Complexity Management to design and produce customer-specific hydraulic controls for mobile applications

Dr.-Ing. Martin Krüßmann, Dr.-Ing. Karin Tischler

Engineering Mobile Controls, Bosch Rexroth AG, Postfach 300240, D-70442 Stuttgart
E-mail: martin.kruessmann'at'boschrexroth.de, karin.tischler'at'boschrexroth.de

Abstract

Complexity management is the key to success for mobile machinery where the variety of customers and applications requires individual solutions. This paper presents the way Bosch Rexroth supports each OEM with hydraulic controls – from specification and conception towards application and production. It gives examples how platforms and processes are optimized according to the customer needs. The demand for flexible, short-term deliveries is met by an agile production with the technologies of Industry 4.0.

KEYWORDS: Complexity, mobile machinery, hydraulic controls, connected industry

1. Introduction

Manufacturers of mobile machinery require components that have been optimized to their specific application. The global competition results in enormous market and cost pressure. Short delivery times are necessary to meet the increasing volatility. Nevertheless the product requirements still expect a high performance level and individualized needs from each customer. The supplier has to develop, test and document the product according to high-quality processes to fulfil strict safety regulations. The trend of electrohydraulics is increasing the complexity of the system with hardware and software. These circumstances demand more and more interdisciplinary and global teams. Bosch Rexroth meets the challenge of increasing complexity together with strong cost pressure. The "one fits all" approach is no longer a position that suppliers can take in the current market conditions. Instead, by means of complexity management the structure of product variants as well as the processes are improved. The variety of products is also a challenge for the logistics and production. Industry 4.0 provides cutting-edge solutions for a flexible and efficient production.

2. Basics of complexity management

Complexity management deal with variants in the product portfolio through the complete development process from concept to series production and then ultimately delivery to

the customer. The overall approach includes the analysis and reduction of variants that have grown during the life of the product as well as controlling and optimization of new variants. Looking at the value chain, complexity management impacts both the organization and all of the processes. It needs a strong networking within the global matrix organization to integrate the different topics of the customer specific solution. The challenge is to identify the main drivers in terms of cost, time and functionality. These factors provide the organization with transparency in the interrelations and help to derive a strategic orientation. Components and processes on different levels are reviewed regarding the feasibility and benefit of standardization or individual handling. To increase the efficiency and quality routine engineering tasks are either automated completely or moved to external sources for processing. The sourcing of a large number of different part numbers is improved by sorting and bundling packages of similar components. The decision about make-or-buy is based on the identification of core competences. In case of buying / outsourcing, considerable expertise is still needed to handle appropriately the specification and interfaces. For example, during production this is accomplished by internally manufacturing prototype parts. Moreover, this approach enables a flexible and fast reaction to new orders.

The product variety required by the market results in a complex product portfolio. As basis for its management a full table of requirements is generated. This table along with the product specification provides an overview about the available solutions and individual configurations. To manage the product portfolio, it is essential to get transparency concerning the variants, their values and related costs. This includes the main control valves as well as accessories like joysticks or special functional modules. In the field of mobile machinery a long life cycle has to be considered in the road-mapping. If possible, new products should be designed to replace an earlier product 1:1, but in most cases improvements require external differences among products. Therefore, a procedure to phase out obsolete products needs to be established to curtail the increasing variance. Triggered by zero consumption for several years, a product is shifted from series towards service processes.

The first challenge for a platform development is an appropriate structuring of the customer requirements. In the domain of mobile machinery a wide variety of machines must be handled. As shown in **Table 1** the requirements of the applications are sometimes mutually exclusive and require different solutions. The concentration on key applications is helpful to restrict the considered subject. Depending on the basic needs, the market is clustered in segments that are served with different platforms.

Topic	Agricultural Tractor	Small construction machinery	Heavy construction machinery
Quantities	High	Medium	Low
Flow & pressure range	Low - medium		Medium - high
Standard functions	Accurate flow No leak (internal)	Parallel movements with good controllability	
Optional variants	Low number	High number	
Actuation	Mechanic / EH	Hydraulic / EH (option)	

Table 1: Requirement structure in the domain of mobile machinery

3. Valve Development

The aim of the complexity management in the valve development is a clearly structured portfolio with standard parts and defined variants that are modularly used. Appropriate standardization and modularization within a platform are supported by design kits and rules that are determined by the experts in a SE (simultaneous engineering) team. Detailed engineering requirements must be developed for the target applications to make sure the design meets the market and customer needs. A platform level development effort must have the product requirements formatted in a structured way like in **Figure 1**. The classification and assessment of requirements is the basis to derive the product functionalities and technical solutions leading to the concrete components. In parallel the target costs are generated based on a value and cost analysis of the functions. The decision for standardization and modular variants is done respecting cost-effects as well as exterior interrelations and functionalities.

