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The quantitative Working Space Model – Generating Knowledge in the K Space

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Abstract

Understanding a systems behavior is essential for designers to evaluate different design solutions. C-K Theory (Hatchuel & Weil, 2009) empowers practitioners to design innovative systems. Generating knowledge in the K Space about concepts in the C Space is mandatory to assess the solution space which is spanned by different concepts. Existing modelling approaches are evaluated based on a literature review. The quantitative Working Space Model (qWSM) is introduced as a tool for C-K theory and a way to model physical systems using conservation quantities. Originating in the work of the Beetz et al. (2018), the qWSM is presented as hybrid approach combining heuristic with analytical models. By pointing out the underlying principles of the model, it is discussed how practitioners gain insight in the system's qualitative working principles and the quantitative relations between design parameters and function. The significance of a model based on conservation quantities is derived from a review on models focusing on the flow of force, in particular the Contact and Channel-Approach. The conditions for a successful use of the qWSM are presented and the limitations in terms validity of qWSMs are pointed out. For the concept of a hydraulic ram knowledge about the underlying working principle is generated using the qWSM. Using the knowledge to identify the function determining design parameters the authors examine the quantitative relation between function and embodiment of the hydraulic ram. Following the analysis, a prototype of the hydraulic ram is designed using the qWSM. The authors point out the qWSM's potential as a new tool to generate knowledge for concepts in the C-Space encouraging designers to take innovative design concepts into consideration by providing insight about the quantitative impact of design solutions on the main function of a system. The vision of multi physical modelling is derived from the performed research. Lastly, necessary further research to enable the qWSM to serve as a multi physical model is pointed out.

Keywords: Working Space Model, modelling, C-K design theory, design knowledge, innovation

1 Introduction

To satisfy the needs of modern society, designers have to provide innovative products, meeting high standards in terms of efficiency, individuality, originality and others. At the same time, companies have to decrease the time effort of development cycles to be competitive. So how can designers face the conflict of objectives of being innovative, accurate and fast in the design process? The research field of design theory provides numerous approaches to support designers in their work as reviews like (Le Masson et al., 2013) show. One possibility to systematically support innovation is the Concept-Knowledge theory or C-K theory introduced by Hatchuel and Weil (2003) and comprehensively developed since its introduction (Hatchuel et al., 2017; Hatchuel & Weil, 2009). In this contribution, the quantitative Working Space Model (qWSM) is introduced as one possible approach to generate knowledge in the K Space for concepts in the C Space, providing a powerful tool for designers. The qWSM offers a possibility to understand the behavior of a system, based on the general concept or reference systems. Unlike other models, the qWSM focusses the balance of conservation quantities, enabling practitioners to explain system by the flow of e.g. charge or thermal energy. Figure 1 shows the underlying principle of the former Working Space Model (WSM), which divides systems into volumes to describe each one regarding their function, boundaries and interaction with surrounding volumes.

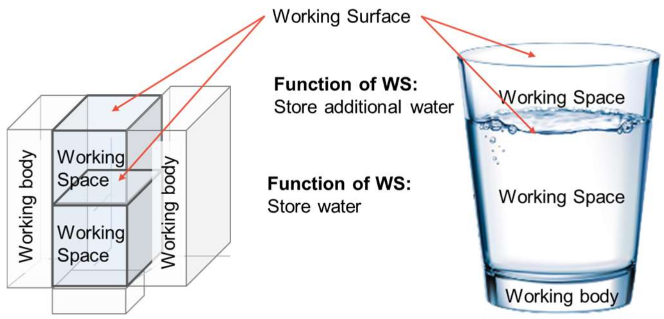

Figure 1 Working space model following (Beetz & Kirchner, 2019)

Understanding a systems behavior can be achieved by different approaches. The gathered information can be categorized in observed behavior and behavioral models. When discovering a system, the human brain starts to build up knowledge about the structure and behavior of the system, (Javanmardi & Liu, 2020). Observing the system generates information about how the system acts in the context of a specific time, state, condition and by the effect of a specific input. A set of heuristic data about the systems behavior results from this observation. By gaining insights about the mechanisms determining the changes of the systems' state and output for a given input and initial conditions, a behavioral model is developed (Padilla et al., 2018). The simple observance of a system leads to heuristic models of its behavior, which, simplified, can be reduced to a relation in the form of:

- *"If input a acts on system x in the initial condition x_0 the systems changes it's state to x_1 and the output b is emitted."*

An estimation of the systems future behavior in the aforementioned form is only possible if the observation can be reliably reproduced and the conditions of the experiment are the same as those of the application. A reliable prediction of future behavior can only be achieved by a proper understanding why the system behaves in a certain way. The relation therefor needs to be extended to:

- *"If input a acts on system x in the initial condition x_0 the systems changes it's state x_k to x_{k+1} following the relation $x_{k+1} = f(x_k, x_0, a)$ and the output b is emitted."*

The developed behavioral model can be developed either by explaining the overall observations or by analyzing the system in its components and their inner relations. On the one hand, a model explaining observed behavior can help to identify the effects of input and initial conditions on the output. On the other hand it can predict future behavior based on inter- and extrapolation of experimental data. Those predictions usually lack of accuracy depending on the present database and the parameters a, x_k, x_0. Generally speaking the insights gained by heuristic models focus on the main function of the system. Analytical approaches require a profound understanding of every part of the system. If all relevant parts can be described both in their individual behavior and in their relation to surrounding system parts, the system's behavior can be described by the link of its components.
These observations lead to the following categorization of how models are developed:

- The heuristic approach, cf. Figure 2 Heuristic modelling approachis more intuitive and can generate a proper understanding of the main function of the system while minimizing the modelling effort for simple systems with a limited range of input and initial conditions.

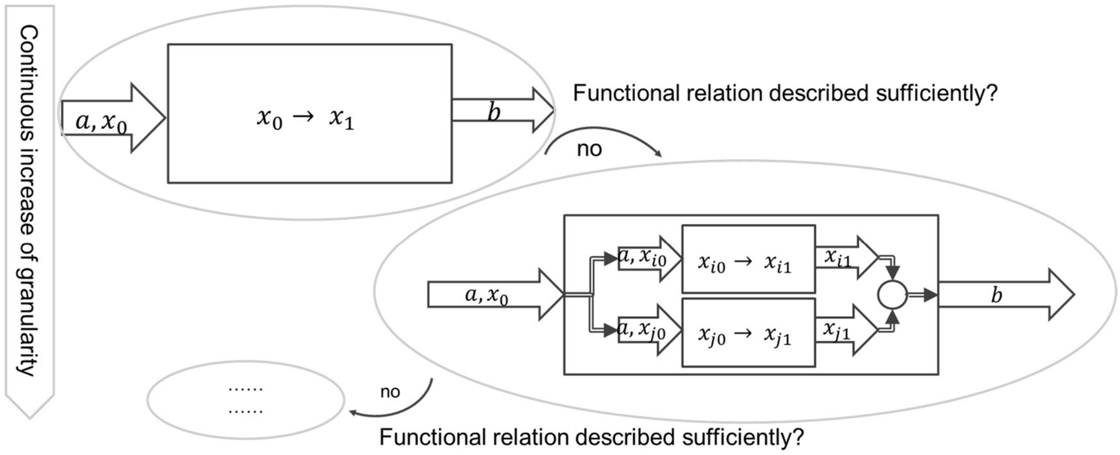

Figure 2 Heuristic modelling approach

- The analytical approach, cf.Figure 3, creates a profound understanding of the system, the subsystems as well as their inner processes and relations between them. Simplifications may lead to a violation of the models validity.

