Computer-Aided Development and Optimization of Electrohydraulic Pump Actuators for Mobile Applications

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This article describes the analysis and selection of an electrohydraulic pump actuator by means of simulations in order to optimize operation for any given hydraulic system. The focus is on developing a multidisciplinary method of analysis. This involves interlinking various submodels such as the electric motor model, pump model and cost model with a system model. With the help of this method, a large number of designs can be analyzed automatically for the purpose of assessing the behaviour of the overall system. This delivers a preferred design variant tailored to the customer's requirements.

Keywords:
Multidisciplinary analysis method, electrohydraulic pump actuator, product development process, cost models
Target audience:
Mobile applications (automotive), components (pumps & motors), design process (new approaches & methods)

1 Introduction

In times of increasing complexity when it comes to technical systems the challenge facing companies is to develop products that are "smart" in every sense of the word. A smart solution is one that achieves the most extensive integration of system functions in a single product, while at the same time streamlining costs and reducing the overall installation footprint. This requires an in-depth understanding of customer systems and the associated subsystems – achieved by applying the THOMAS principle of "Sense-Think-Act". Innovative and smart solutions can only be delivered if all elements within the system harmonize perfectly with one another.

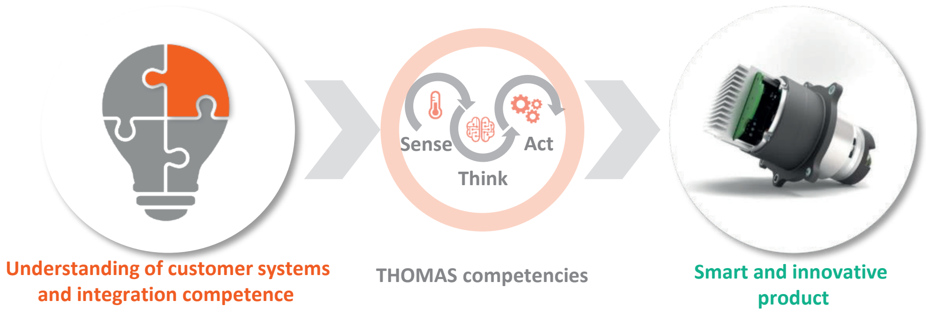

Figure 1: THOMAS' development chain - from customer requirements to smart and innovative products comprising the integration of many system functions like sensors, electronics, software and actuators

Electrohydraulic pump actuators are an example of a smart and innovative product: compact mechatronic units that comprise an electric motor, a hydraulic pump, a control logic system and power electronics. Designed as a self-contained assembly, the units only have specific electric and hydraulic interfaces. Unlike traditional valve-controlled hydraulic drives, the use of variable-speed pump actuators can help to make a wide range of hydraulic systems significantly more energy-efficient. Uses for actuators include deployment in the aviation industry or in mobile equipment. In the automotive sector, the units are used to actuate gears or actively influence the drivetrain, for example.

The electric motor and the hydraulic pump are two subassemblies that experience particularly strong interaction during operation, both with each other and with the system. The drive under development is intended to perform the drive task entrusted to it, while not being excessively large and falling within the target budget. Therefore, the developer needs an in-depth understanding of the inner physical interrelationships. However, simply basing the design on experience would not be expedient due to the system's non-linear behaviour.

An automated design method was therefore devised as part of the investigations being presented in this paper. This enables preferred variants to be identified systematically from the large number of influencing parameters from the actuator's various subsystems, especially if commercial aspects and installation space requirements also have to be taken into account alongside the need to perform a certain function. In addition to the aforementioned advantages regarding the method of optimizing any type of hydraulic system, this approach also provides a deeper understanding of hydraulic system behaviour as a whole.

After identifying the optimized variants with regard to specific actuator characteristics and commercial targets these variants are subjected to finite element calculations, followed by prototyping and testing. At the end of the development process, the focus is on comparing the test results with the simulation results and adjusting the detailed finite element analysis accordingly.

2 Modelling approach

Satisfying customers' requirements and presenting an optimal price-performance ratio are the main objectives of development activities in the industrial sector. The first step, therefore, is to identify the needs and requirements of the customer. Based on these specifications, the design space (see Figure 2) is defined. During this concept stage no limitations are made on the design space except for the defined parameters in the book of requirements. This produces a large degree of freedom in respect of characteristics and physical property.

