is the more Data can be processed – the level of detail will increase.
2.) New developed methods allow to process unstructured information like in videos on youtube or in messages on facebook and twitter
3.) More sources of data will be available

Big data has always to be seen in a context and will be cross functional – that means many departments could be direct affected from the conclusions to be made. The cross functional modular organization structure, where module teams are linked cross different platforms ensures the optimal usage of information in those departments where the information is needed.
Furthermore – to analyze the information flood it is important to implement an information chain within the process partner structure to ensure that each affected department is integrated in the filtered information flow and decision process. The process starts where the data is created – like customer relation management systems, call centers, dealerships, etc. First steps to analyze big amounts of data are already made [50] – webLyzard an Austrian company offers technology able to analyze already a high amount of data which emerges in today's internet. In their showcases there is e.g. an analysis of big data in the context of climate change [50] – information in combination with "climate change" is linked with where it emerges and the substance of the sentence where the word is used. Thus family trees and relations between notions are build.

Another important feature will be the prediction of the change of data/parameters out of Big Data. This predicted needs and the level of ilities and ivities will be used for decision making at the beginning of the concept process of a new vehicle. The principle of prediction is already working which can be seen e.g. at amazon which suggests products based on our interest behavior, or at the TV show "house of cards" which was designed based on the knowledge of Netflix – a video platform [44].
Of special meaning for development 4.0 will be the data generated and processed regarding quality. Predictive product quality analysis will be important in the future.

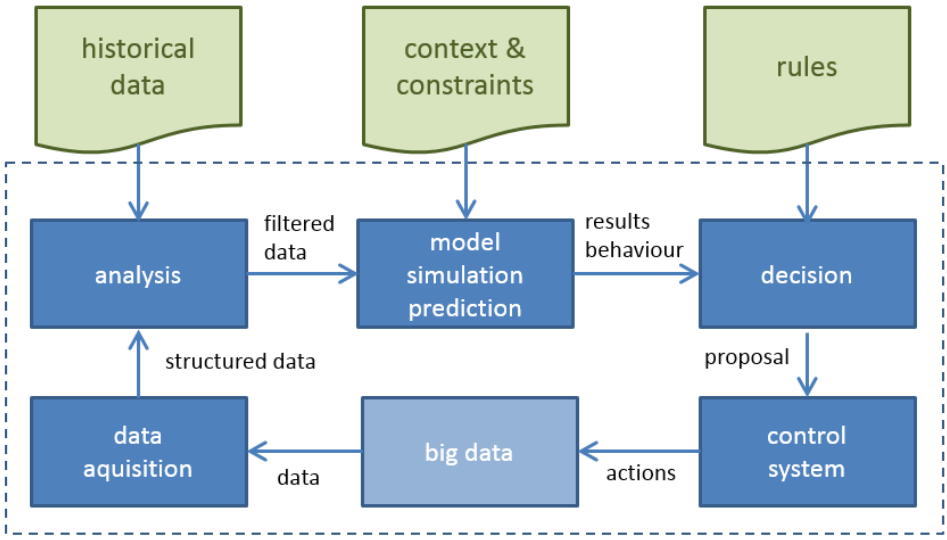

Figure 25: usage of big data – a concept for value adding– source IBM – picture adopted [14]

A concept of how to integrate big data in a lifecycle management process is shown in figure 25.

3.3.7 Smart mobility [14]

Another aspect of big data is smart mobility. More and more components in a vehicle will be electrified. Emission regulations lead to cost intensive technologies for combustion engines. As soon as rechargeable batteries have a longer range and a better price in combination with a quick charging infrastructure – electric driven cars will become a relevant competitor for conventional cars. In parallel sensors and actors are connected by car to x communication with the IoT. The car realizes its environment with laser and radar sensors within a range of 200 m. In the future cars will by using wireless technology be able to use hot spots in their environment to connect with the cloud and has access to a broad range of information. The car produces big data and uses big data to navigate, identify nearby services or simply to reserve a parking lot. Figure 26 explains how available big data will be used to predict customer relevant information in the context of mobility.

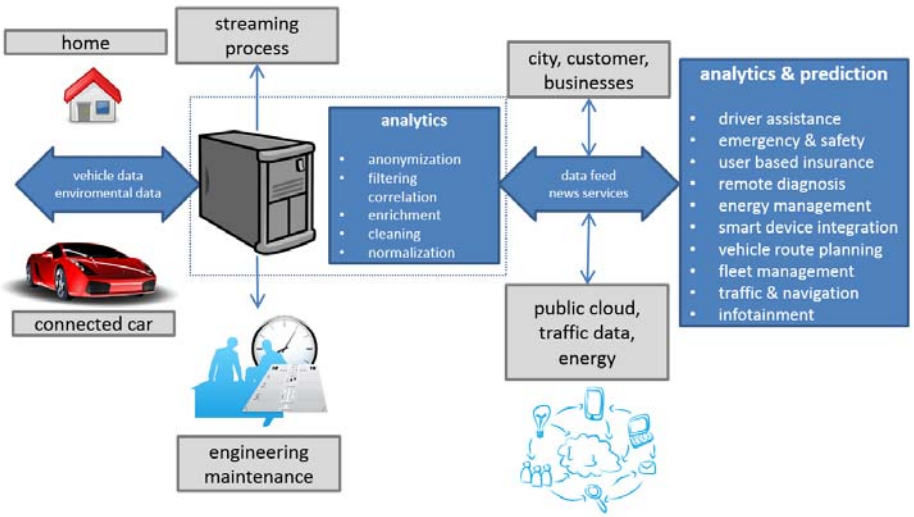

Figure 26: smart mobility source [14] – source IBM picture modified

3.3.8 Summary industrie 4.0

The following product lifecycle relevant subjects summarize the key ingredients of industrie 4.0 (Table 1) and will be used in the concept deduction of development 4.0. The validity and the compatibility of current development concepts will be scrutinized based on these findings.

subject	Industrie 4.0
lean	Lean production and development processes are the baseline for industrie 4.0
production network	Each component of the production facility including the product is linked (smart products)
product lifecycle management (PLM)	All information of a product from the beginning to the recycling is respected
cycle times	Are more flexible and shorter
data structures	Enormous amounts of data must be processed – big data
cyber-physical systems (CPS) including cluster intelligence and other methods	CPS are essential for autonomous production behavior
adoption of embedded systems	Necessary to create CPS within an integrated company network
change from physical prototypes to virtual models	Cost reduction – less testing is necessary Working on “the model”
modularization	Intelligent components connected by “smart mobility” data – information is available at any point of time, plug and play abilities of modules
PLM software	Concentrates currently on existing process steps like design, simulation and production control, will be adopted in the future regarding big data requirements

Table 1: elements of industrie 4.0

3.4 Industrie 4.0 development process

Industrie 4.0 product lifecycle concepts already include today ideas on how a future development system must be designed to fulfill the requirements of industrie 4.0. The idea of cooperation within the product lifecycle management process [18] is to use virtual models without printed documents as a base. This is called **model based system engineering MBSE.** The models are modified during the development process based on the maturity of the system/models.

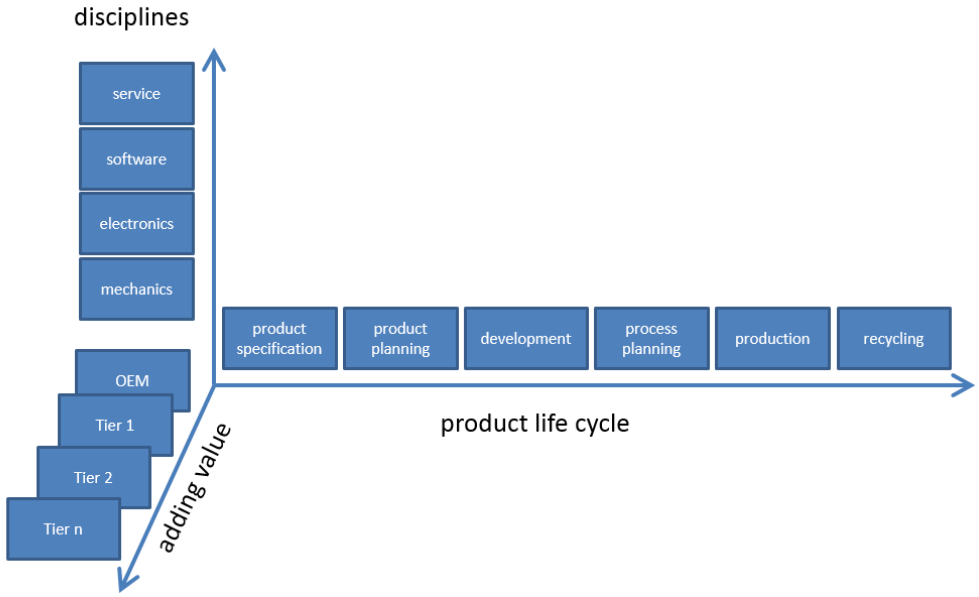

Figure 27: [18] multi-disciplinary product lifecycle. - from Eigner M, Stelzer R (2009)

The conventional development process consists of four phases [18] which are linked by loops if testing of components is necessary. The MBSE process is interdisciplinary during the whole product lifecycle involving OEM and Tier n – figure 27.

- Requirement management
- Conceptual design
- Designing
- Elaborate in Detail

Each phase of industrie 4.0 PLM is linked with the next phase – the results of each phase is called artifact which is used as data base for the next phase. The grade of artifact orientation are as follows

Level 0: no documentation
Level 1: paper based documentation
Level 2: isolated software tools
Level 3: isolated software tool chains – no tracing of artifacts
Level 4: artifact orientated system development with standardized data base and single point of truth principle (no redundancies).

An artifact is the entirety of information of a system which is the core of the database of a system used during SysLM. All tools involved to run the systems use the artifact model which is derived from the requirements of the system – the system architecture.