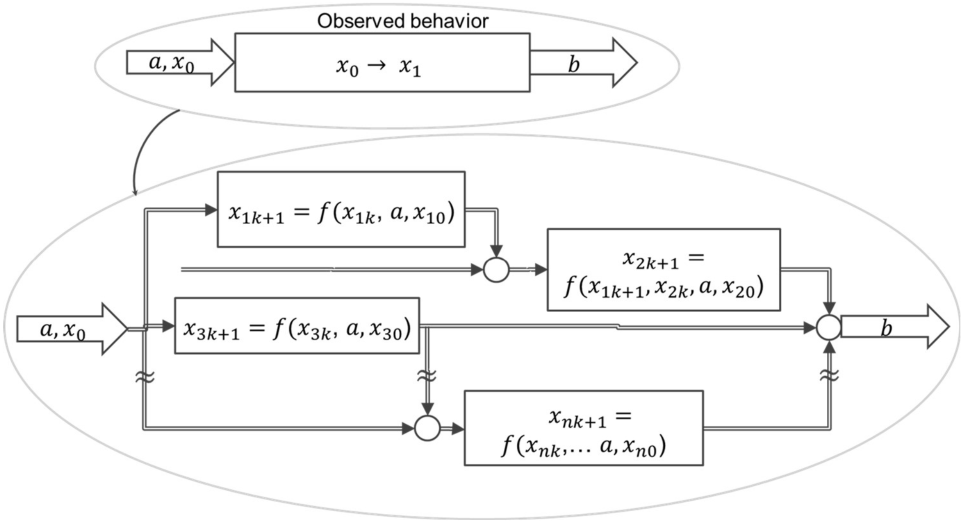

Figure 3 Analytical Approach

Furthermore, hybrid approaches, cf. Figure 4, exist which support gradually increasing complexity of the systems model, if it is required to understand the desired relation inside the system or with the environment. They enhance heuristic models of a gradually increasing complexity by an analytical modelling of important subsystems to explain to super system's function.
The purpose of this contribution is to present the quantitative Working Space Model, originating in the work of Beetz et al. (2018), (Beetz & Kirchner, 2019) and now enhanced by the ability to actually calculate the state variables of the system and its sub systems. This enhancement is driven by the idea of balancing conservation variables in each working space (WS) of the system, deriving their individual state equations and coupling them to each other by coupling equations.