2.1 Simulation-aided development process

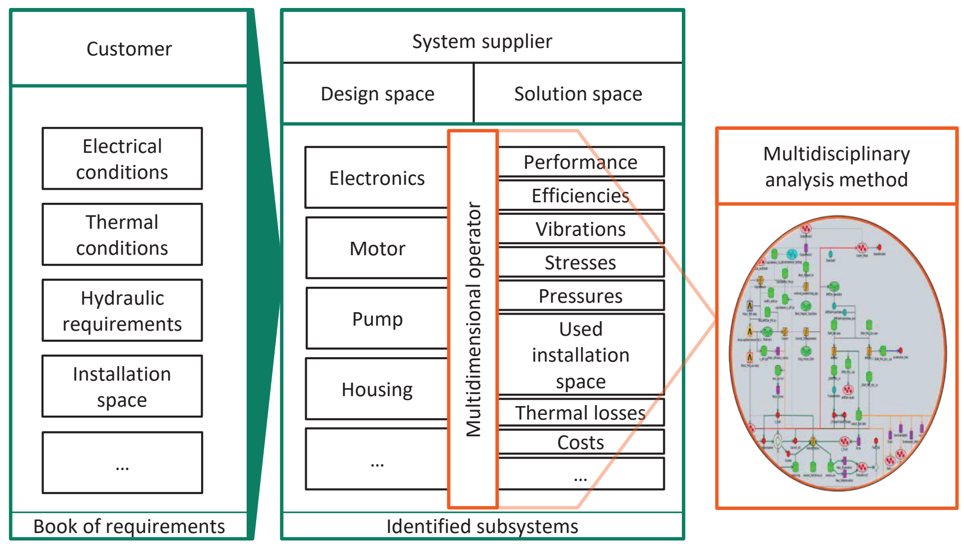

Figure 2: Abstract scheme of the simulation-aided development process and the applied modelling approach as a multidisciplinary analysis method

The multidimensional operator (see Figure 2) is an abstract definition for the interrelationships between the physical and commercial interfaces and the operator maps on the solution space. The level of abstraction shown in Figure 2 shows clearly where the new modelling approach is applied. The multidisciplinary analysis method deals with parameters and models of the system design and contains some algorithms to connect each other and to adjust the system model for subsequent calculations. The aim of this method is not to design a motor pump unit in a single step but, rather, to deliver optimal combinations of system components that need to be assessed in detail as part of further investigations (see Figure 3).

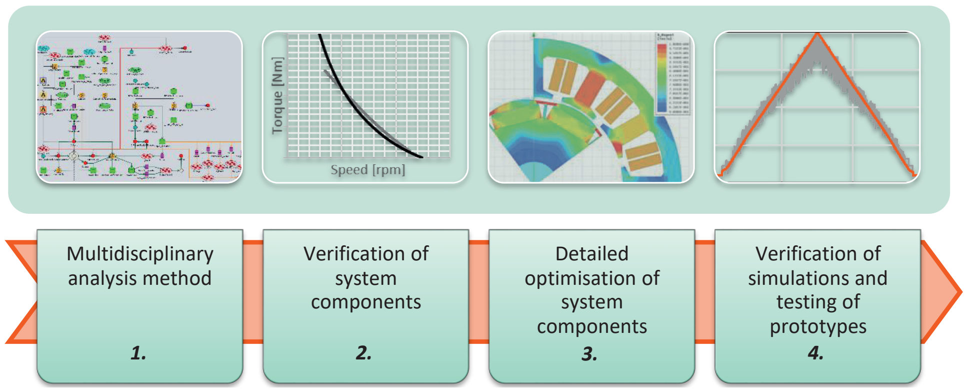

Figure 3: Simulation-aided development process

After the best-possible motor pump combination has been identified the next steps include the verification and optimization of component behaviour using detailed finite element analysis. Finally, the development process includes the verification of the motor pump unit in the form of testing prototypes or subsystems such as motor, pump and power electronics.