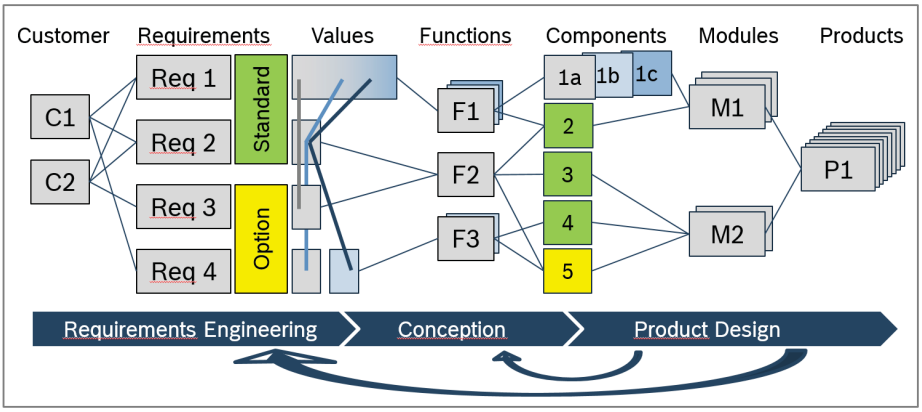


Figure 1: Platform conception – from requirements to product design

Besides the component design, the standardization of tools, methods and processes is improving the quality while reducing the development time and risks. This includes simulation and testing as well as an advanced sourcing strategy and quality methods.

Part of the zero-defect strategy are concerted activities with focus on functionalities, tolerances and processing capability for defined hot spots.

3.1. Platform conception

The conception is the essential starting point for the platform development that defines most of the achievable costs and functionalities. For example, the contemporary mono-block casting for heavy construction machinery with high pressures and flows is replaced by sandwich technology. The complexity management is facilitated by the approach of modularity: the slices with diverse functionalities can be configured and combined more flexible to form an individual block. With the resulting valve platform a broad range of requirements from different construction machines is fulfilled.

Due to high quantities the domain of agricultural tractors benefits particularly from a modular platform. A specified number of functionalities has to be provided in flexible configurations. To create the master specification document the requirements of all customers are collected based on longtime experiences with the product. The topics are verified in accordance with criteria such as complete, clear, correct and consistent. Then, the requirements are structured, prioritized and clustered. The development of functions and technical solutions is supported by methods such as QFD (Quality Function Deployment). The resulting concept is consolidated in one master layout of load sensing control. It covers the mechanical actuation of the valves as well as the electrohydraulic variants in all sizes. In addition to the auxiliary control valves come the electrohydraulic hitch control valves EHR that are based upon the same slice layout. Within the platform similar parts are used as much as reasonable in order to save costs and increase the quality. For example, all tractor valves are equipped with the same electrohydraulic actuator unit. Part of the modularization is to encapsulate the new pilot module to ensure an easy exchange in case of maintenance. Furthermore, this enables the protection of the module from external influences.

Table 2 shows the new electrohydraulic valve platform for agricultural tractors optimized regarding complexity management. The concept ensures the needed functionalities in combination with a competitive price and flexible production supply. Most of the variety is included in the casting and the spool of the slices is modularly combined to the requested configuration. Optional functions like the thermal relief are standardized by similar components across the valve sizes. Where needed, solutions are scaled to provide the suitable dimension of flow within the master layout. To meet the request for a high performance electrohydraulic valve in small size, the SB11 deviates in some aspects from the geometry of SB24 and SB34 that come with the same flange-pattern.