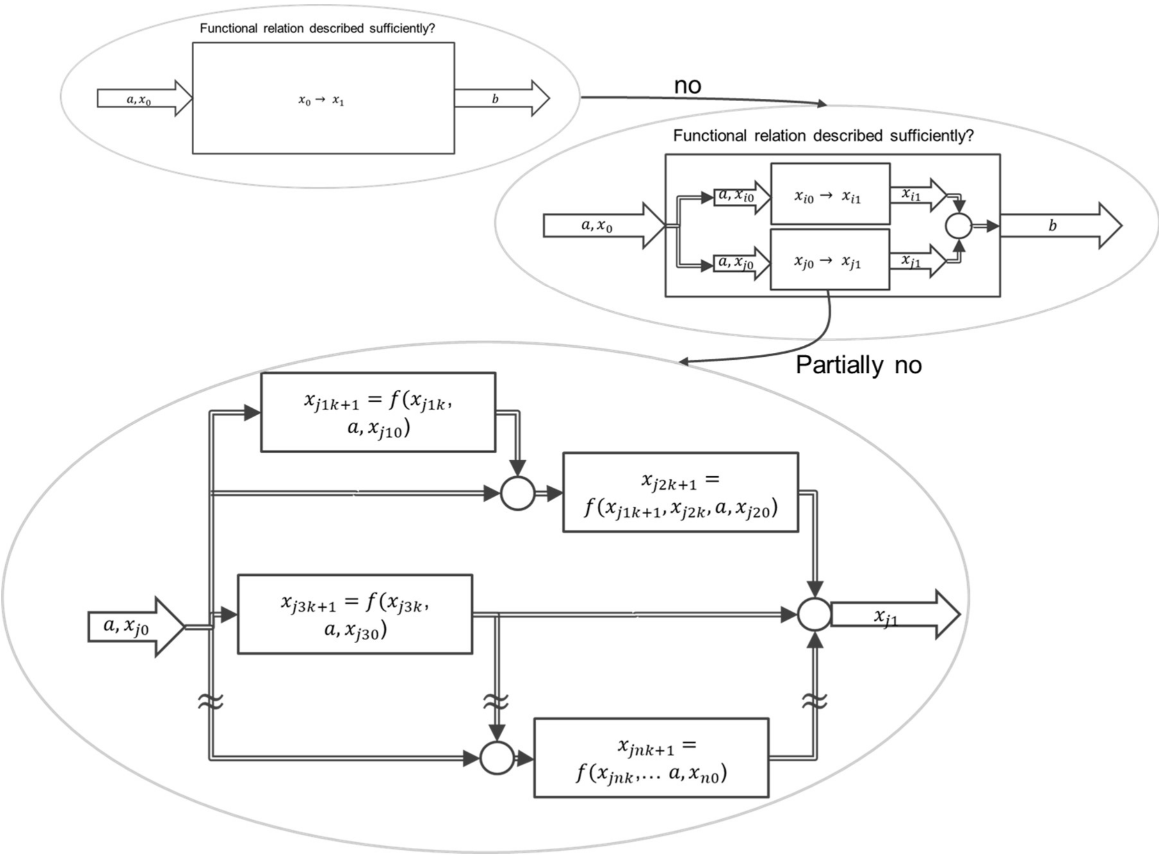

Figure 4 Hybrid modelling approach

2 Aims

Initially, the advantages of the qWSM will be derived by discussing its benefits in the process of product development and in the first place while analyzing the system of interest. To make a long story short we need to evaluated **why** and **when** the qWSM is advantageous for designers compared to other modelling approaches.
This question implies one important information about the use of the qWSM, which is: **Who** is meant to use it? In this contribution, we define product designers as the target group.
The elements and rules of the present WSM will be explained in section 3, now the essential characteristics and the vision of the qWSM are presented.
The WSM is a volume based model in which the total volume of the observed system is divided into sub volumes, the so-called working spaces (WS), that are linked to each other as well as

their environment. Similar to the methods of (Bird et al., 2006; Euler, 1757) conservation quantities such as mass, energy, charge can be balanced between in- and output of the WS. Combining this idea with quantifying the state of each WS, e.g. temperature, depending on the balanced quantities, one can describe each sub system individually and their entirety as the super system. This description does not support a simulation or exact calculation as it is limited to relations that are valid without taking into account the detailed embodiment of the system due to the need of limited complexity of the systems representation.

Like any other model the qWSM requires a modelling objective defining the required granularity of the model. If the granularity of the system's representation is not sufficient to answer the arising questions, the granularity can be increased to answer them, cf. Figure 4. To illustrate this approach we use the example of a pressure cooker.

The main function of the system is to drive a certain cooking temperature above 100°C for fast cooking. The modelling objective is to describe which state variable is determining for the main function and how it is affected by design parameters. In the first iteration we divide the cooker in the subsystems WS1 (water), WS2 (steam) and WS3 (wall & casket, solid domain). To enable the main function the content of WS1 has to experience pressure $p_1 > 1$ bar to prevent it from vaporizing at 100°C, cf. Figure 5. The critical state variable to enable the main function therefor is the pressure p_1 of WS1. The volume WS3 contains WS1 and therefor has to withstand p_1. The critical design parameter of the system can be located here. To further investigate what is the critical parameter the granularity of the model is increased as can be seen in figure 5- right, using a sectional view in WS3.The critical design parameter is identified as the wall thickness d. Now a minimum for d can be calculated using the boiler formula (DIN EN 13480-3:2017-12). To enable practitioners to identify and quantify reliably the relations between the (main) function of a system and the critical design parameters as well as the boundary conditions a method of building qWSMs will be developed in the course of this work.

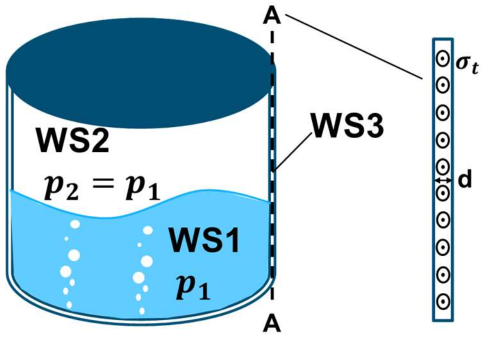

Figure 5 WSM of a pressur cooker

3 Significance

In the following section, the theoretical foundation of the qualitative WSM will be presented. First inspiration is found in the ideas of Franke and Kaletka (1996) who suggested a categorization of physical effects responsible for a systems behavior and the design features determined by the effect. In this way they achieved a description of working spaces and working surfaces (WSU) that gave insight in the consequences of the working surface pairs' (WSP) shape. The developed effect catalogue for example describes the expectable friction losses in case of a WSP of two cylindrical surfaces. Motivated by the contact and channel approach (Albers & Wintergerst, 2014; Grauberger et al., 2020; Matthiesen et al., 2018) and the contact and channel model (Braun et al., 2009) the Working Space Model was introduced by (Beetz et al., 2018; Beetz & Kirchner, 2019) as a modelling approach for the analysis and following the development of hygienic products. Beetz and Kirchner (2019) describe the limitations of existing product models, focusing on the C&C²-Approach, when analyzing systems with the modelling objective to identify unwanted interactions between working spaces. Such interactions can e.g. cause contamination or leakage and are therefore crucial for hygienic design. Figure 6 shows two models of the hydraulic ram and illustrates the different modelling approaches C&C² and WSM.