2.2 Description of the multidisciplinary analysis method

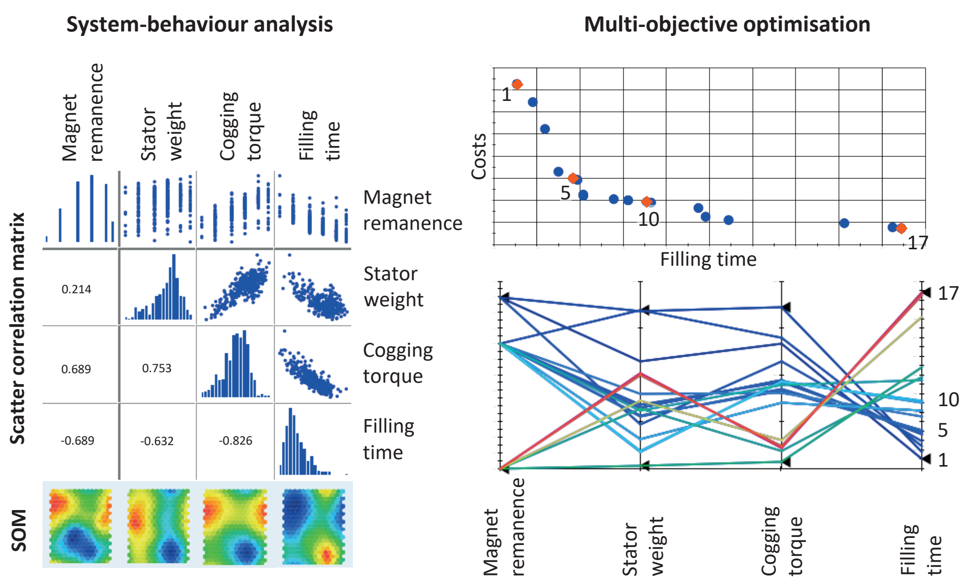

Figure 4: The two key elements of the multidisciplinary analysis method: system behaviour analysis and multi-objective optimization

The behaviour of the motor pump unit is studied by means of different analytical tools. First and foremost, the correlation matrix illustrates the linear dependencies between the individual parameters. However, not all parameters display linear interdependency. Instead, they may display non-linear behaviour, e.g. logarithmic or quadratic behaviour. Therefore, it is advisable to use scatter plots for the purpose of illustrating these dependencies. This example shows the linear interdependence between filling time/cogging torque on the one hand and magnet remanence on the other.

SOMs (**s**elf-**o**rganised **m**aps) have a higher abstraction level; they provide a visualization of the dependence of parameters by means of neural networks (/1/). Applying this visualization method, it is possible to group the parameters into similar behaviour categories. In the background of the multidisciplinary analysis tool an algorithm sorts the respective system designs into different properties and delivers a special weighting of these properties. In the case of extensive systems with hundreds of parameters this method simplifies the process of analyzing dependencies and makes the process more intuitive. As a result, hidden interrelationships within the system are made clearer (see Figure 4).