[14] The distinctive feature of an artifact compared to other information is that it is absolutely necessary for the next development step. Thus the lean principle of no waste is implemented. The relationship between artifacts is understood and used to check and simulate the model behavior – figure 28. The MBSE uses the artifact model to incorporate the relationship between properties, systems, functions and components.

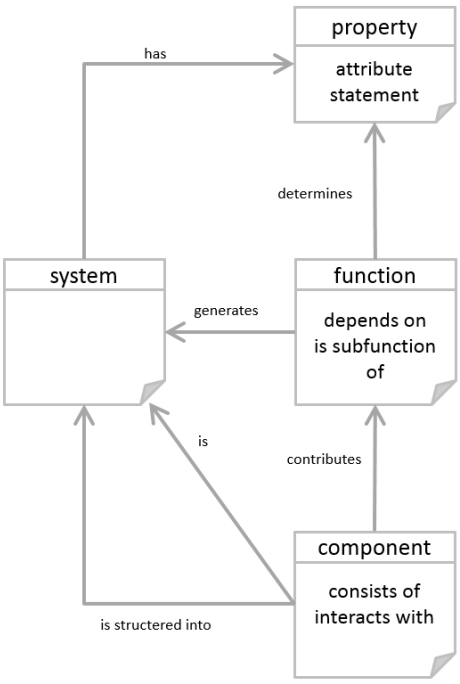

Figure 28: Meta model for artifacts

When MBSE methods are applied it is important to differentiate between processes and methods. A process is a logic cascade of activities to reach a target. The process defines what to do and not how. The how to do is described in the methods that are used to fulfill the necessary activities. Tools are software solutions applied to support the methods in the context of a process. The environment describes the influence factors that are supporting or disturbing the processes.

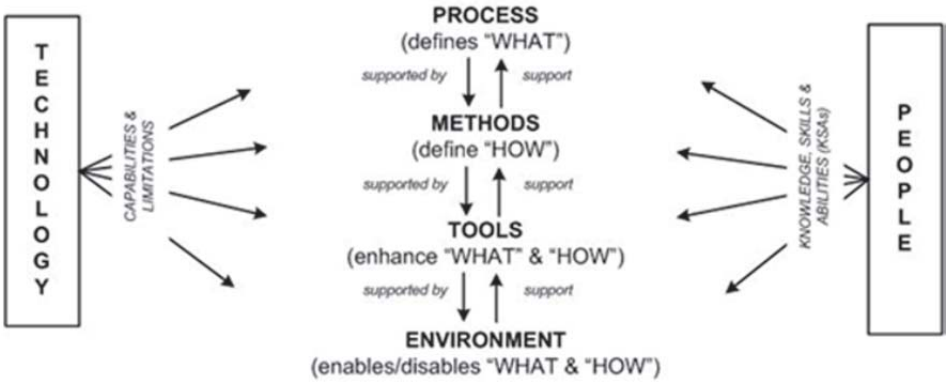

Figure 29: [53] basic principles for industrie 4.0 development, involving technology and people

All these ideas of MBSE can be used in our development 4.0 concept. But that is not enough to fulfill the real development 4.0 requirements. Although there are singular ideas about how to integrate the consequences of daily available new data in the PLM cycle there is no conclusion available to me so far regarding how to modify in detail the development process. Another fact that industrie 4.0 PLM concepts

identified today is a different understanding of mechatronics – figure 29. Today cars differentiate still between mechanical systems and electronic systems. The modules and components which have a high interactive behavior between mechanics and electronics are today seen as the intersection set of those. Industrie 4.0 has only components which are electro mechanic hybrids linked by software systems. This idea is a main requirement for development 4.0 concepts.

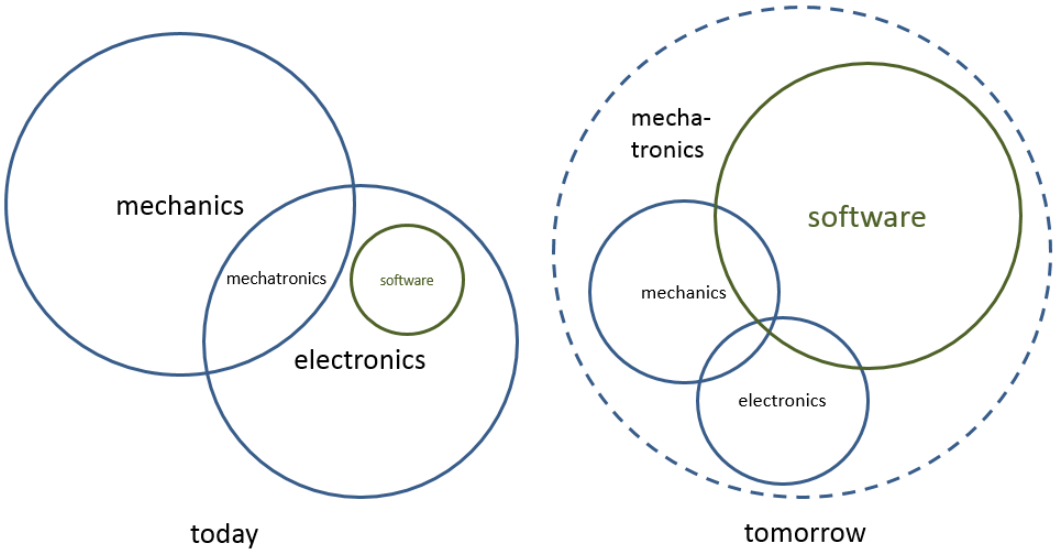

Figure 30: [18] software is the integrating factor of mechatronic systems

The point is that these requirements are seen from a production point of view. Development processes today have timings that are mainly influenced by testing and prototype acquisition cycles. In an ideal case simulation has the potential to reduce the necessary testing of prototypes to zero. A positive simulation technology trend is visible but the progress of simulation possibilities does currently not allow to skip all hardware testing – that means within the next years we will still have to consider testing times as a limiting factor. Another limiting factor is the acquisition of tools for hardware. In my opinion in production processes industrie 4.0 ideas could be implemented faster since the level of production simulation is already very high. To react on this production possibilities it is necessary to design development processes and methods in a way that enables the production of cars with good quality which are able to fulfill the industrie 4.0 requirements at the currents stage of implementation. Software and algorithms are the integrating factor – figure 30.
Current industrie 4.0 development concepts must be extended based on optimized processes to reduce development time.

4. Development 4.0

Development 4.0 in automotive industry is defined as a process that fits into the industrie 4.0 PLM concept, using methods to achieve highest flexibility in developing "customized" cars with a minimum batch size in production – in extreme down to batch size one. To develop customized cars as flexible and quick as possible it is necessary to react on trends which occur within the normal vehicle development time of 50 month. This means new or modified targets lead to changes, which are a risk in today`s development process, especially when they occur late. At first it is necessary to find a method to decide if a change makes sense for the customers and the OEM. To incorporate a change within an ongoing development process it is necessary to have then a clear picture of the current development process stage and how long it takes to realize the change. Thus the development 4.0 process is made to improve the product and development flexibility. To understand the concept of development 4.0 it is necessary to be familiar with the process and the necessary methods to fulfill the requirements of customers and the production boundary conditions of industrie 4.0. This will be explained in the next chapter.

4.1 Development 4.0 process

The main difference between development 4.0 and current development processes is that the function and component orientated development which emerged historically[5] in the 1970´s. The change was the introduction of the integrated, architecture orientated SysLM (System lifecycle management) development. Here the deduction of functions and requirements considers systems at first. Then the ideas are narrowed down to modules and then down to components. Development 4.0 integrates in a second step at the drafted modules with specific functions a control loop. This loop uses data out of testing activities, the field and customer trends out of big data.

Thus the feedback of test results or field experience is transmitted as an optimum in real time into the development department. The development time thus can be in principle reduced since the developer gets direct feedback as soon as the test data is available or a field problem occurs. Currently the incorporation of real time data is not possible immediately since the rework of designs and the acquisition of prototypes is often a significant time factor – solutions to that will be explained later at the chapter development 4.0 methods.

Furthermore the level of information will be increased. Due to the use of CPS, intelligent components and architecture models more necessary information can be transmitted automatically into the simultaneous engineering team. This can be very detailed information – e.g. driving conditions when an incident or failure occurred, pressures, temperatures as well as historical data on how the component was used until the incidence.

Since industrie 4.0 production concepts can offer vehicle production in batch size one based on a single customer order – the necessity to react on customer trends during the development 4.0 process will be examined. All these factors (timing, necessity, and batch size or production method) together form the development 4.0 concept.

The development 4.0 process is based on a normal development process, as described underneath. But there are extended process determining key factors which will now be identified.

