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MATURITY-MODEL-BASED DESIGN OF STRUCTURAL COMPONENTS

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1. Introduction

The impact of computer-aided (CA-) technologies in contemporary product development is generally accepted. Here, one of the main challenges is to maintain an all over closed tool and information chain in development and manufacturing in order to use and process existing knowledge within digital prototypes. Especially in automotive development, special software packages have become accepted for certain niche design activities like generation of mechanical concepts and structures. A bidirectional communication between such tools and the corresponding computer-aided-design (CAD) systems is still a lack in most cases since the single systems are addressed via specific data types that are not fully translatable in common exchange formats [Hirz et al. 2013].
Additionally, depending on the progress in the development process, a designer uses geometry with a certain abstraction level or level-of-detail in order to keep simulation and optimization loops as short and efficient as possible. Information exchange between design and simulation departments is highly frequented since weight optimization is of high significance in automotive engineering [Dungs 2008]. With respect to digital prototypes, these levels of abstraction are also related to modelling efforts of the single CAD models. The higher the level-of-detail of a CAD model, the more complicated is the formulation of a model that is robust against conceptual and parametric changes in order to set up a large solution space the designer can configure his model from [Vajna et al. 2009].

1.1 Motivation

There exist a number of contributions which show highly specialized development processes and tool chains for applications in the automotive sector, e.g. car body design or chassis design, as well as for design of truss systems. A general framework for the design of structural components is only formulated in an abstract way in design methodology literature [Koller 1998], [Roth 2001]. Other contributions are set up on the breakdown of the development process introduced by Pahl/Beitz [Pahl et al. 2013]. Here, in a first step of coarse drafting, dimensional aspects as well as layout and material requirements are determined. Based upon this, the clarification of all spatial boundary conditions leads to the design of the component's architecture. In the following steps, the shape of the individual components is determined and then increasingly refined.
With regard to the use of CA-tools for the development of structural components, there are numerous sources of literature that consider both specific methods as well as specific applications in detail. The mapping of each (sub-) stage of development through closed synthesis / analysis tool chains is examined in the field of structural optimization, whereby the focus is set on single features and strengths of each method. An overview can be found in [Saitou et al. 2005] or [Zavala et al. 2014].

A general framework that sets design methodological aspects and the relevant CA-tools in one context is not known until now. Within this article, the authors present their current research on such frameworks and the formulation of a maturity model based upon CA- synthesis and analysis tools.

1.2 Structure of the paper

The remainder of this article is structured as follows. In section 2 the theoretical framework for the development of structural components and maturity-models is presented. Based upon this, section 3 introduces the maturity-model based approach form point of view of requirements, boundary conditions, design parameters and CA-tools. Section 4 then contains an application example of a structural component of a wheel loader. In the final section 5 the conclusions and further research questions are presented.

2. Theoretical background

In this section the theoretical background for the development of structural components is described. At first, different aspects for the design of such parts are summarized and categorized into a classification scheme. Afterwards, the theory behind maturity-models is briefly characterized.

2.1 Development of structural components

Structural components are a part of nearly all technical systems which contain functional elements that use mechanical energy as either input or output. So, such a structural component is described as product component which purpose and main function is to absorb or transmit mechanical energy in form of forces or torque [Gembarski et al. 2015]. This group of parts is thus of great importance because without them the overall function of most technical systems could not be realized. In practice numerous technical systems can be found that illustrate this aspect, Figure 1 illustrates four such product components exemplary. A closer look reveals that the components shown in spite of functional similarity (transmission of forces / torques) have a completely different shape.