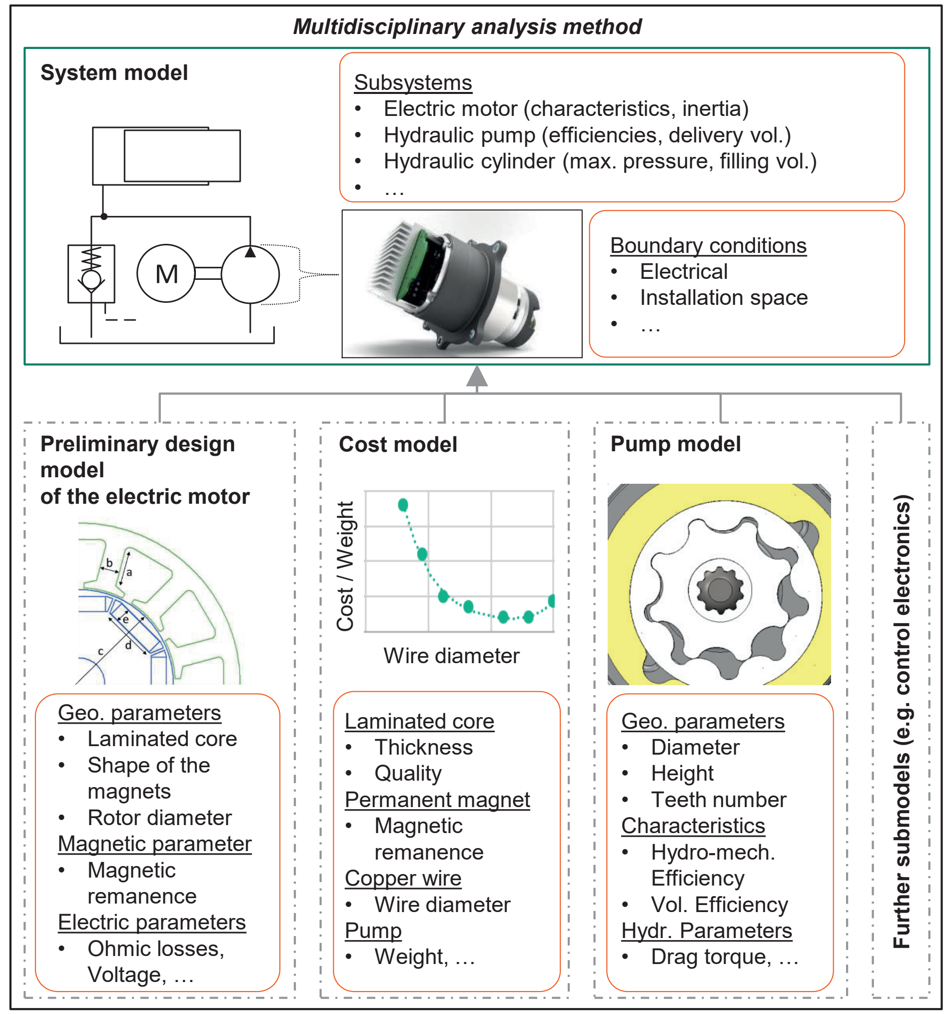

Figure 5: Connection of the system model with submodels by means of a multidisciplinary analysis tool

MOO (multi-objective optimization) delivers Pareto optimality. An optimum on the Pareto front cannot be improved in one objective without diminishing the other. Another plot used for the purpose of further analyzing the calculated optima is the "parallel coordinates" plot. In this case, the most important parameters of the optima are compared; it provides a basis for the most appropriate system design.

By modelling the motor pump units with all participating parts, it is possible to optimize the overall system while also analyzing overall system behaviour if different components are taken into account. In many cases, different components could be used to achieve the specified objectives in the list of requirements. Therefore, it is essential that such aspects are discussed with the customer by analyzing the system designs together. For this purpose, the method includes an extensive database to perform such analyses; all influencing cost attributes and all important physical parameters at the different operating points are considered.

The simulation-aided design method is built around the system model of any given hydraulic application (e.g. a gearbox coupling) including the pump actuator to be designed, see Figure 5. Using a multidisciplinary analysis tool (*Optimus* software application in this example), additional submodels (preliminary design model of the electric motor, cost model, etc.) are linked up to the system model for parameterization or expansion purposes.

2.2.1 Pump model

The case being presented here uses a simple analytical model to map the pump that specifies the piston displacement and the hydromechanical and volumetric efficiency, based on measurements. Depending on customer requirements, one has to specify the inputs: fluid type, worst-case temperature(s), pressure and/or volumetric flow data. It is necessary to check whether the pump model has been fully determined and to ensure that no degrees of freedom remain that are not considered to be reasonable variables for the system. After adding a model of physical or even commercial behaviour it is useful to check the boundary conditions and restrictions for each new variable in the system. The outline of the system must always be present and if one variable in the system has no restriction it follows that the system model throws out an unphysical or a non-reasonable "optimal" system design.

In our case, we have various variables relating to the pump which have to be restricted by the system (e.g. the volume or the height of the pump). The first boundary conditions are related to the physical requirements of the system behaviour. These include the specified pressures and volumetric flows and the dynamic specification of the system. Other constraints must relate to the commercial behaviour of the size of the pump, which depends on the defined variables (e.g. the height of the pump), or it has to be a constraint based on the installation space requirements (or preferably both).

In addition to the characteristic maps of efficiency of the pump, the specific drag torque has to be varied depending on the weight of the pump, too.