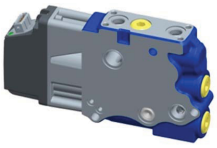
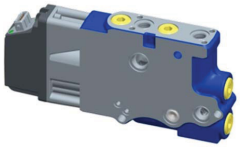
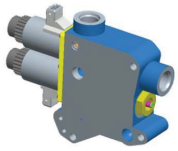
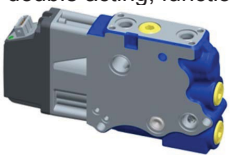
<table>
<tr><th>Topic</th><th>SB11
  </th><th>SB24
  </th><th>SB34
  </th></tr>
<tr><td>Specific characteristics</td><td>• <80 l/min
• 1 check-valve
• Small dimensions</td><td>• 80-120 l/min
• 1 check-valve</td><td>• 120-190 l/min
• 2 check-valves</td></tr>
<tr><td rowspan="2">Standard Interfaces</td><td colspan="3">• One compact master layout with load sensing control
• Interface for electrohydraulic pilot module due to intermediate flange</td></tr>
<tr><td></td><td colspan="2">• One flange-pattern
• Position of customer ports (A, B)</td></tr>
<tr><td>Standard components & modules</td><td colspan="3">• No leak check-valve
• Pressure compensator
• Electrohydraulic pilot module</td></tr>
<tr><td rowspan="2">Options</td><td colspan="3">• Thermal relief (standardized component)</td></tr>
<tr><td colspan="2"></td><td>• Manual override</td></tr>
<tr><td>Hitch control valve</td><td colspan="2">EHR11
• Basic functionality
• Single acting
  </td><td>EHR24
• SB master layout & pilot module EHS1
• Secondary relief valve, 1 check-valve
• Single or double acting, functional options
  </td></tr>
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Table 2: Portfolio of electrohydraulic controls for agricultural tractors

One focus of the platform concept is the flexible and easy integration in the customers' machine which is improved by a compact design and simplified interfaces. Despite an individual combination of different slices SB24, SB34 and EHR24 the result is a compact block with aligned ports as depicted in **Figure 2**. This simplifies the system integration and installation of the suitable valve block on all different machines.

Figure 2: Modular SB24/SB34 control block

As a result of the complexity management, the modularization and standardization of the platform leads to cost-efficient variants of high quality. Moreover, the customer can realize savings by choosing the appropriate valve configuration.

3.2. Platform design

The standardization within a platform is particularly relevant for the design of the main components and technologies, i.e. for slices, spools and compensators as well as flange interfaces and the sealing concept. The mechanic, hydraulic and electrohydraulic actuators are considered as key modules. Due to the platform structure it is worth to invest a higher engineering effort in the design of the main components. From these a variety of solutions can be derived in short time at a high performance level.

The development is supported with the calculation results of simulation tools in order to improve the valve design. Due to the complex interdependencies of design modifications different tools have to be combined in a smart way. For example, the design is focused on the energy-efficiency of the valve requiring a small flow resistance. Simulations with CFD (computational fluid dynamics) are rather costly in terms of modeling and calculation time. Therefore, the initial design for the modelling should be already elaborated. After an overall calculation critical areas are identified and locally optimized based on detailed simulations, as shown in **Figure 3**.

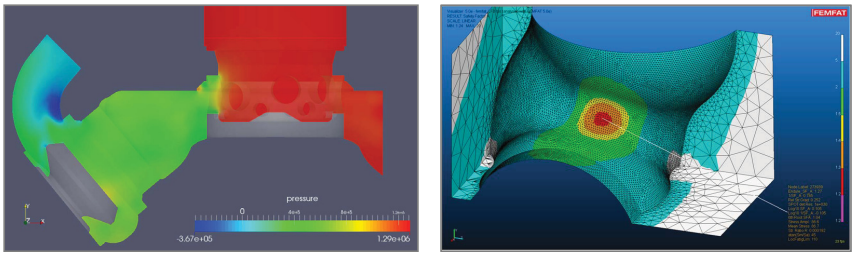

Figure 3: Simulation with CFD (left) and FEM (right)

The optimization is handled as an iterative process: the effects on mechanical strength and casting capability are evaluated before continuing with the flow optimization. FEM (Finite Elements Method) calculation is used to simulate the effects of load pressure. Based on the results the design is improved with regard to safety values for fatigue strength, elastic deformation and gap enlargement at the flange face. The identification of critical points in terms of fatigue strength as in Figure 3 enables the efficient consideration at an early stage of the design. This ensures a high performance of the main components within the product platform.

The third element of the optimization is the casting process. By virtual tests as depicted in **Figure 4** the valve geometry and the position of the feeder head is optimized. The main criterion is the prevention of shrinkage holes or porosities. In parallel, the casting costs are considered.