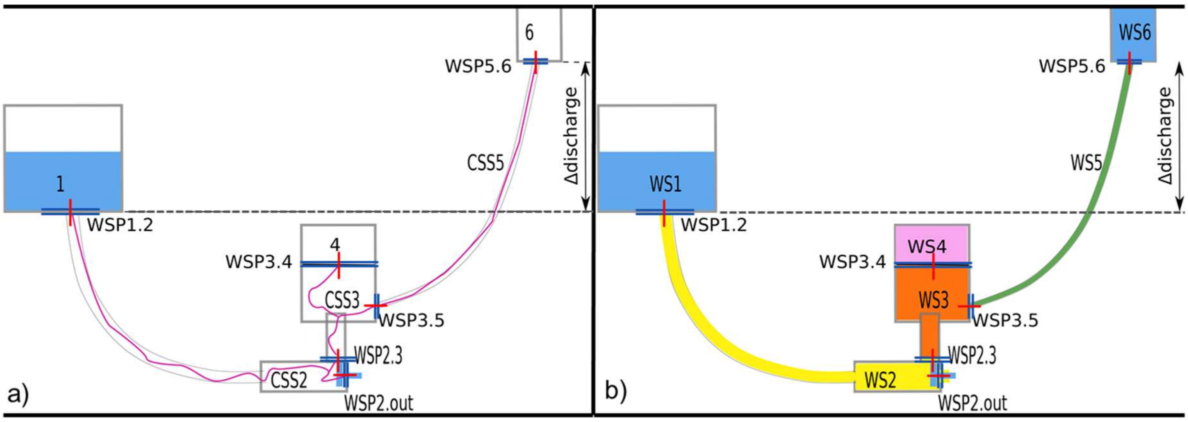

Figure 6 a) Contact and Channel model of a hydraulic ram; b) WSM of a hydraulic ram

At first sight, both modelling approaches show many similarities. Both divide the observed systems into separate areas or subsystems, describing them separately to reduce the complexity of the model. The subsystems interact by forming so called working surface pairs. The working principle of both approaches is a qualitative, graphic analysis, aiming to understand the systems' behavior and to derive design solutions to overcome existing shortcomings.

The fundamental difference between WSM and C&C² however can be found in the content of the subsystems themselves. The C&C²-Approach describes a permanently or occasionally present connection between physical structures of solid bodies, liquids, gases or fields as a so called channel and support structure, (Albers & Wintergerst, 2014). The WSM assumes a static or dynamic subsystem changing its state following a deterministic behavior based on input conducted through the adjoining WSP. Therefore, the model supports the concept of balancing e.g. energy to explain the function of a system. The significance of this distinction is illustrated by Figure 6, which shows two representations of the hydraulic ram.

The C&C² model, Figure 6 a, can explain the function of the pumping system only by the pressure caused by the fluid column. Therefore, it suggests that the pictured reservoir 6 cannot be reached as no additional pressure is applied along the channel and support structures. The WSM, cf. Figure 6 b, however can describe the working spaces by using state variables such as fluid velocity or temperature. The state of a WS changes by interacting with other WSs and is dependent on the coupling conditions at the WSP. Such a description is mandatory to understand the working principle of a hydraulic ram, which is based on the conservation of momentum and therefore requires knowledge about the state (velocity) of the WSs 2, 3 and 5 (Kypuros & Longoria, 2004).

Prior to building a systems model, designers have to choose the most suitable model for their development objective. As a variety of different models is available and all require comprehensive knowledge about their use as well as training, practitioners are supported by available reviews of models like (Eisenmann et al., 2021; Matthiesen et al., 2019).

Based on the review on existing models as well as the comparison of C&C² -Approach and the WSM the shortcomings of present models for the objective described in section 1 are identified. First, the most important advantages of the qWSM are derived.

Similar to any other model the qWSM shows a simplified representation of the observed system, generated to obtain a predefined modelling objective. The given objective specifies the information the model has to provide in an explicit or implicit way. While it is possible to build a model of the whole system, the usability increases by focusing on the precise description of only the subsystems that are relevant for answering the questions emerging from the modelling objective, compare the approach of Figure 4.
But how can the qWSM as described in section 1 support the work of designers?