[5] See also [18] page 101

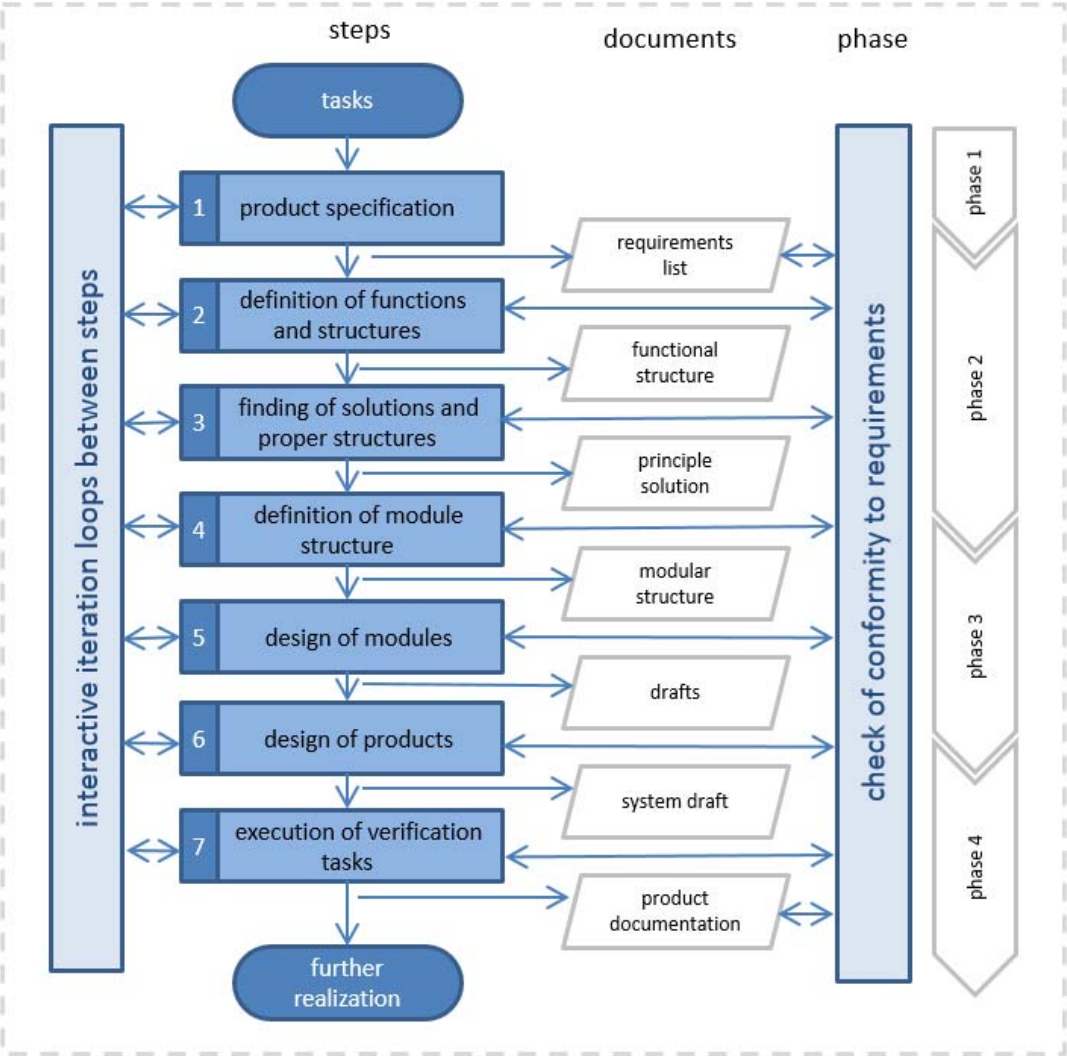

Figure 31: [19] the design process based on VDI 2221

Figure 31 explains the design process defined by VDI 2221. This process is used in classical development projects. There are several iteration steps for each task. The subtasks are measured based on if the sub-goals are achieved. The main problem is that the vehicle targets must be set at the project start – any change of targets during the initiated process leads to additional workload within the development department. The likelihood of a change becomes higher the more unstable the vehicle targets are. The problem today is that the time of 5 + years (figure 33) is possibly too long to react on new trends occurring within the time of 50 month development. The ability to react according to new customer trends will be a significant market advantage in the future. On the other side this ability to react implies that the development process is flexible. Today the flexibility depends on simulation capabilities and the time for prototype acquisition and testing. Development 4.0 has to consider these factors as well as to identify methods and production concepts that are capable to increase the reactivity of the OEM development process. Figure 32 explains how targets are set during the concept phase based on historical information at the beginning of a project.

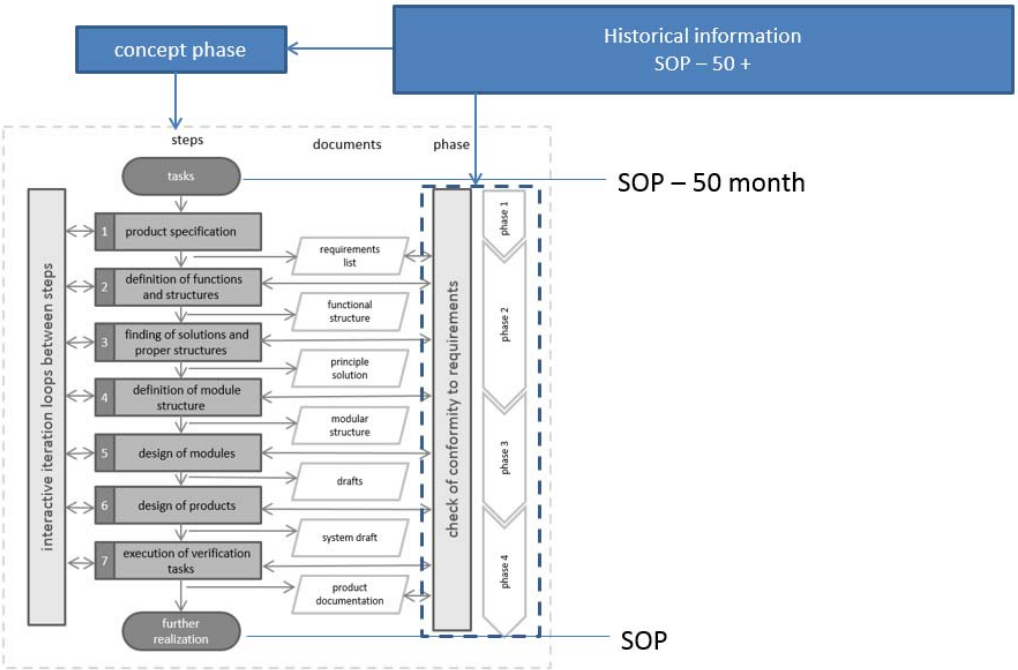

Figure 32: conventional development process

Big data creates information in real time. The processing of this information will identify relevant information based on the behavior of the customer in real time. The target of development 4.0 is to fulfill the wish of the customer with superior quality as soon as possible. Figure 33 points out the influence of big data. New concept relevant information will be available during the whole development process. The arising trends must be filtered based on if they are of stable customer value within the next years and a sustainable economic advantage for the OEM.

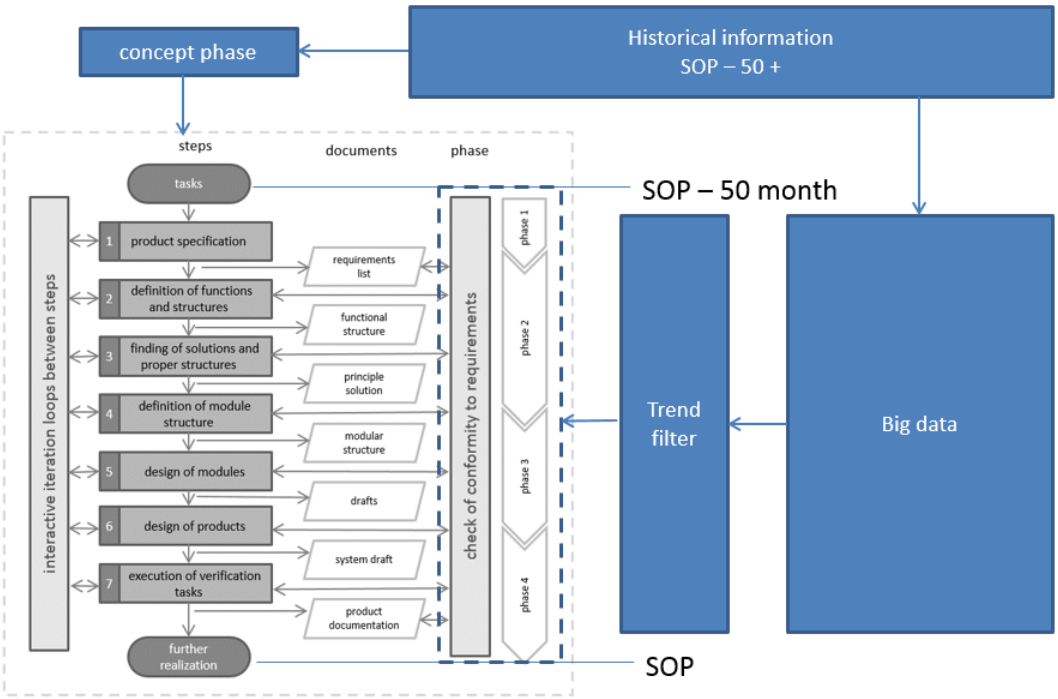

Figure 33: the influence of big data

Today there are already possibilities to deal with new “big data” requirements. Especially when modules or functions are involved which can be changed easily like software features or applications in the context of connectivity. These systems have seldom the necessity of hardware tests and the verification of the change can be done virtually by simulation. Components which are relevant for structures like chassis or engines must stick to the conventional development plans – that means they cannot be changed even if new information is available. This is since testing is necessary and to implement new components in production takes long, due to the fact that new tools are necessary or modifications of a production line have to be done. Table 2 shows how existing industrie 4.0 concepts can be used as part of development 4.0 having in mind to develop vehicles for small batch sizes.

	Industrie 4.0 - requirement	Development 4.0 - requirement
Data structure / timing	Continuous data flow in production CPS, networks	Cyclic data usage in development CPS, networks
Cyclisation Cycle time	Flexible since the production unit is self-organizing	Quality cycle time Development cycle time Big Data trend filter cycle time **- Pulse 4.0**
Parametrization	Parametrization of relevant product properties	Parametrization of relevant product properties Differentiation between - Data that can be changed - Data that must be considered at a later point of time – a new development cycle
Ilities and ivities	None	The customer value of a property must be checked **differentiators & communalities** Development must be flexible, robust, changeable, evolvable and sustainable
Artifact orientation	Objects and their level of network integration	Baseline for development 4.0
MBSE	High level of simulation Working on the model	Baseline for development 4.0
Production method	Components out of classical tools (presses, injection molding). Assembly in lines or in flexible production modules	Fast production methods (welded structure using standard pipes (chassis), 3D methods) Assembly in production modules an cells

Table 2: industrie 4.0 concepts transferred into development 4.0

4.2 Development 4.0 methods

Methods are procedures which lead to solutions that enable the next process step. Industrie 4.0 concepts offer already methods about how to integrate development in the PLM process – see Table 2. The idea of incorporation big data real time requirements in development is not yet possible. Current development methods can hardly be changed as long as there is necessity to test prototypes. So the key to development 4.0 are methods to fulfill the activities within the ongoing development process depending on the correct point of time for introduction in combination with avoidance of prototypes and testing. The target is to qualify modules fast und thus accomplished more reactivity to real time information out of the IoT which needs to be incorporated. Based on the analysis of current lean product development systems in combination with industrie 4.0 principles we will evaluate the process determining factors in regards to moving component targets within an ongoing development process.
Development 4.0 has mainly three process determining factors – figure 34.