2.2.2 Electric motor model and its simplification by means of a preliminary analysis tool

The description of the electric motor within the system model is based on characteristic maps inherited from the preliminary design model of the electric motor. As the electric motor structure is so complex, this plays a key role in the dynamics and the costs of the resulting actuator and is therefore determined in greater detail using a preliminary design routine. Using analytical motor theory /2/ and equivalent magnetic circuit methods, the applied software (*ANSYS RMxprt*) calculates machine performance. This model encompasses all the key variables that may potentially influence the efficiency of an electric motor, with iron losses, global saturation effects in the iron circuit and ohmic losses all being calculated.

Although there are no design restrictions relating to the type of electric motor in principle, in this case we are restricting ourselves to a three-phase permanently energized motor whose dimensions and the strength or whose permanent magnets in terms of performance and in terms of costs are of particular interest. Similarly, both the copper wire and different grades of sheet metal have an impact on costs and therefore need to be varied and combined in order to expand the solution space.

As mentioned before, the aim of such pump actuators is to raise the energy efficiency of various hydraulic systems. Just as the pump has its very own efficiency characteristics depending on operating pressure and volume flow (or speed), the motor has its own nonlinear efficiency characteristics depending on rotational speed and operating torque (see Figure 6). Thus, there will be a different overall degree of efficiency at each operating point; this has to be taken into account when it comes to optimizing the motor pump system. This underlines the importance of including all requisite components in a system model for the purpose of selecting the most energy-efficient system design as early as possible.

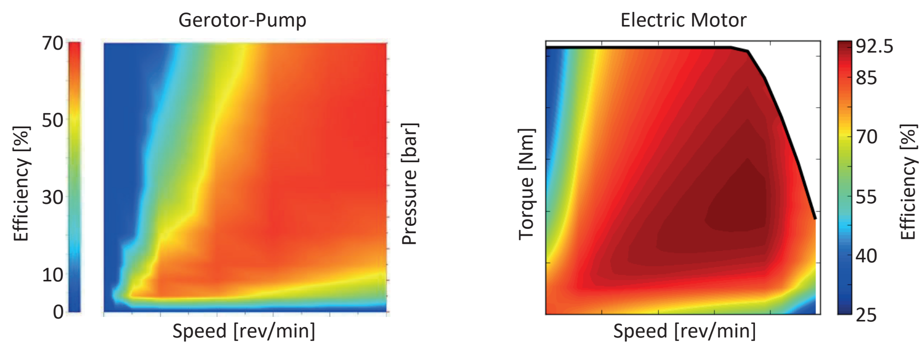

Figure 6: Left: Example of the global efficiency map of a gerotor pump.
Right: Example of the global efficiency map of an electric motor.

A common method is to analyze the motor pump unit with co-simulation of motor and pump by using FEM. To reduce the calculation time and to increase the number of possible design variants, we use an analytical and preliminary analysis tool to describe the motor within the system model. The advantages of such an analysis tool are the high-speed calculation of motor characteristics such as torque against speed, efficiency against speed or inductivity against electrical angle and the calculation of the losses in the magnetic circuit at different operating points. However, this does not include a calculation that delivers details of temperature or local magnetic losses. Therefore, it is necessary to combine the motor analysis with a thermal model that determines the magnet and coil temperature in the motor. Another option is to restrict the copper losses in dependence of the weight of the motor or even to restrict the current density in a stator slot to ensure that the motor design is valid.

A simplification of the analytical model exists in the cylindrical rotor design of the preliminary analysis tool. As a consequence, the cogging torque and the electromechanical force cannot be improved significantly. For such optimization efforts, it is necessary to conduct a comprehensive analysis of the pole geometry in order to assess the saturation effects in the tooth tips of the stator and in the ribs of the rotor design and, in addition, to look at the local magnetic fluxdensity in the magnets of the rotor to ensure that the magnets are perfectly matched.

As illustrated in Figure 7, there is only a small discrepancy between the results of the preliminary analysis tool and the results of finite element analysis. This confirms that initial improvements can be made at a system level and that more specific fine-tuning can be performed at a compenent level. This includes the optimization of the pole and tooth geometry for the purpose of improving specific requirements such as cogging torque, torque ripple and slot fill factor, if possible.