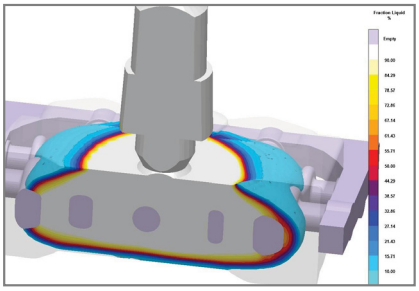

Figure 4: Casting simulation – cooling and solidification of the liquid fraction

Together with the mechanical and casting optimization the pressure losses are improved by the geometry of the channels and the compensator and by the stroke of the check valve. Finally, a reduction of flow resistance up to 20% is achieved while improving strength and casting capability as well as the product costs.

3.3. Quality and testing

Performance and quality within the platform are improved by a consistent concept and guidelines for testing, reliability and zero-defect. Standardized test procedures with improved efficacy cover the complete range of functional, endurance and environment testing. Oil contaminations or aeration are considered as well as deep temperature behavior and internal leakages. The zero-defect strategy includes concerted activities with focus on functionalities, tolerances and processing capability.

In the case of high quantities as in the tractor application, statistical tolerancing is a valuable approach to ensure the requested manufacturing quality. For example, the combination of spool and housing has to fulfill a narrow tolerance range to reduce the internal leakage while preventing any sticking. Within the SE team the physical correlations are investigated in detail and reflected against the variance in the manufacturing processes. Further part of the statistical modeling is the consideration of the measuring accuracy. To verify the functionality significant indicators are identified and used for the planning of manufacturing and quality control.

To provide a cost-efficient solution, products are specified according to the operational stability. Within a platform an efficient test strategy is derived: the most critical part is

tested in detail and the result transferred to further configurations. The methodology of testing is improved to get a high significance of the resulting S-N curve (Wöhler curve). Hence, the local stresses, the strength and thereby the reliability of the products are calculated. If necessary special design elements are verified by a selective testing. Depending on the result the product can be optimized, e.g. in terms of system structure or material selection. It is also possible to derive the approvable pressure of the product in a specific application more precisely and sometimes higher than the general value. The customer gets a quantified probability of default depending on his load spectrum.

Precondition for a meaningful result are realistic test loads that correspond to the loads occuring in the field. This information is difficult to get due to a broad range of operations and little data from truly occuring loads. Therefore, representative load collectives are recorded together with the OEM. A software tool was developed to automate the evaluation of the gathered measurements regarding the application specific product reliability. This includes a detailed understanding of the complex system behavior inside the valve and the local mechanisms of damages due to different maneuvers. /1/

4. Customer-specific application

The control system determines the behavior of a machine. Therefore, the specific application is an important part for the user experience. Especially in the field of construction machinery with a broad range of machine types and operations the machine-specific solution needs an individual product planning. This process can be supported by a configuration software tool. Depending on the requested performance of the machine it is necessary to carry out an individual product application and machine optimization including prototype testing. Due to the lower variance and high quantities in agricultural tractors, it is more useful to specify a priori the needed block configurations with the tractor OEM. This portfolio enables the customer to order automatically in short-term the needed product. Each market is served with regard to its needs.

4.1. Configuration tool

Within the field of construction machinery the external variance of functions and solutions is high due to the wide range of applications and operations. For multi-application valves the structured portfolio is used to setup a configuration tool. During the order process the software tool supports the customer to get a complete configuration of his individual valve. For example, the configurator of the load-sensing valve M4 is guiding through all parts to specify as shown in **Figure 5**. The choice of contradictory parts is prevented based upon the object dependencies determined in the background. The challenge is to

build up a configurator with an ergonomic interface that supports the user by an efficient handling. Therefore, the development is focused on the user-centered HMI (human-machine-interface). A research study including interviews and observations with different users gave findings and hints to improve the tool. As a result the configurator depicts not just verbal options but displays the hydraulic circuit and drawings as much as possible.