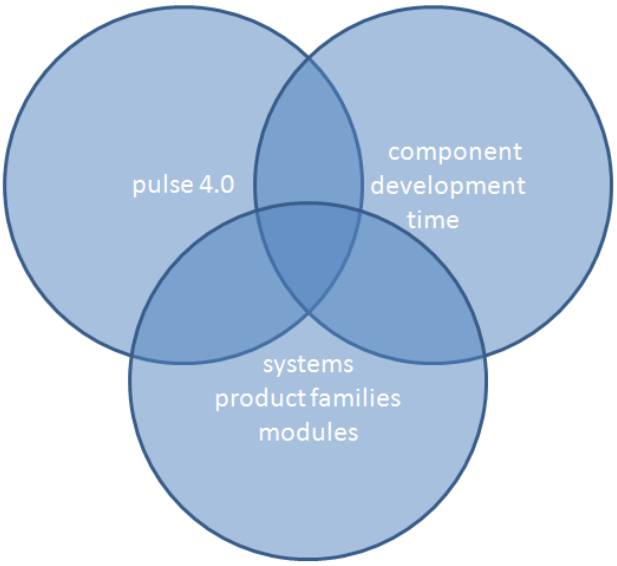

Figure 34: key components of development 4.0

The first will be called pulse 4.0 and is determined be the stage of the project. Only those changes or innovations on components which are introduced at the right point of time can be considered to be incorporated in the product. Puls 4.0 can be understood as the heartbeat of the PLM, it defines if and when changes can be introduced. Pulse 4.0 is the frequency of right points of time and is mainly defined by the maturity of the project.

The second factor is the necessary time for development mainly influenced by the lead time of components (i.e. for prototypes in development as well as the lead time for industrialization) and the question if testing is necessary or if function and durability can be checked using e.g. simulation methods.

The third factor of relevance is the economic point of view – this is handled by the choice of systems, product families and modules which should have value for the customer and an acceptable business case for the OEM.

4.2.1 Pulse 4.0

The possibility to incorporate changes in a given development process depends on the stage of the project (maturity). Pulse 4.0 defines times where changes can be incorporated based on detailed information about the change.

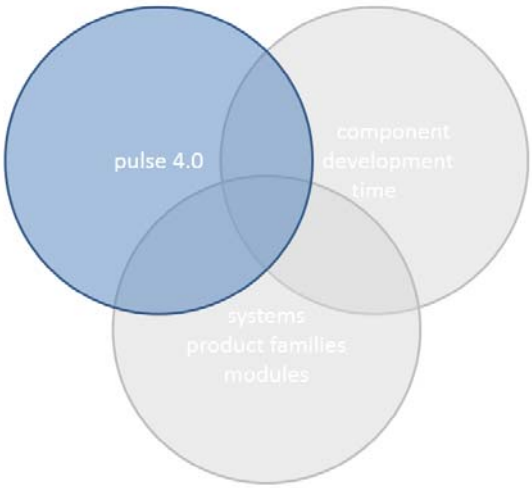

Figure 35: the timing of development 4.0

Product data used in a conventional development process consists of field data or knowledge of the previous development project. The development of the predecessor product is finished, all data collected out of the experience is stored and used in the development process of the next product. The timing allows stepwise improvements on vehicles in the frequency of approximately 50 month.
This product development process is experience based – the experience is out of the past and the development cycle relevant data is acquired based on the prototypes used in the testing environment.

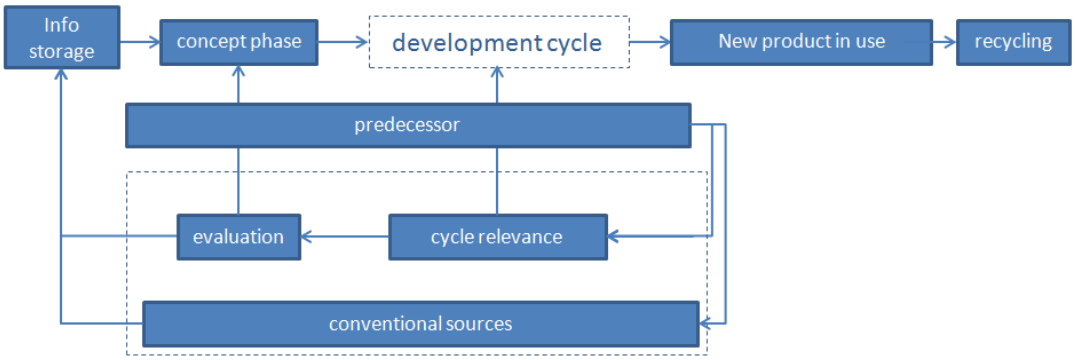

Figure 36: conventional development process

This procedure (figure 36) works if concepts are stable and no changes of targets come into play. In case changes are necessary a lot of additional effort and capacity is necessary. Normally special teams are nominated to deal with the unforeseen change and additional testing is necessary.
To incorporate changes in a new car under development it is mandatory to decide if the change can be applied without harming the quality of the product. Therefore it is important to understand the stage of maturity of the car.
Figure 37 is a draft for an alternative – in this case a steady development “cycle” would be necessary. Here the classic cycle of vehicle development is deactivated. The information storage becomes smaller since the possibility to incorporate data

out of usage is given. The development cycle could in theory be endless, if no information storage is needed. The point is as soon as conventional development is finished no further vehicle or system testing is planned. In fact changes on the existing vehicle can only be done if the subjects do not require testing and simulation methods are 100 % reliable. An exemption are changes which can be tested without normal vehicle testing e.g. using component test rigs.

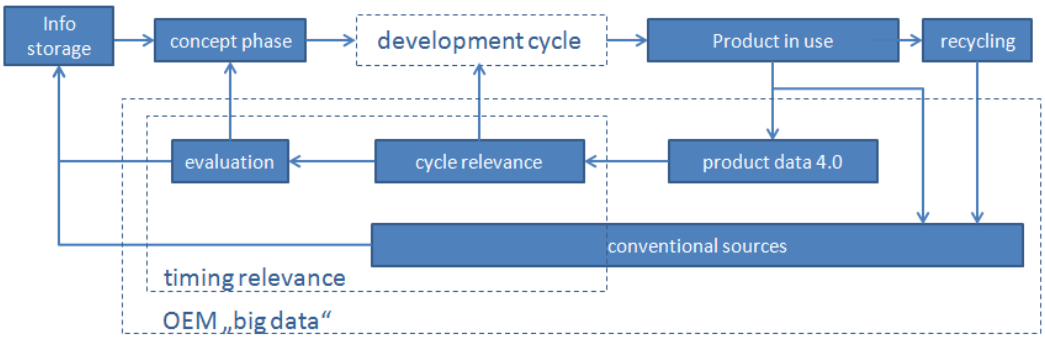

Figure 37: decision if a change can be introduced or must be done during the next concept phase

The product development cycle has a specific timing, which structures data into information which can be incorporated in a new product in a certain stage of the development process, and data which must be stored and evaluated for new products. Especially those components which need winter and or summer testing must be tested at the point of time when the team of test engineers is at the testing location – this shall be called seasonal testing.

The need to store information leads to staggered rework of vehicle platforms – figure 38. If new high relevant product properties relevant information is created that cannot be implemented in the continuous development process the store must be cleared and a total rework of the platform must be initiated.

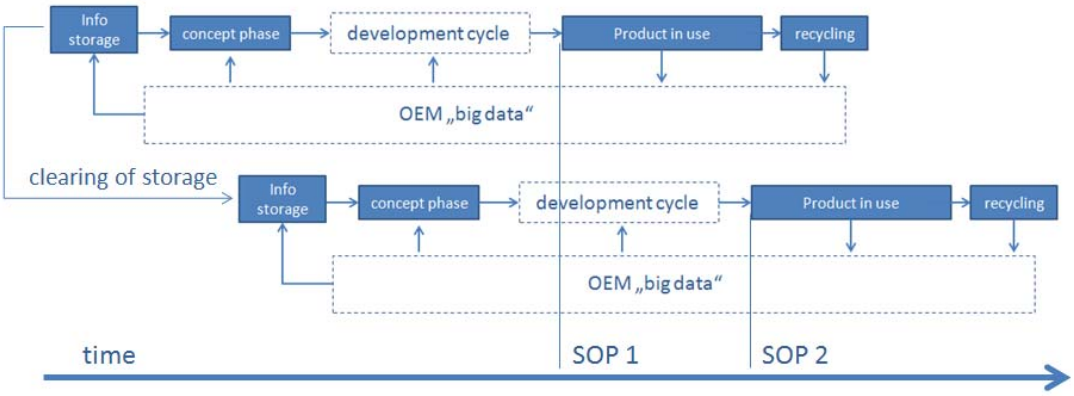

Figure 38: staggered vehicle development process

The consequence of this is that there will always be a point of time when a “new vehicle” of a certain platform must be introduced. Today this time span is approximately every 4-5 years. Customers with requirements which cannot be fulfilled within the timeframe between development and SOP are in the worst case lost if other OEMs offer vehicles with new features of customer value.