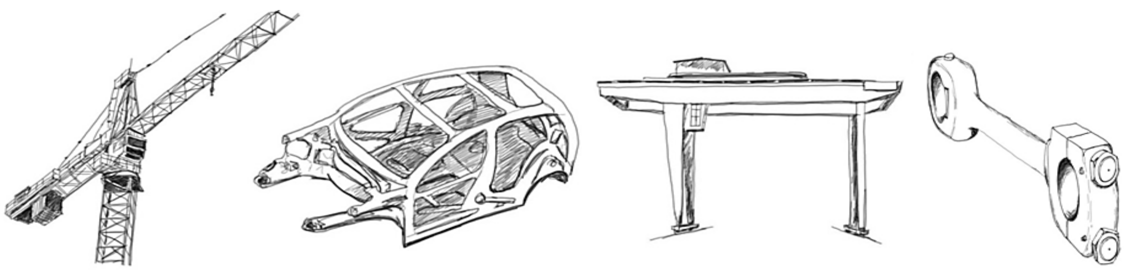


Figure 1. Different structural components

The tower crane mainly consists of truss structures, which is due to the size of the structure and the requirements regarding assembly and transport. Out of beams and ropes, especially lightweight structures can be created that stand large forces and deform only little. The main load direction is clearly describable, the load case for most parts of the structure is bending [Scharnowski 2011].
The vehicle body is considered as differential design of beams and sheet metal. The physical design space is severely limited by the given aesthetic requirements and the interfaces to adjacent components. The load application points are multiple, load cases usually may not be derived analytically for each area. Thus, there is no globally definable load case [Dungs 2008].
The travelling bridge shown in Figure 1 is designed as box construction which is compared to a truss framework clearly more massive despite the lower working space. This is due to the fact that the travelling bridge is dimensioned for much larger loads.
The connecting rod in turn is designed as integral construction. The load cases are clearly defined on the basis of operation in a piston engine and described analytically, so the design is comparatively easy. The design as massive forming part is due to high occurring forces and the required lightweight goal. Additionally, the design allows a good production efficiency since the manufacturing process is of mass production character.

These examples illustrate that a variety of application specific boundary conditions affect the shape of structural components that need to be taken into account during development. With respect to the functional requirements of power transmission structural components can be differentiated according to the classification shown in Table 1.

Table 1. Design aspects of structural components

Index	*Type of boundary conditions*	*Single boundary conditions and restrictions*
1.	Load Application Points	Number, location and orientation of load application points.
1.1	Load Cases	Number, value, direction and orientation per application point.
1.1.1	Physical Design Space	Number, location and shape of restricting areas.
1.1.1.1	Pre-fabs and Raw Materials	Geometry and material.
1.1.1.1.1	Manufacturing Technologies	Available processes and their design guidelines (process related like all types of welding parameters, combinatorial restrictions due to jig design etc.); logistics and transport restrictions (clearance outlines, container sizes, weight); final assembly; lot size

The illustrated distinctive features provide a step-by-step exploration and limitation of the possible solution space for the development of structural components. In this article, a workflow sequence is derived from the described classification index, in which the boundary condition groups should ideally be taken into account in the development process. Nevertheless, the shape of such components is furthermore triggered by additional boundary conditions like stiffness and strength, fail-safety, economic requirements like cost effectiveness or lightweight design. In Figure 2 the classification is applied to the four example structures above. The required properties are included as attributes in terms of their case-specific relevance.

The groups "load application points" and "load cases" are strongly simplified in this catalogue. More specifically, the four examples presented differ in the first classification point due to the different position and orientation of the load application points. Nevertheless, the diversity of different shapes and geometries due to the single characteristics is adumbrated.

Based on the application examples the decisions made during development can be derived in terms of design: A fundamental decision concerns the architecture, here a distinction is made between differential, integral, composite and modular design. Here as a great driver, the dimension of the structural element due to the position of the force application points and the physical design space has to be considered. On the one side, semi-finished products are available only up to a certain size. On the other hand, the capacity for machining, in-house handling, transport and final assembly must be taken into account. In simple cases, the semi-finished product to be used is determined directly from the type of load, as this can be assigned due to its geometric characteristics. But in the majority of applications this statement is not possible due to functional requirements (e.g. the position of the load application points) and the disability to predetermine load cases and their superposition in every use case. Therefore, semi-finished products (pre-fabs) need to be combined in accordance with these requirements. Regarding the vehicle body, certain pre-fabs can be used for individual areas due to the prevailing type of load. Their combination determines the overall behavior of the structural component. Referring to the travelling bridge, this is different. Here, the load case is known, but no pre-fabs exist that are large enough, so a suitable intersection has to be composed of other existing, simpler pre-fabs like metal sheets.