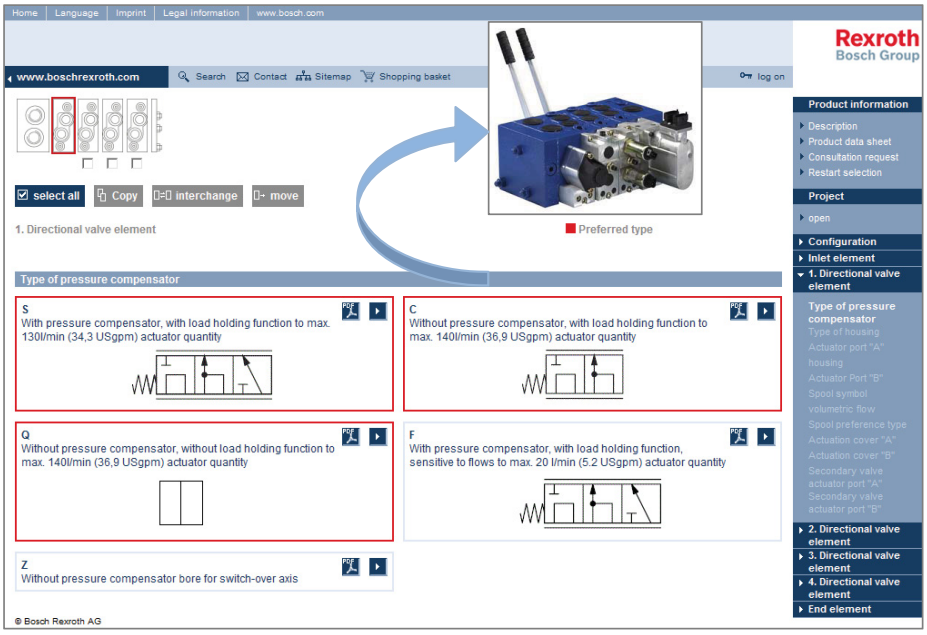

Figure 5: Configuration tool for multi-application control block M4

To get a cost-efficient solution it is recommended to choose standard components that are labeled in bold/red. Where needed, special requirements can be covered by additional parts. As result the customer receives instantly a sales price and specific product documents. These include a 3D drawing to check the integration into his application as well as a technical documentation of the defined product and the SAP number for ordering. Internally, the valve order is placed together with a bill of material and the testing plan. If the individual valve block is configured completely with preferred types of components, it can be delivered within three weeks. By means of complexity management, a flexible solution for small quantities is provided on demand.

4.2. Machine application

During the application of the control system the characteristics have to be optimized to the construction machine which is a skill-intensive individual process. An automation makes no sense but it is useful to generate systematically the expert knowhow.

Beginning with single movements the optimization of the real machine has a focus on parallel moving consumers, e.g. boom and arm of an excavator. Together with professional test drivers the complete system is optimized for typical maneuvers as digging or leveling. In addition to the controllability and handling of the machine the energy efficiency is an important criterion. Bosch Rexroth supports the OEM with the energy optimization of the system and developed a methodical procedure for the assessment /2/. If detailed parameters of the machine are available the prototype setup and the analysis of relations may be supported by simulation. Bosch Rexroth offers with the tool *Simster S* a powerful multi-domain simulation platform for modeling and optimizing controlled drive systems. For particular purposes of the customer a valve block can be provided as individual 1-D model in AMESim. According to the simulation targets the model specification has to include the scope, interfaces and constraints, the needed variable parameters and model accuracy. The derived valve model is validated and provided to the customer in form of libraries together with a documentation.

4.3. Implication of electrohydraulics

Bosch Rexroth offers a high range of control technologies including accessory functions and actuators. This is an ideal condition to support the trend towards electrohydraulics while the complexity management gets more important. For example, Joysticks are provided for hydromechanical or electrical actuation, on demand with SIL2-capability, touch detection and backlighting. In hydraulic control valves most of the variance is concentrated in the spool design. Through the electrohydraulics a part of this variance can be transferred to the software. This enables more flexibility in the control characteristics. Depending on the machine configuration the valve control can be adapted by specific software parameters. The OEM and the user respectively get the chance to choose between different modes for fast or fine control, high power or energy efficiency. For the basic application a rapid prototype software environment is used. This enables early functional tests on the machine and leads to the final software specification. Due to the increasing complexity and interdependencies of the overall system with hardware and software the concept of application and parameterization is the key to an efficient process and an applicable solution.

5. Production

The approach of Industry 4.0 offers new opportunities in production and logistics to cope better with a high product variety. It merges the real world of machines and human beings with the virtual world of the internet and information technology. This enables an agile

manufacturing in sequence of customer specified blocks. Basis for the entrance into the world of Connected Industry are the following factors:

- Decentral IDs of worker, machine and product, so they can be identified by all players or can identify themselves.
- A central virtual picture of the line, its processes and data, to sum up all information at one place and share it between the players.
- Intelligent communication interfaces and systems, to travel information vertically and horizontally between the systems and all players.