At first it is necessary to understand the motivation for new platforms or new vehicle types. Platform changes are mostly initiated to prepare the introduction of new technologies or new vehicle types. Motivators are e.g. the necessity to find space for

batteries for an electric drive, new lightweight concepts which ware important for CO2 consumption and drivability, or the continuous growth (outer dimensions) of vehicles.
Here again a clustering of values has to be done.
For example growth will be limited since otherwise the segmentation of the market will be destroyed – assuming an average growth e.g. of the track gauge [39] of 15 cm within 10 years in combination of the global trends like megacities, with traffic jams and a lack of parking space, or strict regulations regarding fuel consumption it becomes clear that the growth of the dimensions will be saturated not only regarding the vehicles with the highest dimensions. Also within the vehicle classes the growth is limited since otherwise an overlap to the next vehicle class would take place.

Lightweight concepts and alternative drive concepts have to be seen in a different way – they will sustain the necessity to develop new platforms as long as the technologies are mature.

This means that the need for platforms will be here also in the future. That's why we have to differentiate between new platform developments and the continuous development of existing vehicles. The continuous development cycle is important for development 4.0 with regard to the potential need to meet short arising but sustainable automotive trends.

Consequences of synchronization

As long as the development cycle time is determined by prototype testing and parts which need some time to be industrialized, the synchronization of the continuous data flow out of industrie 4.0 products can only be incorporated partially. The change of long running parts (determined by the time for tools) is at a certain stage difficult or not possible. The consequence is that a lot of data has to be stored in the information processing system as long as a new development cycle begins.

The synchronization of changes to be introduced in a development process becomes easier the shorter the development time for the affected modules of the systems is.
Stable and easy to modify modules allow to reduce the time necessary for the validation of the system in terms of interactions. The development 4.0 process is then in the best case reduced to the system development. It is clear that today not everything can be simulated and prototypes are not available immediately. But innovative production methods do already exist [31, 32] – e.g. there are concepts which could change the understanding of the development of body structure. Current steel, aluminum or other metals dominate the auto body. Future bodies could us a combination of 3D printing and fabric skins – see chapter development 4.0 methods.

4.2.2 Systems, modules and product families

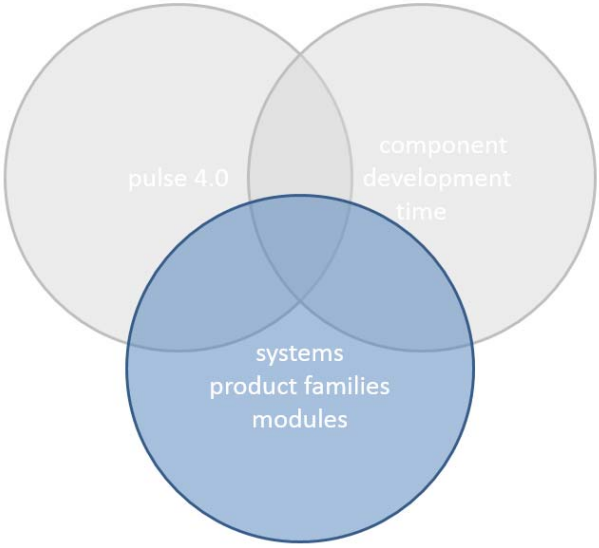

Figure 39: systems, product families and modules

During existence of a product, which is the time from idea to recycling, different kind of product data is created. In the context of development 4.0 two types of information clusters are important. The differentiation criteria is if the information leads to a change of a component or system and if the change can be implemented in the development 4.0 process. [34] Data is created by components and systems – systems that are flexible and evolvable are here of certain interest for development 4.0. This is since they have the potential to be exchanged during ongoing production and developed in the extended development cycle – see figure 38.

Whenever new technologies or optimizations of existing systems are created they are most likely infused at existing vehicle platforms. This is the most common case, since normally vehicles are not designed from scratch and there are already predecessors available. Even if new vehicle variants are designed the experience (platforms, systems, modules, components, etc.) of existing vehicles is used.

A method to decide which changes and innovations can fulfill the requirement to have a good customer value and are also affordable for the OEM regarding introduction is described in [37]. According to the idea of the authors the economic value of a technology infusion subject is defined as net present value. The second factor of interest is how easy a product can be implemented in the existing vehicle and its given manufacturing process at which risk. To describe the risk the wording invasiveness is used, and the structuring is done by technology groups from A-D, which are set into relationship to the expected economic value for the company - figure 40.

A: easy to implement but only small improvement
B: good return and low invest
C: highest return but high invasive and risky
D: invasive but only less value for OEM and or customer

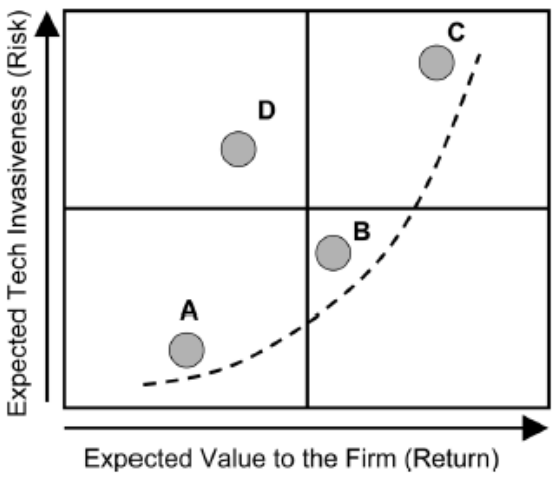

Figure 40: invasiveness and value, risk versus return of technologies [37]

To decide between different sets of invasive technologies a design structure matrix – figure 41 is used. The changes to this design structure matrix are optimized based on the evaluation of the aforementioned four categories. This procedure is a filter to find out which technologies can be implemented at which point of time (pulse 4.0) in a development 4.0 process.
The decision is made based on recommendation out of a Monte Carlo simulation which is done in the first step, followed in the second step by fuzzy Pareto filtering. The filtered scenarios should have optimal customer value, be good infusible (acceptable risk) and have an acceptable net present value for the OEM (or in other words an acceptable price for the customer).

4.2.3.1 Clustering of modules

This two dimensional model assumes that the customer value is direct proportional to sales which then leads in combination with suitable costs to an acceptable business case.

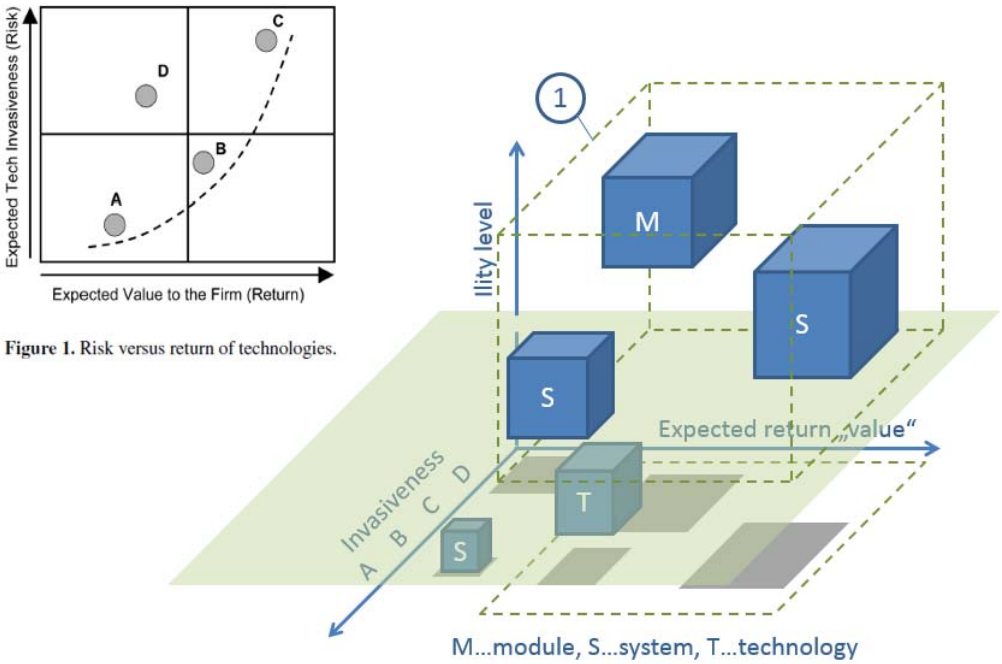

Figure 41: clustering of modules

Figure 41 explains that the possible changes must be filtered based on the evaluation of risk (invasiveness), business case (expected return or value) and customer value (ility/ivity). As described before the ility level consists of base requirements like quality and the level of differentiation having in mind the customer value (differentiator). Since the data which has to be considered is enormous (big data) and the decisions have to be made using an optimized scenario – all information must be networked and the evaluation must be supported by powerful simulation technologies. This 3 dimensional model reduces the number of possible changes figure 41 - ①. In fact a high ility level can be associated with an adequate number of sales.

Based on these factors the chosen systems must fulfill a further criteria which is the decision at with which pulse the change can be incorporated into the development 4.0 process – figure 42. Subjects which have a too long development time are not realized within the necessarily short pulse 4.0 cycle.