4 Method

The authors intend to keep the qualities of the existing WSM, which is also able to identify non-functions and malfunctions. Exceeding the abilities of its predecessor and competitive models the qWSM can give an insight how exactly non-functions such as a leakage can be fixed. A non-function describes a not existing but intended function such as missing sealing as the cause of leakage (Beetz et al., 2018). An example can be seen in Figure 7. In the case of leakage at the radial shaft seal an increase of pressure $p_1$or decrease of the sealing face A_2 leads to an increase in the normal stress σ_N that is responsible for the sealing function. This relation is described by equation (1) (Bauer, 2021)

$$p_m = \frac{F_r}{A_2} = \frac{p_1 \cdot A_1}{A_2} \tag{1}$$

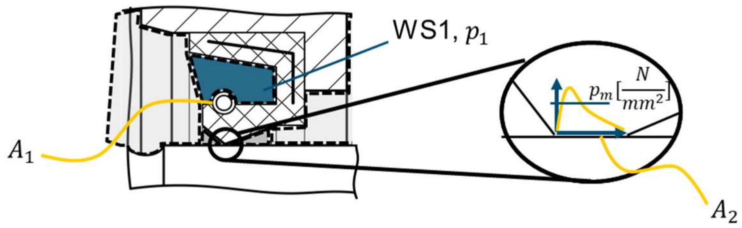

Figure 7 WSM of a radial shaft seal based on (Bauer, 2021)

Regarding the presented ability to describe the relation between design and process parameters (A_1, A_2, p_1) and function (sealing) the main topic of this contribution becomes clear: The qWSM can derive the determining design and process parameters for either manipulating existing (mal-) functions or generating new functions by overcoming identified non-functions. Furthermore, it gives a good quantitative estimation about the effects of changing the design parameters by supporting developers with a simplified quantitative description of the relations in and between the WSs of the super system. Summarizing the last aspects, the qWSM answers two crucial questions for a designer:
What do I need to change to achieve the development objective?
How much do I need to change it?
After addressing the potential of the qWSM the question arises how the designers can exploit it. As a first step, the model has to support the balancing of conservation variables in working spaces, generating state equations of the WSs, as well as coupling equations between the WSs. Applying the idea of Figure 4 the model complexity shall be limited by only modelling the WSs that are relevant for the modelling objective in detail. Other parts of the system should be described by simple representations in the form of Figure 2. Completing the first stage of developing the qWSM a set of guidelines for modelling physical systems is necessary.
Based on the aforementioned potentials the following research hypotheses of this contribution can be derived as:

- The qWSM does support the identification of critical parameters of a system for achieving a given development objective.
- The generated model describes the relations between design parameters and function sufficiently for supporting decisions in early phases of the development process.

To investigate the presented research questions, the authors design an exemplary hydraulic ram based on a predefined development objective.

Hydraulic rams as described in section 3 are designed to pump water or other fluids to a higher level of potential energy, using only the kinetic energy of flowing water as source of external energy (Kypuros & Longoria, 2004). Regarding this, the significance of those systems in terms of water supply becomes clear. In remote areas, especially if small and indigent communities inhabit them, it becomes a crucial part of healthcare to guarantee a safe supply with fresh water. Assuming a source of fresh water is available, in most cases a pumping system is needed to make it accessible for example in a central storage tank. As communities such as the described mostly do not possess a reliable and affordable source of energy, a pumping system that works by using naturally occurring sources such as wind, sun or flowing water can be essential for assuring their access to fresh water. The working principle of a hydraulic ram requires only mechanical and hydraulic components such as pipes, valves and tanks. All components can be designed following the principles of robust design (Vogel et al., 2018) to ensure the function in rough environmental conditions such as speed and temperature of the water flow and to withstand the acting forces of the ram. These boundary conditions suggest a relatively simple hydraulic system, which does not require electric components and can therefore be installed and in need repaired by the local communities themselves. Considering the described advantages of using the hydraulic ram to supply small, remotely located communities with fresh water the question arises, how a certain discharge head can be achieved for given environmental conditions. From this question, the development objective is derived as follows:

- Pumping water to a height of X using a water flow of the speed Y.

To achieve the developed objective the qWSM is put to the test by using it to:

1. Explain the function of the hydraulic ram
2. Identify the function-determining working spaces
3. Identify the function-determining design parameters and
4. Quantify their mathematical relations to the quantity of interest
5. Derive a suggested design solution to achieve the development objective.