The question which pre-fabs have to be combined in which way is particularly hard to answer, when the number of force application points is high and the kind of force introduction is very diverse. Then, different variants of a structural component are gradually adapted in multiple synthesis and analysis loops to the boundary conditions and the required properties.

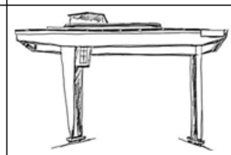
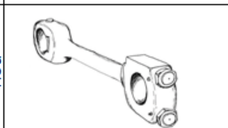
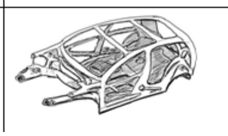
Index Structure					Application Example		Selection Characteristics				
Load Application Point	Load Cases	Physical Design Space	Pre-fabs	Manufacturing Technologies			Stiffness	Strength	Durability	Leight Weight Design	Cost effectiveness
few	few	little restrictions	Beams and Sheet Metal for differential construction	Technologies of steel construction, specific assembly conditions	Tower Crane		mid	high	high	high	mid
				Technologies of steel construction, no specific assembly conditions	Travelling Bridge		mid	high	high	low	mid
		severely restricted through bounding box	solid construction	Forging	Connecting Rod		high	mid	high	high	mid
multiple	multiple	severely restricted inside and outside	Beams and Sheet Metal for differential construction	Technologies of automotive design	Car Body		high	high	high	high	high

Figure 2. Classification catalogue for application examples

2.2 Maturity models

According to Akkasoglu maturity models represent a step-by-step development model of a specific and quantitatively difficult describable viewing object (i.e. process, product or system) in order to determine the maturity level based on qualitative indicators. The maturity in this case represents the development status of a particular evaluation gate" [Akkasoglu 2008].

Maturity models are often used in conjunction with software development projects or process and organizational development. Known approaches are the Capability Maturity Model (CMM) or Software Process Improvement and Capability Determination (SPICE). A very well-known maturity model with respect to the development of physical items is the Technological Readiness Level (TRL) which was pioneered at NASA [Oberkampf 2007]. Maturity models originate from the necessity of shortening product development times. The basic idea is that some viewing object may be assessed even in early stages of product development through distinct dimensions and criteria. So, the development process can target the most favorable design.

3. Maturity-model based development of structural components

Based upon the above considerations, a maturity model based approach with 4 distinct maturity gates is proposed:

1. Gate: Determination of a structure concept to define the structural shape is finished.
2. Gate: Definition of main parameters regarding geometry and architecture is finished.
3. Gate: Embodiment Design of single Parts is finished. Within this phase, the product architecture is not altered any more, geometry is changed only locally.
4. Gate: Detail design of all parts finished, all parameters and characteristics which are necessary to manufacture the component are known and documented.

In order to introduce and justify this division of the development process in four maturity levels, three different views are presented in the following sub-sections. The first consideration is carried out on basis of the required properties, boundary conditions and their hierarchical structure mentioned above. Secondly, the shape definition in the different phases is discussed with regard to design parameters. Finally, CA-synthesis and analysis tools are associated with the phases.

3.1 Maturity level consideration based on constraints and required properties

The described scheme of boundary conditions is suitable for a more distinct characterization of maturity levels because different characteristics are focused in the phases differently. In Table 2, the constraint classes are assigned to the four phases.

Table 2. Constraint classes

	Structural Concept Model	Bar and Shell-Model	Solid Model LoD1	Solid Model LoD2
Characteristics	physical design space	physical design space	physical design space	physical design space
	loads	loads	loads	loads
	load application	load application	load application	load application
		pre-fabs	pre-fabs	pre-fabs
		manufacturing technology	manufacturing technology	manufacturing technology
			manufacturing restrictions	manufacturing restrictions
				adjacent design restrictions
Properties	stiffness	stiffness	stiffness	stiffness
	weight	weight	weight	weight
		strength	strength	strength
			manufacturing concept	manufacturing concept
			assembly sequence	assembly sequence
				manufacturability (quality and process stability)