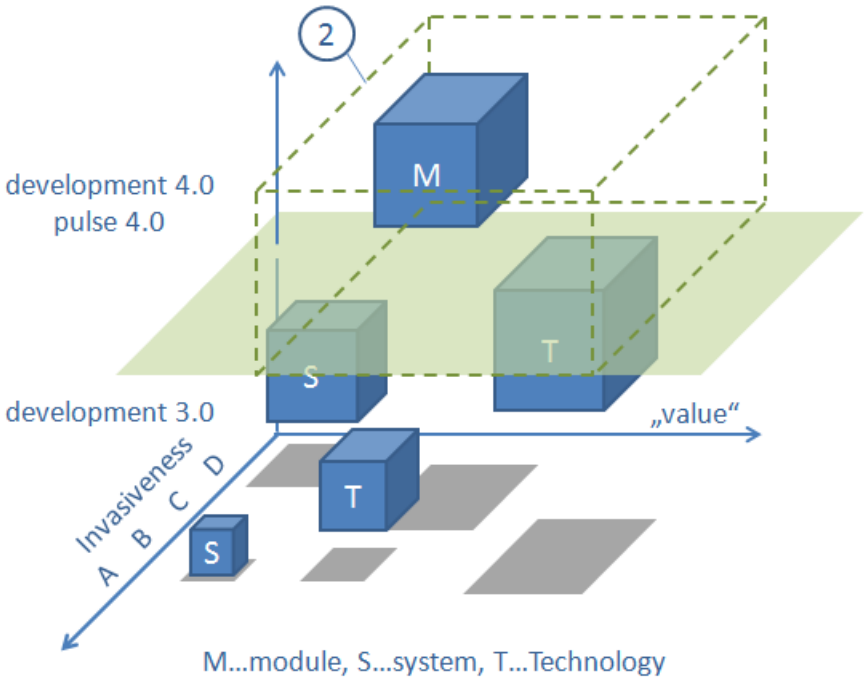

Figure 42: the influence of development 4.0 cycling – pulse 4.0

The decision process regarding which technical content will be implemented must consider the stage of development – and the current maturity of the product. The status of the hardware testing must be known in real time – this determines the pulse 4.0 – which is the frequency of possibilities to introduce changes and qualify them according to the quality target of the module or system. The combination of networked prototype hardware, vehicles in the field and the information out of big data leads to a cyber-physical system, which is one of the characteristics of development 4.0.

The components which are used in a development process need to know in which stage they are, and which level of maturity is reached. As soon as a need for change occurs the cyber-physical system requests the status of the component. This status includes the information that the module can be adopted at a given SOP, and which testing is necessary to qualify the change. If the next panned SOP is not reached the CPS can offer an alternative SOP which then leads to a different business case. Based on this information the SE Team can decide if the change will be initiated.

To calculate the pulse 4.0 the times for tooling changes and industrialization are needed. The influence of prototype hardware and industrialization will be explained in the next chapter. An example for a reduced number of elements ② - filtered by the criteria pulse 4.0 is shown in figure 43.

Before the decision is made the development department reviews the implication, checks the capacity of the engineers and decides if the proposal can be realized.
Based on this feedback the cyber-physical system will review the accepted or rejected ideas and optimize the suggestions to reverse the systems or modules in iterative steps.

4.2.3 Component development time

4.2.3.1 Prototype lead times

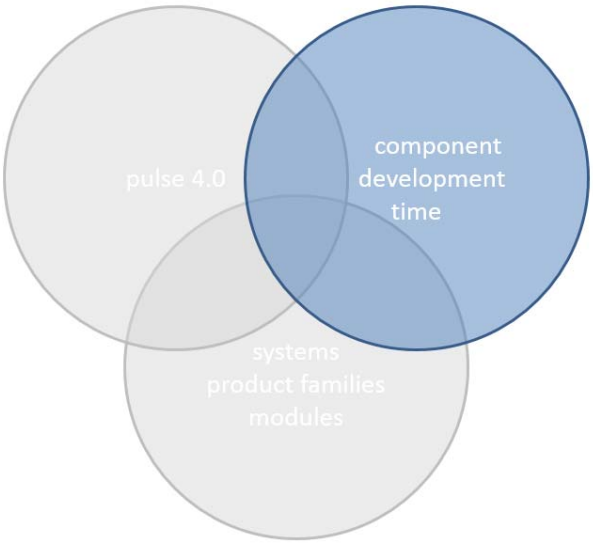

Figure 43: component lead time

Component lead time is important since it determines the total time for development. The development time for modules and systems consists of three parts – the time for design, prototype acquisition and the time for testing of the system. The series production method determines if a component can be modified in the current development cycle – or if a rework will be necessary based on a longer timeframe – e.g. after 50 month, during the development cycle of a new vehicle.

The potentials of rapid prototyping in terms of reducing the delivery time for prototypes are a fact. For example cast components are earlier available if rapid prototype foundry molds are used. Already in 1999 a reduction of costs and lead time by 80% was predicted for cast parts. Meanwhile this is reality. To save time from a testing point of view it would be necessary to strengthen the current rapid prototype processes and technologies to be used in a serial manufacturing environment – with a delivery time per component which allows to deliver in tact. Furthermore if rapid prototype technologies can be used to create series quality components the time for testing could be reduced significantly as well, since not parts out of series tools must be used for final tests.

4.2.3.2 Seasonal decoupling

During vehicle development it is important to test a car under all possible environment conditions. That means all components are checked during testing in the summer on hot locations – or during winter testing on cold locations. Normally more seasonal pairs of testing (summer and winter) are necessary – since the concept must be evaluated in the first step and then confirmed in the second step – this leads to a rough development time frame of two years minimum.
This can be shortened if climatic chambers are used. The problem is that the investment for climatic test rigs is high, which limits the amount of available test rigs at OEMs. For conventional platform development processes seasonal decoupling (independence from seasons) would bring more flexibility into the process, but it would not solve the general process of conventional development. At development 4.0 the necessity of seasonal testing is a core criterion in the filter process – each

change which demands seasonal testing on site in hot or cold climate without test rig would lead to a low pulse 4.0, thus the chance to incorporate the change gets smaller. Modules which depend on seasonal testing would be often excluded automatically from the development 4.0 process. Climatic test rigs would help to evaluate specific problems independent from the seasonal reality.

4.2.3.3 Simulation

Simulation as a tool is nowadays very powerful see figure 44 – the development time due to the improvement of simulation methods was reduced by 40 % between 2002 and 2008. The current state and the potentials of CAE are not discussed here due to the limitation of this master thesis. In the context of development 4.0 simulation is a key factor to reduce hardware testing with prototypes. In extreme if every detail and system of a car could be simulated and durability or quality over lifetime could be predicted by software. The pulse 4.0 time would be reduced to the necessary simulation time for the computers and the timeframe for industrialization of series components. Currently the reality is different high complex system must be tested in real life to a certain extent.
[61] One initiatives in the field of virtual vehicles and system simulation is for example the VIRTUAL VEHICLE Research Center in Graz, where 200 researchers work on different subjects in the mentioned field.

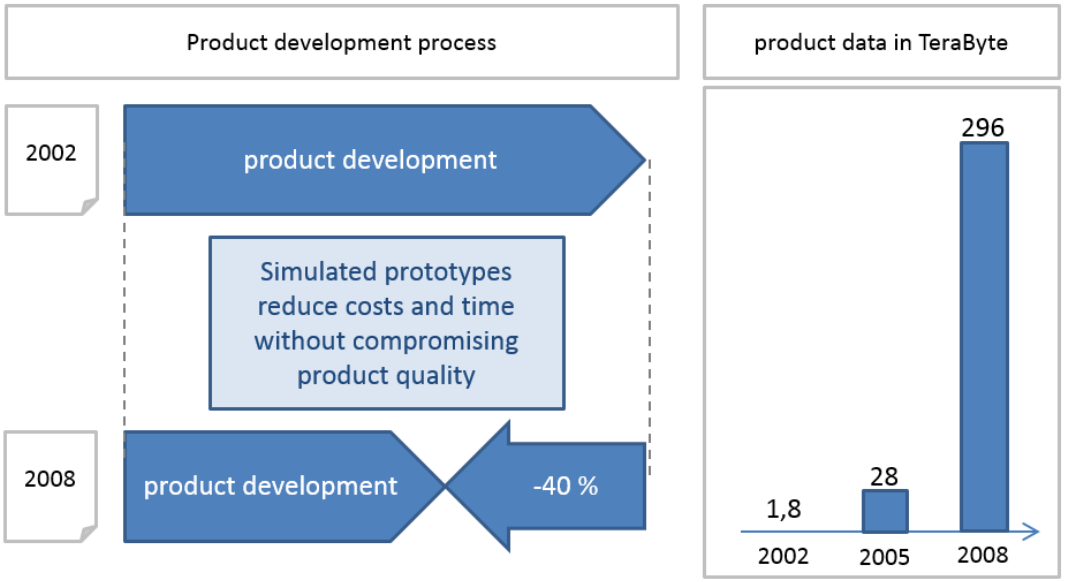

Figure 44: acceleration of development processes with simulation [16]

4.2.3.4 New production technologies – 3D technologies

In a car there are different materials used – structural parts are normally out of steel or aluminum. Outer skins are today already often made of plastics or carbon fiber.
Flexibility and short production times are contrary targets. Machining centers which are very flexible like milling stations are slow compared to if the same part can be produced e.g. in a press or when a component is injection molded. To get pressed chassis parts it is necessary to have large tools and press lines. The lead time for these tools and production facilities are long – e.g. up to one year. These factors determine time to introduce new vehicles as well.

A high potential to lower the gap between flexibility and production time could offer 3D manufacturing methods like printing or hammering.

3D printing and 3D hammering

3D printing of metals and plastics will become more important for structural parts as well as 3D hammering for sheet metals used in an automobile, as soon as the need for customization increases. Today there are already printers available to create molds for metal parts. The part itself is then casted based on the printed mold.

Figure 45: Königsegg One:1 – source Königsegg

Another example of 3D printing [52] is the exhaust tip of the Königsegg One:1 which was printed within 3 days and save 400 g of weight for the sports car.