Lastly, a prototype is developed to evaluate the quality of model and the gained information.

5 Results

The underlying principle of balancing conservation variables is the mayor novelty of the qWSM as a tool for the design process. The approach combines a graphic representation suitable for a qualitative explanation of the system’s functional structure with the possibility to derive physical equations describing the quantitative relations that determine the embodiment of the functional structure. Doing so, designer are enabled to explain the effects of different design solutions on the intended function. For the given example, first the systems working principle is described qualitatively, following the representation is detailed iteratively and finally the effects of variable cross sectional areas in the pipes on the discharge head can be evaluated by a detailed analysis of the affected working spaces.

Starting with the example of section 3 the function of the hydraulic ram will be explained. If we assume the hydrostatic pressure as the underlying physical principle in WS2 the discharge head shown by Δdischarge, cf.Figure 6 could not exceed the height of the reservoir WS1. This finding leads to the first iteration of the model. The function can not be explained by a representation following the idea of figure 2. Instead, a model following figure 4 is required which is shown in figure 8. As neither mass nor energy except of the water itself is introduced into the system, the function must be explained by balancing the momentum of the water in WS2. It is the only WS directing the flow of water actively by closing the valve at WSP2.out. The conservation of momentum in WS2 results in the following set of equations:

$$p_{in} = p_{out} \tag{2}$$

The momentum of a fluid in a pipe of the cross-sectional area A, length l and the density ρ equates to:

$$p = m * v = A \cdot l \cdot \rho \cdot v \tag{3}$$

$$p_{in} = A_{in} \cdot l_{in} \cdot \rho \cdot v_{in} = A_{out} \cdot l_{out} \cdot \rho \cdot v_{out} = p_{out} \tag{4}$$

As the density of water is constant in this application, equation (4) can be simplified to:

$$A_{in} \cdot l_{in} \cdot v_{in} = A_{out} \cdot l_{out} \cdot v_{out} \tag{5}$$

As the speed of the water leaving WS2 is determining the possible discharge height, it is the function-determining quantity. Therefore, a relation between this critical quantity h_2 and design parameters must be derived. Solving the equation for v_{out} a relation between the state variable of the fluid in WS3 and design parameters ($A_{in}, l_{in}, v_{in}, A_{out}, l_{out}$) of the hydraulic ram results:

$$\frac{A_{in} \cdot l_{in} \cdot v_{in}}{A_{out} * l_{out}} = v_{out} \tag{6}$$

The discharge head can now be calculated by the uniformly accelerated rectilinear motion against gravitational acceleration with a positive initial velocity of v_{out}:

$$h_2 = -\frac{1}{2} \cdot g \cdot t^2 + v_{out} \cdot t \tag{7}$$

$$h_2 = \frac{1}{2} \cdot \frac{{v_{out}}^2}{g} \tag{8}$$

$$h_2 = \frac{1}{2g} \cdot \left(\frac{A_{in} * l_{in}}{A_{out} * l_{out}}\right)^2 \cdot {v_{in}}^2 \tag{9}$$

Now the possible discharge head can be calculated based on the cross-sectional area and length of the working spaces WS1&WS3, compare figure 8. The velocity v_{in} can be determined either by the height of a tank and therefore Toricelli's theorem (Torricelli, 1644) or by the speed of the supplying water flow such as a river.