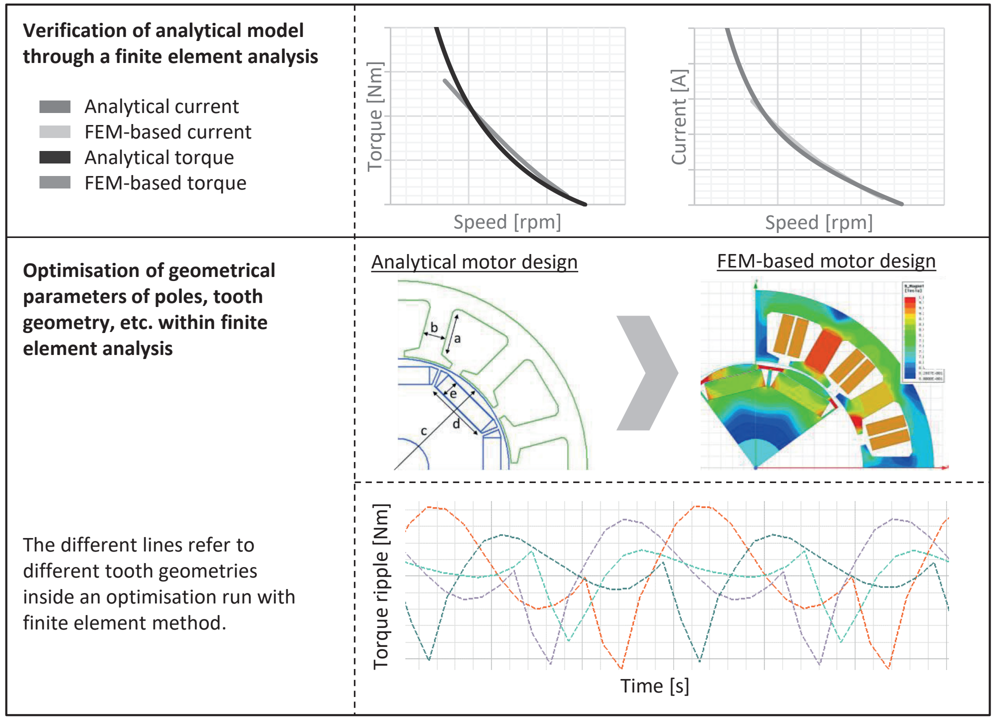

Figure 7: Top: Verification of the motor designs resulting from multidisciplinary analysis by means of FEM. Below: Optimization of the simple analytical design with the power of FEM

2.2.3 Cost models

Varying a number of input parameters will give rise to all the possible variants for a pump actuator under the specified conditions. The costs for this pump actuator will be automatically calculated once the design has been determined in full. The costs are modelled using regression functions based on supplier's quotations, e.g. for sheet metal, permanent magnets and copper wire (see Figure 5). After analyzing the supplier's quotations, the main attributes are identified and the regression functions of the different parts are written in the form

$$\text{costs} = V^{k_v} \cdot {M_1}^{k_1} \cdot {M_2}^{k_2} \cdot {M_3}^{k_3} \cdot\ 10^c, \qquad (1)$$

where M_i is the attribute i and V is the annual quantity of motor pump units and k_i and k_v their regression coefficients. 10^c is the constant factor of the regression function containing some general costs.

The advantage of such a cost model is the possibility of analyzing and optimizing the different attributes to minimize costs or risks. This leads to a better understanding of the sensitivity of system costs regarding the different attributes such as material-specific cost attributes and part-specific cost attributes or the annual quantity of motor pump units.

3 Practical example

For a practical example the pressure inside a cylinder is to be increased within the time using a pump actuator, see Figure 5. The technical development objective is to minimize the cylinder's filling time. From a commercial point of view, costs need to be minimized as well. Multi-objective optimization can be derived from these two aims that can determine optimum pump actuator designs by giving varying weight to each within the multidimensional scope of the solution.

As we restricted ourselves to the three specific subsystems (electric motor, pump, costs), it was necessary to limit the copper losses to a certain experience-based value. The magnets were selected from a list with the required temperature class featuring the specified magnet properties such as magnet remanence. The cost driver of this system is the electric motor. Therefore, the costs were restricted to motor-specific costs and were distinguished in cost models for the sheet material, copper wire and rare earth magnets.

As regards the multidisciplinary model, the pump weight is iterated to ensure the right size for the actual motor design in question. Thus, each bubble (see Figure 8, bubble plot) contains a pump that is perfectly matched to the actual motor design in question.