One main influence factor on industrialization time is the time necessary to create sheet metal structures under series conditions. Ford has pointed out opportunities to produce sheet metal parts using 3D printing technologies [56]. The technology is called Ford Freeform Fabrication Technology (F3T) where a sheet metal part is fixed at the outer rim and then hammered into shape using a 3D hammering device. The process is currently limited regarding the production capacity but it is over all cheaper since no expensive special tools are necessary. This is possible as long as the amount of produced pieces is small and the costs for the low volume parts are lower than the tool. At some components the delivery time could be reduced from 6 month to 3 days due to the hammering process. On average conventional methods to produce sheet metal components take 60 times longer. The system is fully flexible since it has a similar principle as 3D printing machines. The 3D hammered sheet metal parts have according to ford the potential to customize vehicle bodywork. The project was done in cooperation with the Northwestern University, The Boeing Company, Massachusetts Institute of Technology and Penn State Erie.

3D printed plastics

Today there are already many different 3D printers for plastic available on the market.

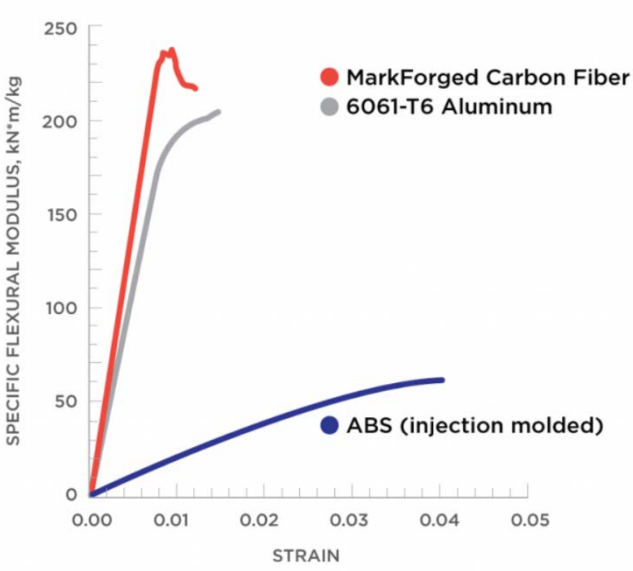

Figure 46: comparison glass fiber reinforced plastics vs. aluminum [59], [60]

The ultimaker 2 [57] has a layer resolution up to 20 micron and can build dimensions of 23 x 22.5 x 20.5 cm. The print speed is max. 300 mm/s and the travel speed is 350 mm/s with a nozzle diameter of 0.4 mm. Industrial printers like the voxeljet Vx4000 [58] offer dimensions of 4000 x 2000 x 1000 mm have a layer thickness between 150 and 300 microns and a vertical speed of 15,4 mm/h. This printer can fill his full available working space within 65 hours. Possible materials are polypor and silica sand for molds. To print the total volume of a passenger vehicle with a 3D printer would take approximately 8 days. Another key feature is the material used. Currently polyamide with reinforcement glass fiber is a common material in automotive components. This material can also be used by 3D printers [59], [60] the company markforged offers carbon fiber reinforced plastics with a higher strength than aluminum – figure 46.

An astonishing example of a body in white production was made by Edag [31], [32] where a “spider web” structure out of the 3D printer is covered with a water resistant fabric as light as 19g/sqm (in comparison paper has 80g/sqm) provided by Jack Wolfskin. The result is shown in figure 47, 48.

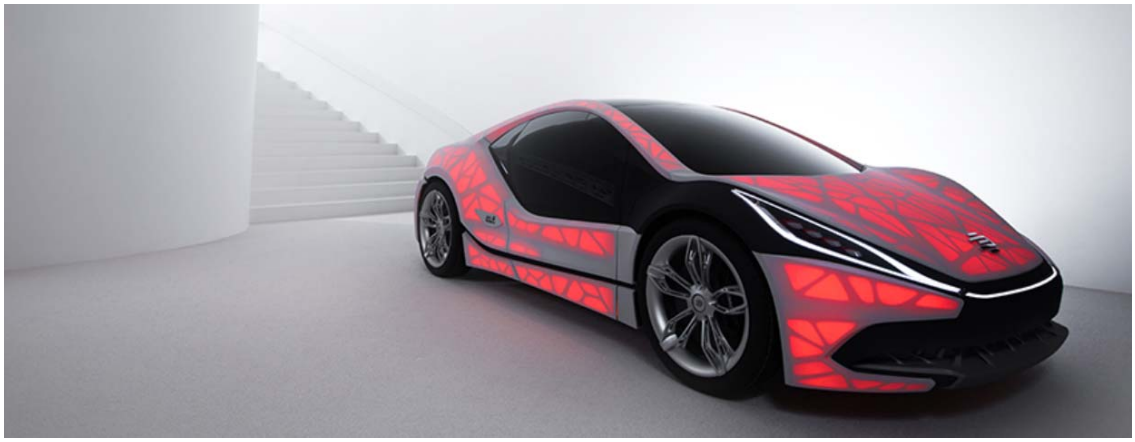

Figure 47: [32] Edag genesis concept

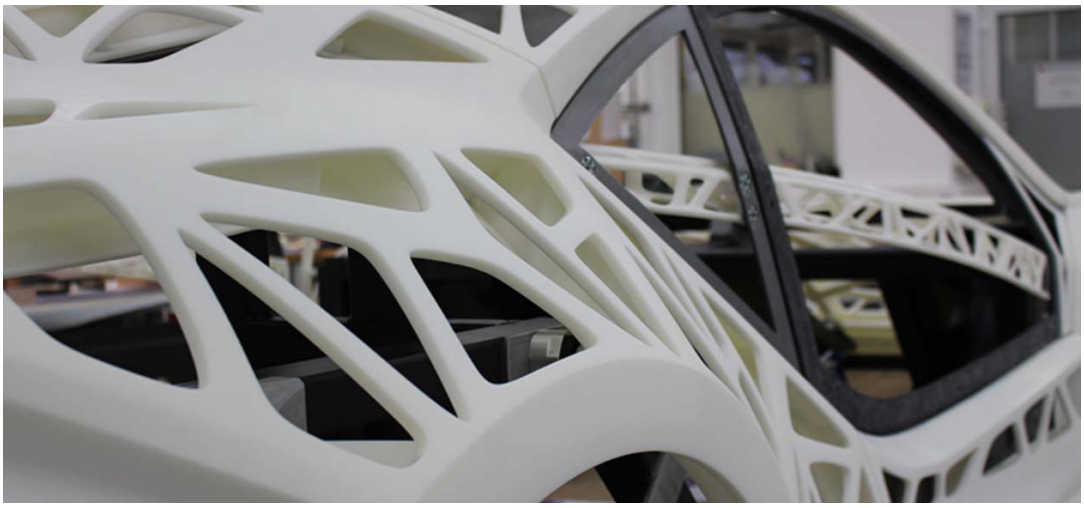

Figure 48: [31], [32] Example 3d printing technologies – self-supporting body.

The local motors strati – figure 49 was printed within 24 hours. It is an electric car with 3D printed chassis, interior and body. The strati uses a special reinforced carbon fiber to support the durability of the vehicle, which was developed together with the Oak Ridge National Laboratory.

Figure 49: Local Motors strati – 3 D printed car

3D Printing potentials

In the construction business there is a company named Yingchuang in China which prints houses (20 feet x 33 feet and 132 feet long) in less than 24 hours. [54] The walls are printed in concrete layer by layer with a computer controlled concrete extruder. The important fact here is the short time for printing large dimensions. If this comparatively short printing time can be achieved for other materials as used in cars – the potential for use in the car industry in the high customized segment could be high.

3D technologies are in my opinion possibilities to reduce the time for having prototypes and serial parts for small amounts of vehicle significantly. 3D printing and 3D metal forming methods could reduce the development and series introduction determining time down to approx. one sixth of today.

4.2.3.5 Best practice new technologies and product flexibility - Local Motors

Local motors [41], an automotive company founded in 2007 by Jay B. Rogers combines the idea of crowd sourcing and open innovation. Design and technology challenges are core processes. An open community of people decides which vehicle will be produced next, how it will look like and which technology is used. This process is supported by experts for design, engineering, etc. The designs and technologies are evaluated in an open challenge. After the end of the contest the winning design is selected and the development process starts.
During this design process a number of “standardized” elements are used like wire frames for the chassis, engines and gearboxes from existing vehicles, etc. The development effort is concentrates on subjects that are perceived as differentiators by LM Motors like interior, exterior, vehicle concept. After testing the components which are not purchased like existing parts from a supplier or OEM – the vehicle testing start (crash test, etc.). Apron finite element simulation is performed. Only 2000 vehicles per specific design are produced. Thus the costs can be reduced since for limited number of vehicles cheaper small series tools can be used.

Figure 50: source Wikipedia – LM Motors Rally fighter.

Another example of reduced time to market is the LM STRATI – see figure 49, which was the first 3D printed full functional car. The time to print the base of the chassis was 44 hours, which is much compared to the time necessary to produce a chassis in a conventional vehicle plant. But the 3D printing technology allows to implement changes easily. This level of flexibility will never be achieved for steel chassis – since the delivery time for tool, set up of presses, etc. would take approximately one year.

4.3 The influence of development 4.0 on industrie 4.0

Today lead times for tools and production lines dominate the timing for industrialization. To utilize the potentials of development 4.0 flexible factories are necessary. Components suitable for series production as well as flexible assembly methods have to be considered in industrie 4.0 production concepts.

4.3.1 Micro factories

The flexible assembly concept for cars in local motors production facilities is unusual. This is because it is done by the customer himself in one of the workshops called micro factories of LM Motors, with the help of experts within 3 days.
The target of micro factories is to build cars in the location where they are needed. The use of local products should help to reduce logistic costs, create local jobs, reduce waste and decrease the time to market. Since not every customer wants to assemble the vehicle on his own the concept could in the future be modified.

A similar scenario is explained in [45] where the vehicle production without tact is discussed. Here the high number of variants could lead to logistic problems if more and more different vehicle types are produced on one line. The fear is that the storage capacities that still are needed are not sufficient. The Frauenhofer Institute for Produktionstechnik und Automatisierung is working on a vehicle platform which can be produced without tact and line. The idea is to assemble not at the line but within free modules. Robots and transport systems work autonomous and are organized by an intelligent network.