In phase 1 (structural concept model) the first three structural classifications "load application points", "load cases" and "physical design space" are addressed. As it is shown by the above-mentioned catalogue, these three constraint types are largely decisive for the basic structure of the structural component's shape. In phase 2 the essential geometric parameters describing the building structure and also the available pre-fabricated products and production technologies are included as constraints. Nevertheless, if force application points, load cases and physical design space are identical, still different designs result due to different boundary conditions with regard to semi-finished products and manufacturing technologies. In phase 3 - if the product architecture is finalized and frozen - the specific manufacturing technology and design guidelines for detailed design of all parts are considered. These are extended in phase 4 then by adjacent design activities like tooling and fixture design which can only be executed on basis of the fully detailed production design.
In addition to the boundary conditions, the required properties can also be assigned to the four stages. In the first phase the developed structural concepts can already be assessed with regard to stiffness and weight, although no exact statement can be made. The second phase allows a basic evaluation of strength due to the additional description of the contour. Stiffness and weight can be determined more precisely at this phase. Also, due to the consideration of pre-fabs and production technologies a rough cost estimate is already possible. Phase 3 allows a more exact evaluation of the targeted properties. Here the focus is in the assessment of the production concept and the assembly sequence. Finally, in phase 4 reliable predictions of all properties are available. Also, manufacturability and related characteristics like manufacturing quality and process stability may be determined.
The sequenced focusing of different characteristics leads to a stable development process. However, it should never be forgotten that the development of structural components is a multi-criteria optimization problem which always has dependencies due to the underlying mechanical field problems. The proposed approach systematizes the development process in so far that the interdependencies between shape parameters, boundary conditions and properties are easier to understand and to consider.

Furthermore, the use of design guidelines like Design for Manufacture and Assembly (DFMA) and applying this framework are not a contradiction. The framework points out that the manufacturing technology has already to be considered in a very early stage when the structural concept is known. Here, DFMA may deliver valuable information for the later design of the different solid models.

3.2 Maturity level consideration based on design parameters

The different design parameters which are specified in the corresponding stages lead to a further perspective within the model. Roth, Koller and Pahl / Beitz classify design parameters (though slightly differently) that are necessary for a complete description of components, as follows:

- Topology: Parameters describing the inner structure of a part are related to this group. From a mathematical point of view the topology defines the number of invariant regions of a part definition, e.g. the number of holes in a profile.
- Dimensions: All parameters which define main dimensional characteristics of a part, like length or angle dimensions are related to this group. Depending on the topology this parameters are the framework for the parameters and dependencies of the following parameter groups.
- Shape: Roundings, fillets and special designed surfaces of a part – commonly described as shape or contour – append several design parameters to characteristics.
- Number of elements: Focusing shape elements which special functional properties there are parameters to describe the number of such elements, e.g. the number of sprockets of a gear or the amount of stiffness ribs of casting parts.
- Tolerances: In Addition to the solid definition of a part there are tolerances for dimension, position and shape. Related to manufacturing this group is also important because for the definition of tolerances the capabilities of the manufacturing technology have to be considered and may e.g. have severe impact on the stiffness properties of a welded machine base.
- Technical Surface: Surface quality regarding roughness, orientation of grooves or surface hardness also belong to the group of attributive design parameters which are not explicitly modelled e.g. in CAD. Nevertheless, their applicable definition depends on manufacturing capabilities.
- Material: Finally there is the definition of material which includes the determination of the corresponding physical properties like density, modulus of elasticity, etc.

Table 3. Design parameters for structure and single parts

	Structural Concept Model	Bar and Shell-Model	Solid Model LoD1	Solid Model LoD2
Structure	Topology	Dimensions	No Degrees of Freedom, product architecture frozen	
	Contour	Count		
	Material Family			
Single Part	(Material Family)	Topology	Topology	Contour
		Contour	Contour	Dimensions
		Dimensions	Dimensions	Tolerances
		Material	(Material)	Technical Surface
		Tolerances	Tolerances	

In relation to the levels of maturity this classification refers to both the entire structural component as well as on the single parts which is summarized in Table 3.
In the first phase, the topology of the structural component and the contour in a simplified manner is mainly defined. With respect to the material, a basic definition of the material family (steel, aluminum, composite) is necessary. The parameters of this class allow the previously explained analysis of stiffness and weight. In the second stage, the definition of the single parts and the determination of the product architecture lead to the determination of the dimensions of the parts within the entire structural component as well as their count.