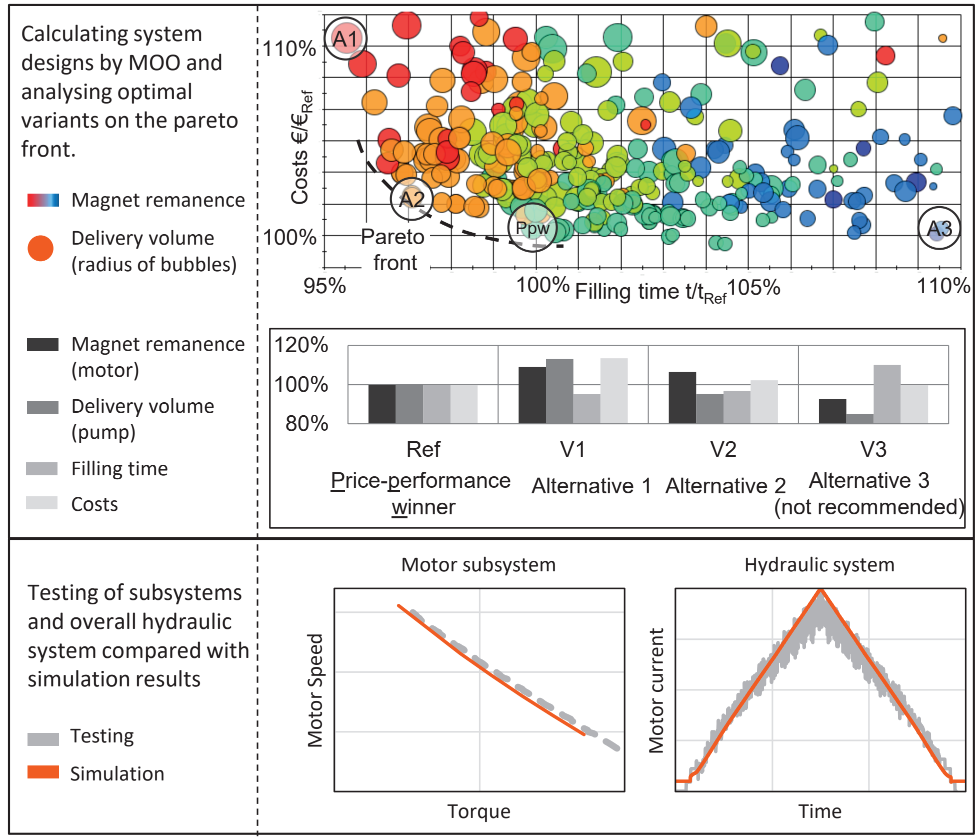

Figure 8: Top: Multi-objective optimization of motor pump unit and its optimal variants. Below: Comparison of simulation with tested prototypes

The multi-objective optimization gives rise to a Pareto front of optimum pump actuator designs for the specific hydraulic system within the scope of the solution. "Pareto optimality" is the name given to a state in which it is not possible to improve a characteristic (filling time) without having to impact negatively on another (costs) at the same time. It is possible to determine the right actuator depending on the requirements, see Figure 8.

After optimization using the finite element method the prototypes were tested and the comparison of simulation results vs. test results was extremely favourable. As regards the differences between the test results and the simulation results, it should be noted that these discrepancies are attributable to specific testing parameters such as pre-resistors and conversative simulations. The actual electric motor produced has a higher degree of efficiency and the overall system requires a lower motor current than calculated in the simulation models.

4 Conclusion

The aim of this article was to present a multidisciplinary method for the design and dimensioning of motor pum units. By interconnecting the respective submodels with the system model for the purpose of detailing the moto pump unit, it is now possible to analyze the interaction between the various components and select preferre designs. This method encompasses not only a technical constituent, such as the determination of the motor an pump, it also covers commercial aspects. These include detailed cost models for individual components of th motor pump unit. They are interlinked with the physical models by means of the multidimensional operator an can be analyzed in terms of sensitivity and optima.

The example demonstrates that the design method presented is capable of mapping the pump actuator from technical and commercial point of view for a given hydraulic system. The complexity of the pump actuator can b studied in even greater detail by adding more submodels to the analytical model to produce a more precis description of the system.

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