4.3.2 Batch size one

The idea of batch size one – products based on customer ideas – already reality. [55] ideas2cycles is a non-profit project which was founded in 2010 by students in Finland from the Aalto University. They produce bicycles which are unique based on customer demand. For cast parts they use 3D printing technology to create the molds for the bicycle joints out of magnesium or aluminum. Pipes or other structural shapes are used to build then the frame.

5 Summary & conclusions

Future vehicles and automotive products properties will mainly be influenced by new technical and technological possibilities of information acquisition. Intelligent analysis systems will identify new trends out of big data with customer value (ilities and ivities) in real time. The sustainability of new ideas will be checked by simulation routines as well as the possibility to react according to these trends from an economic and capacity point of view. The chance to introduce new customer values short after they are identified will be a market advantage. The requirement for this ability is to have a flexible production system (industrie 4.0) and the ability to introduce changes within a development process that secures the necessary product quality (development 4.0).

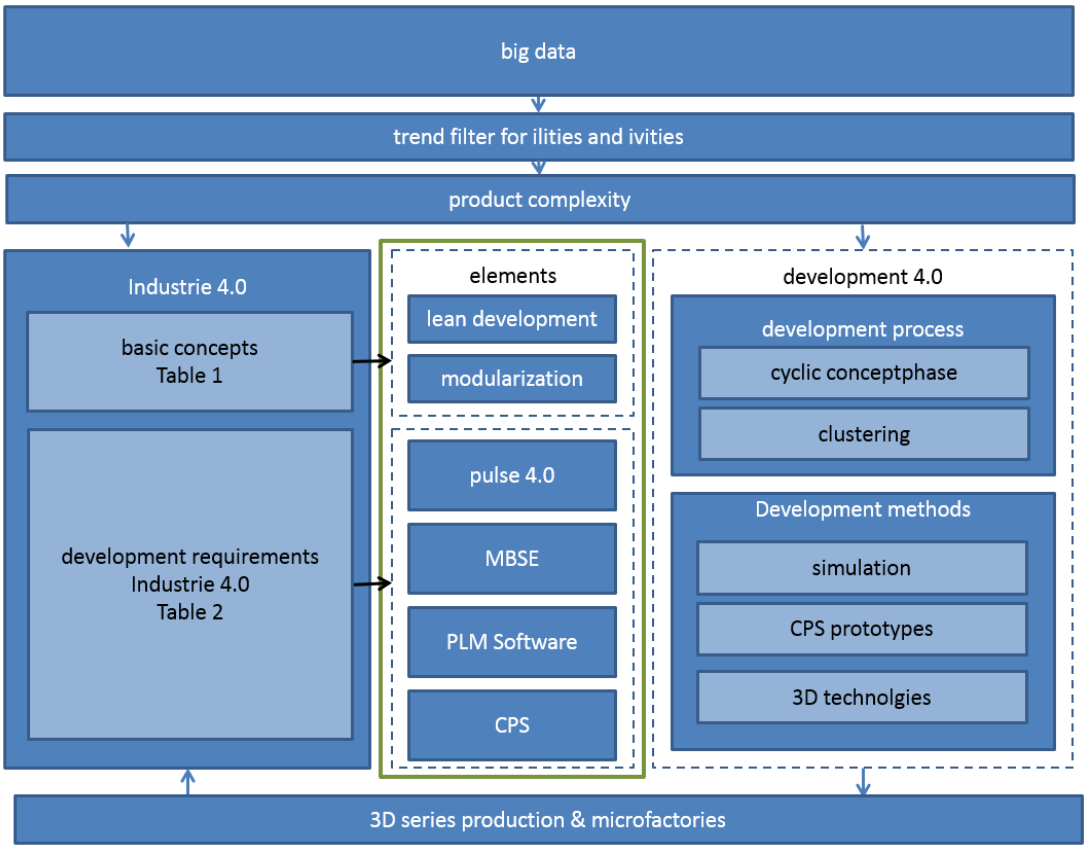

Figure 51: process determining factors of development 4.0

The basic concepts of industrie 4.0 SysLM which are relevant for development where identified and are summarized in Table 1 (page 52). Out of the comparison with the Toyota development process the base pattern of development 4.0 is the same like in lean product development. The buzzwords are “lean (new) stable processes” and “modularization” as examples. The difference becomes visible when the process stability plays a role. A lean development process prevents changes of systems or components in a late phase of development. The main reason is that the stability of the process is endangered if new components have to be tested and the testing takes longer as the planned SOP. Here the key factors of development 4.0 begin to play a role. By nature, to react on quick arising trends means to have the flexibility of qualifying the change (new system, new product, etc.) in time of the development 4.0 process (pulse 4.0). The process determining factor is the time for

development of a change and if it can be incorporated at the current stage of vehicle development.

To achieve an outstanding field quality emphasis on the concept phase is still a key process but is has to be seen in a different way as today. Product complexity, interdependencies between industrie 4.0, development 4.0 and timing begin to play a role. Due the introduction of a shorter development cycle time - pulse 4.0 – in combination with enhanced CAE methods the development time for the concept phase is reduced. The challenge is to shorten the concept phase, but to obtain the same quality. This can only be done by using CPS, self-learning routines and swarm intelligence. Development 4.0 is characterized by using data in the concept phase from previous projects including new real time data from field experience and the IoT. Checklists and other tools will become just backup`s as soon as artifacts and MBSE dominate the development process. The systems has the level of intelligence to understand the implications and the cross dependencies between the different properties in the context of PLM. The emphasis of the concept phase will still be crucial to the system development – especially when the development time is shortened – because of each problem which is not detected will become customer relevant – which has to be avoided by any means.

A CPS will identify the development stage of the affected system by collecting the maturity grade data of all its subsystems and components. In parallel the consequences of the change at a component have to be known. Can the change be qualified without testing just using CAE methods – or is functional and durability testing necessary. The first case leads to the necessity of improved simulation methods, the second to the optimization of prototype acquisition time using advanced rapid prototyping methods and accelerated testing which is independent of seasons – decoupled seasonal testing.

Product architecture is very important during the development process. The base is still front loading (see case study Toyota) which uses enhanced MBSE - artifacts. The model based system engineering uses information created by using and working on the model over the whole product lifetime. The artifact are linked in each step of the SysLM process. In contrary to the conventional development process the development 4.0 artifacts are modified by data created by the SysLM process of industrie 4.0 and the existing product. That is why it is so important to find similarities within systems – and keep the base information of modules as simple and compatible as possible.

5.1 Key findings – process factors

A high flexible development process for a complex product portfolio is determined by following factors.

Lean development is still the base process factor for development 4.0 – since it is high efficient and leads to results with good product quality

Modularization or reduction of complexity during development – clustering of systems, standardization, modules which are used cross platforms, etc.

“Continuous” vehicle or system development using relevant information out of existing vehicles and automotive products. In contrary to that the staggered product development leads to information stores and innovations that can be introduced only in 50 month time period vehicle development time.

Pulse 4.0 is a timing and decision process which answers a group of questions regarding does it make sense to introduce an innovation and can it be introduced at the current stage of vehicle development. If the frequency of Pulse 4.0 is longer than 50 month the innovation has to be incorporated in the next vehicle generation – in case it is lower it can be incorporated in the current development process.
Important is that there will still be a clustering of innovations, but the SOPs could be shortened e.g. down to two or three years if necessary.
The key method of Pulse 4.0 will be the use of CPS, swarm intelligence of development and field vehicles and artifacts as well as artificial intelligence support to find a decision about what to develop and when.

MBSE – Model based system engineering and artifacts improve current CAE methods to a virtual product development – and avoid the need of hardware testing.

Reduction of time for hardware tests – lowers the timing risk if prototypes are needed and testing has to be done – by using climatic test rigs.

Rapid prototyping 3D methods – reduction of acquisition time for prototypes or serial parts depending on the quality level of the rapid prototyping quality.

Industrie 4.0 is necessary to produce high flexible products due to the overall high product complexity

5.2 Scope of application

Industrie 4.0 offers production flexibility – supported by development 4.0 it can be used to integrate product content and changes with high speed to meet quick arising market demands or to customize cars based on ideas of a specific customers. The remaining question is if the customer needs and accepts this flexibility. In design theory there are possible answers to that. Dieter Rams [38] describes what a good “design” implies and during the art period “Vienna modernism” (1890-1910) [38] the term “Gesamtkunstwerk” was introduced.

Rams 10 principles of good design are

Good design is innovative
Good design is useful
Good design is aesthetic.
Good design is understandable
Good design is unobtrusive
Good design is honest
Good design is long-lasting
Good design is thorough down to the last detail
Good design is environmentally friendly
Good design is as little design as possible

These principles are in my opinion not only valid for classic design subjects – they are valid for vehicles and their properties as well. The challenge will be to develop things with customer value in short time which fulfill the criterions of good design as well.

The term “Gesamtkunstwerk” is a synonym for the completeness of a product. The question is if a product that can be customized down to batch size one will be perceived as complete which is important for the perception of the quality of a product. The expectance of quality is mainly influenced by the completeness of the product. The desired level of completeness is derived from the predecessor vehicle. The more the predecessor car is perceived as “complete” the higher the confidence in the quality of the new vehicle will be. The risk is that if everything is exchangeable, in batch size one the product is never complete.

For people who love innovation, customization and want to experience the power of flexible products the combination of industrie 4.0 and development 4.0 will be the right choice.

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Band 4.2: Sicherung der Qualität vor Serieneinsatz (FMEA)
Band 4.3: Projektplanung
Band 6: Grundlagen für Qualitätsaudits - Zertifizierungsvorgaben

Band 6.1: QM-Systemaudit
Band 6.2: Systemaudit - Dienstleistungen
Band 6.3: Prozessaudit
Band 6.4: Systemaudit - Produktionsmittel
Band 6.5: Produktaudit
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