For the parts, a design of the topology, the contour, component dimensions, the material and coarse tolerances is carried out. In the third stage the product architecture is set and frozen, so no further definition or variation occurs at the level of structure parameters. Regarding the parts, topology, shape, component dimensions, material and tolerances are available for variation and detailed definition. In the fourth phase, the majority of design parameters are fixed and only parameters of the classes contour, dimensions and tolerances may be varied until the structural component is finally documented.

This view allows focusing on the required properties as well as structuring them. Moreover, the consideration of relevant design parameters is forced, which is important for application of optimization methods in order to keep the number of parameter variation as small as possible. Also with regard to classic drafting and embodiment design the defined assignment leads to focus on the crucial parameter classes. However, it is to be noted that structural components may have a very large number of design parameters. The division into the outlined classes provides only a first level of structuring. Another classification is therefore advisable, however, due to the application- and company-specific characteristics, this is not further considered in the present article.

3.3 Maturity level consideration based on CA-Tools

Especially in the development of structural components CA- synthesis and analysis tools are now indispensable, since on the one hand shape and parameters can be documented, on the other hand, mechanical properties such as stiffness, weight and strength can be determined by numerical calculation tools in good accuracy.

Table 4. CA-Tools

Structural Concept Model	Bar and Shell-Model	Solid Model LoD1	Solid Model LoD2
3D-sketches + FE-Model	2D-Surface-Models + Shell-FEM	rigid 3D-Solid-Models + 3D FEM	3D-Solid-Models + 3D FEM + Sub-models (e.g. welds)
Topology Optimization	1D-Line-Models + Bar-FEM	parametric 3D-Solids + 3D FEM	Manufacturing Process Simulation (e.g. Casting)
analytical analogous models	1D/2D Surface-Models + Shell and Bar FEM	GDA-Model + 3D FEM	CAM-Simulation
	Concept Modellers (SFE Concept)	Contour Optimization	
	Sizing Optimization		

Furthermore, the tools of structural optimization offer the possibility of synthesis-analysis loops to vary parameters automatically in terms of property optimization. With respect to the synthesis-analysis loops, single tools are combined to form development environments. In Table 4 the single tools are associated to the maturity levels. It can be seen that the commonly used models also have maturity levels.

During the first phase very simplified models are used, since the models in the fourth phase will be (almost) able map all design parameters and determine many properties. Finally, it can be summarized that due to the illustrated maturity model, including the three different perspectives on the development of structural components, the CA-development process can structured and specified in detail. To illustrate the development of the model of the mechanical structure of a wheel loader front frame is described in the following section.

4. Application example

Excavators and Loaders are exposed to significant forces due to the weight of the excavated material. Many such machines - such as the wheel loader with articulated joint depicted in Figure 3 - have a loading device to dissolve, absorb, transport and deliver the excavated material which consists of a hydraulically driven mechanical mechanism. The frame in which the loader is mounted - called as front frame - has to be of high rigidity for proper functioning. At the same time, a robust and reliable design is expected by the customer. The front frame has the main function of transmitting forces which are introduced by the loading device during operation to the contact points, i.e. the front and rear wheels.

The application of force to the rear wheels is done via the articulated joint, that connects the front and rear frames. Additionally, the forces occurring while driving must be taken by the front frame.