Bosch Rexroth provides cutting edge solutions in the field of Industry 4.0 and realized a pilot production as depicted in **Figure 6**. On one multi-product line more than 200 variants of hydraulic valves are assembled originating from 6 valve families – without any modification of the machines. Thereby, the set-up times between different product variations are cut down completely. The work piece and its progress at every step of the process is identifiable through an RFID chip. In this way, the nine stations of the line can recognize which process step is necessary and only the number of parts required for processing is supplied at each station. Displays show the work instructions for the variant – adjusted to the worker's skills and thereby also increasing the quality of the product.

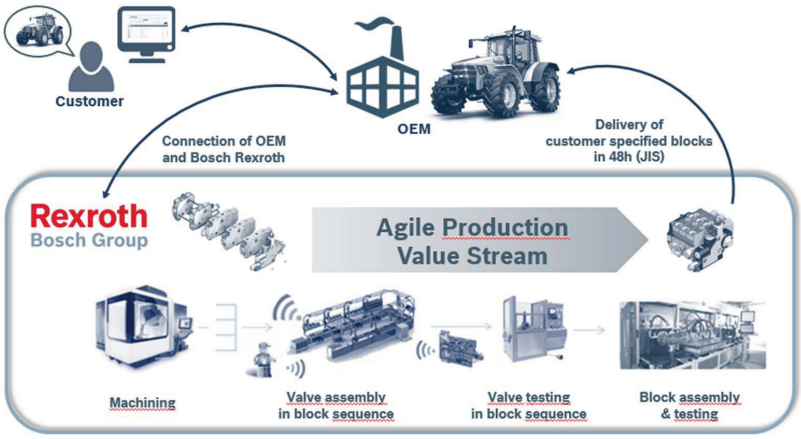

Figure 6: Industry 4.0 – agile, flexible and connected manufacturing at Bosch Rexroth

The machine process is controlled independently, according to the specifications of the higher-level control system using open communication interfaces. The processes are monitored and documented whether they correspond precisely to the specifications. This includes an integrated management of deviations and incidents. The individual product data like component sources or parameters of setup and testing are documented and

available for the customer. In applicable cases the output increases by 10% compared to classical lines, with 30% less inventory. The connections of worker and product with the assembly line enables the output increase. The control blocks for specific tractor configurations are produced on demand: With a direct connection from the OEM to Bosch Rexroth the future aim is a product supply in 48 hours and in customer sequence. Via a direct connection short-term customer changes are still possible, e.g. if another slice configuration is needed. The very responsive production of complete valve blocks relieves the OEM from assembly and testing of the needed product including the stocking of different slices by himself. The flexible handling of blocks in lot size one makes even a JIS (Just-in-Sequence) supply possible.

6. Conclusions

With increasing complexity, the efficient handling of variants gets more and more important. Therefore, Bosch Rexroth applies an integrated approach of complexity management on all processes and products of mobile controls. A detailed understanding of the customer-specific needs is the precondition for a reasonable renewal of the product portfolio. The platform of tractor valves shows the results of a consequent variant management from structured development towards agile production. The appropriate standardization and modularization leads to custom-fit and cost-efficient products. High quality and performance is ensured by a team of experts supported with means of simulation and testing. The approach of Connected Industry enables a short-term supply in customer sequence. In the domain of construction machinery an even higher diversity of products and processes is provided including machine specific applications and system optimization. The trend of electrohydraulics is supported including the necessary knowhow to combine effectively hardware and software.

7. References

/1/ Sandmann, Kai, S. Schomberg, T. Leyendecker, M. Bacher-Höchst, G. Rauch and K.-G. Eulitz: Entwicklung eines Auslegungskonzepts für die betriebsfeste Bemessung von Hydraulikventilen in mobilen Arbeitsmaschinen. 42. Tagung des DVM-Arbeitskreises Betriebsfestigkeit – Bauteile und Systeme unter komplexer Belastung, Dresden, Germany, 7.-8. Oktober 2015.

/2/ Sturm, Christoph: Bewertung der Energieeffizienz von Antriebssystemen mobiler Arbeitsmaschinen am Beispiel Bagger. Dissertation, Karlsruher Institut für Technologie (KIT), Karlsruhe, Germany, 2015.