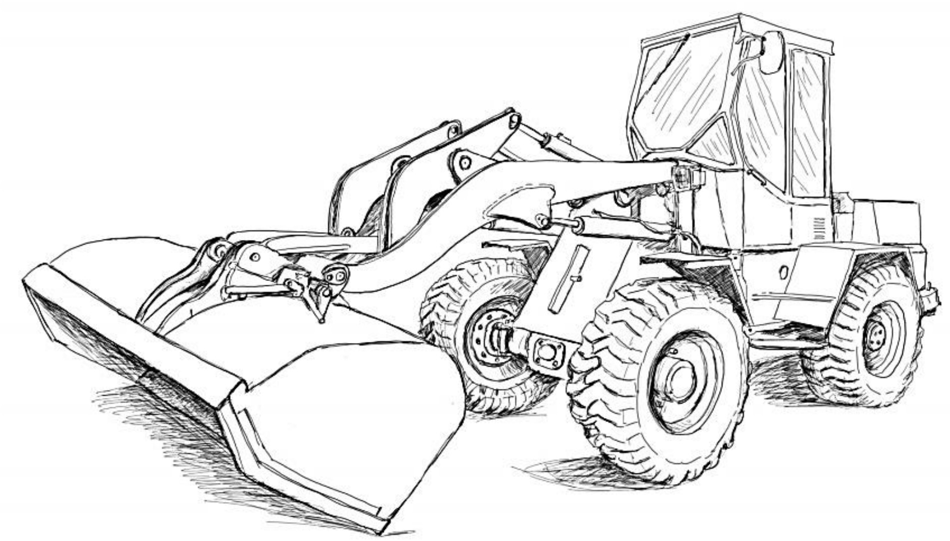


Figure 3. Wheel loader with articulated joint

The front frame can now be examined with the systematics described above in terms of constraints: The load application points are defined by the bearing points of the kinematics of the articulated joint and the front axle. The load cases are derived from operation of the loading device and the chassis. With respect to the physical design space, restrictions are introduced by front axle, loading device, wheels, cab and rear frame. Due to the dimensions of the front frame and small series production metal sheets and profiles are mainly used. Therefore, most front frames of wheel loaders are designed as a welding construction [Kunze et al. 2013].

To discuss the maturity model not only on the final result, the third viewpoint of the maturity model, the computer-aided modeling, is shown for the example front frame in Figure 3.

In the first maturity level coarse structure concept models are designed on the basis of load application points, load cases and design space. These differ in the way in which the force introduction points are connected. For this purpose, the geometries are modeled in a simplified way by sketching and sculpting features designed with a CAD tool. The calculation is done by FE tools which analyze the stiffness properties. Both models are also suitable for calculating the weight. In addition, the use of net-based topology optimization tools with a wheel loader front frame is conceivable. The final result of both development environments is similar: A structural approach, which includes topology and a rough outline of the entire component (Figure 4, left part).

In the second maturity level the use of surface models makes sense to keep modelling efforts low and thus to investigate various building structures. Surface models can be used very well for finite element modelling of shells which then calculate stiffness, weight and strength in the required accuracy. For the computer-aided optimization the use of the sizing optimization is possible, which also is usually based upon shell models. Focusing on manufacturing technology and pre-fabs which has to be considered accordingly to this phase, welding and metal sheets as well as profiles are favorable in this context. Thus, two different architectures may be choses, the one is truss (like the tower crane in Figure 2), the other is box and plate design (like the travelling bridge in Figure 2). With respect to these boundaries, the results of phase one are interpreted by the designer. Since the physical design space leads to a relatively compact design that has to handle relatively big forces, the latter architecture is chosen for further detailing. In this phase two, one work package is the examination of different pre-fab combinations and the variation of their joining techniques. So, different shell-bar combinations are modelled and evaluated by FEA. The resulting design is depicted below (Figure 4, center part).

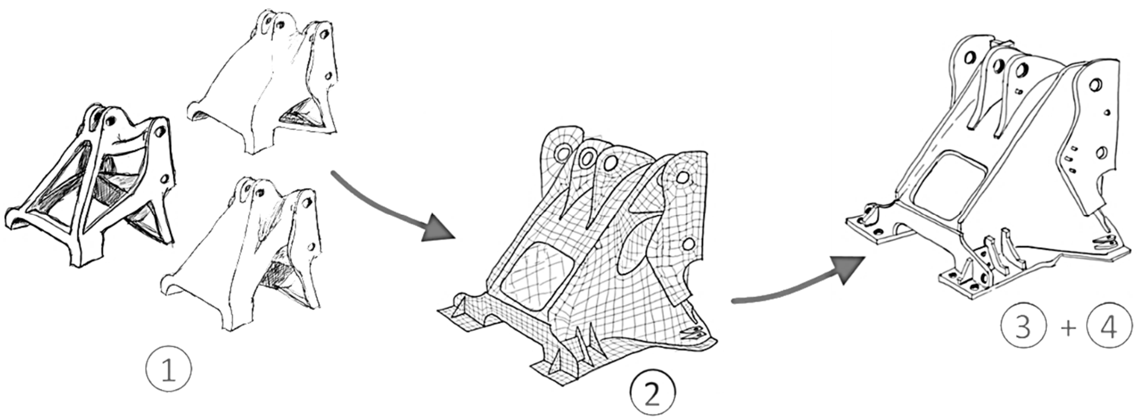


Figure 4. Maturity model based development of a loader front frame

In the third and fourth phase parametric 3D solid models are used (Figure 4, right part). These provide the necessary level of detail. For calculation, 3D solid FE models are used and where necessary for detailed questions, sub-models, e.g. for welding analysis can be introduced. For local strength optimization, for example in the area of the outer contour of the central web plates that serve as attachment for hydraulic cylinders, also net-based shape optimization methods are used. The main difference between these phases is the possible solution space. While phase three focusses on the trade-off between all reasonable constraints (e.g. assembly sequence, over-all manufacturability) and the connectivity to neighbor parts in final assembly, the emphasis in phase four is on final optimization (e.g. tolerances, final product assembly).

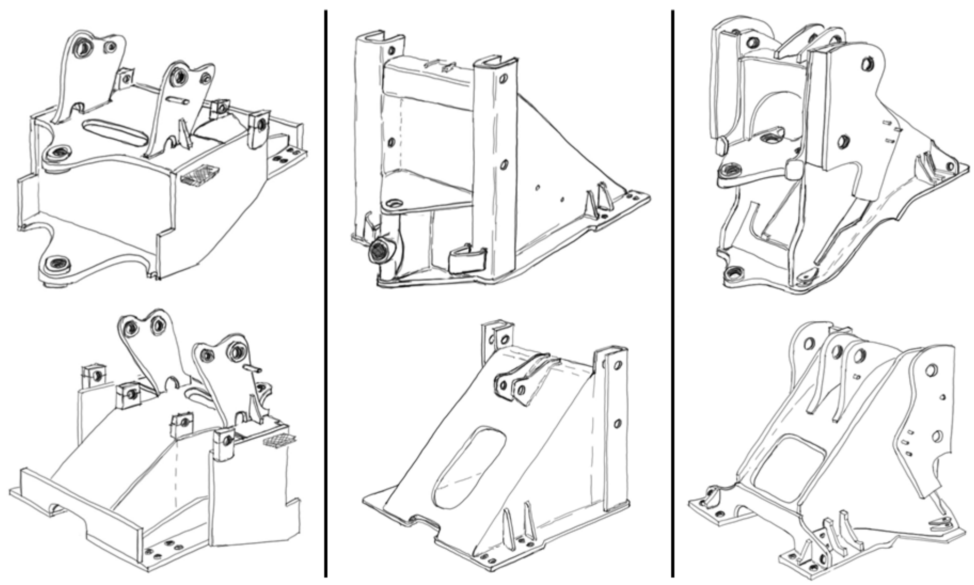


Figure 5. Different designs of wheel loader front frames

The perspective on the maturity model on the basis of CA-tools shows that the engineering of all three models can be done despite their individuality through the maturity model, as problem, design task and selection of CA-tools includes the necessary similarity. Beside the described example, the framework is used in two actual case studies in automotive engineering.
The authors would like to remind, that due to company- and product-specific boundary conditions, restrictions and constraints partly very different designs result as depicted in Figure 5. A detailed discussion of reasons and inputs for the development process is beyond the scope of this article.

5. Conclusion

In the present article a framework and a development process for the design of structural components was derived and presented. Focus of this process is a maturity model based approach where the product is systematically assessed at maturity gates regarding specified characteristics and properties. The process was visualized with a front frame of a wheel loader.
There are still open research questions. On the one hand the development of a maturity model involves distinct measures for assessment of the inspected entity which are still missing in the current approach. This would be e.g. a transparent statement about achievable calculation results to ease decision making (e.g. at maturity gate 1 an accuracy of the stiffness prediction in a corridor between 75 and 80%).
On the other hand the decisions at each gate also have to be documented. Here, a design catalogue might be a suitable solution. Combining this with KBE-techniques in a CAD-system might be an important step towards a closed loop engineering environment.

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