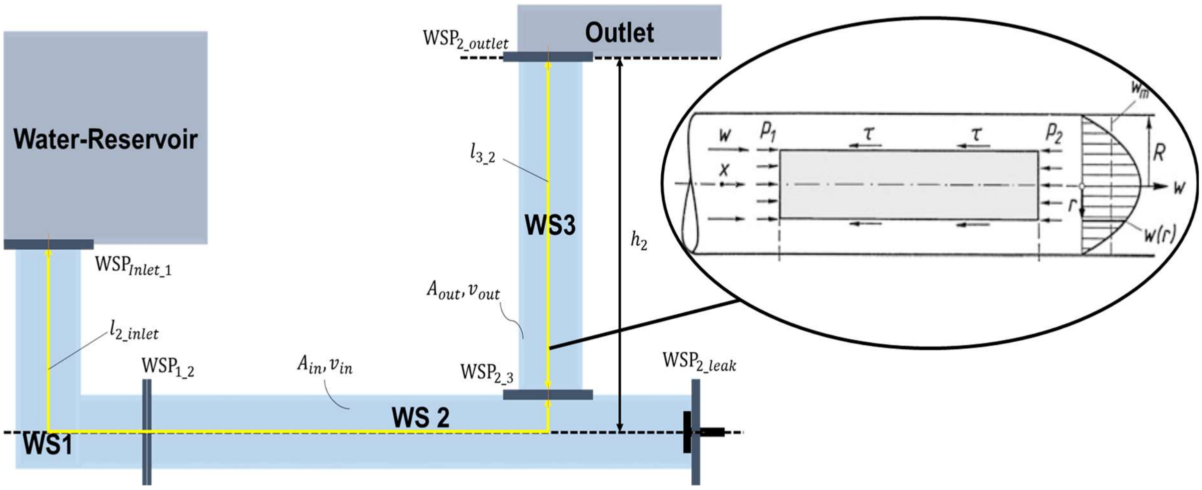

Figure 8 qWSM Hydraulic Ram(left); Detail of the laminar flow in WS3 (right) (Bschorer, 2018)

All equations presented above are a simplification of the real physical system neglecting effects like friction, turbulence, leakage and serve to describe the determining relation between the critical design parameter and the main function of the system quantitatively. Nevertheless the qWSM must be further detailed to quantify the influence of friction on the main function, assuming a laminar flow in WS3. As illustrated in Figure 8 right the velocity profile has a parabolic shape with a maximum in the middle of the pipe. By integrating the sheer stress for a newton approach under the boundary condition of adhesion $w(R) = 0$ of the fluid at the wall the velocity can be calculated, (Bschorer, 2018). For dissipative processes due to friction only the mean velocity is important, which ca be calculated using equation (6). Adding the knowledge generated by the qWSM to available expert knowledge like (Bschorer, 2018), the pressure loss dependent on length and diameter of WS3 can be calculated. The reduced discharge head h_{2_eff} results from applying equation (10) on equation (9) using the hydrostatic pressure relation in equation (11)

$$\Delta p = \frac{32 \cdot v_{out} \cdot \eta \cdot l_{3_2}}{{d_3}^2} \tag{10}$$

$$\Delta h = \frac{\Delta p}{\rho_{fluid} \cdot g} \tag{11}$$

$$h_{2\_\mathrm{eff}} = h_2 - \Delta h = \frac{1}{2g} \cdot (v_{out})^2 \cdot {v_{in}}^2 - \frac{32 \cdot v_{out} \cdot \eta \cdot l_{3\_2}}{{d_3}^2 \cdot \rho_{fluid} \cdot g} \tag{12}$$

The reduced discharge head shows a recursive dependency of v_{out} as it increases with lower cross section surface but the losses due to friction increase with the higher fluid velocity. By simulating different parameter sets for a given viscosity η and density ρ_{fluid} of the fluid a minimal cross section ensuring a reliable operation of the pump system can be found.

6 Conclusion

In this contribution, the idea of the quantitative working space model is derived from a critical assessment of existing product models and their shortcomings in terms of quantitative modelling prior to the phase of elaborating the detailed embodiment. The qWSM is presented as a hybrid approach successively detailing heuristic models with analytic models of subsystems. The qWSM is introduced as a tool to generate knowledge in the K-Space to encourage innovative design using C-K theory. The concept of a hydraulic ram is modeled using a qWSM in order to identify the function-determining design parameters and thus to generate knowledge related to this concept. After identifying and quantifying the relation between discharge head and design parameters a prototype to further investigate the accuracy of the model is designed. Doing so both hypotheses presented in section 4 can be confirmed for the specific application.

The qWSM quantifies the relation between determining state variables, design parameters and the critical disturbance friction to evaluate possible value ranges for the design parameters.

As a next step, the prototype, cf. Figure 9 Shape of the flow (left); Designed Prototype, needs to be tested experimentally to compare the predicted and resulting discharge heads. The authors state that the qWSM is not developed for the simulation of the fluid flow as the assumption of laminar flow is unlikely to be valid for realistic geometries of the system including bended parts of the pipe and changes of cross section. Nevertheless, the question arises, if and how the qWSM can support the preparation of simulation activities throughout the development process. Examples would be the categorization as a static or dynamic, linear or nonlinear simulative problem, which is crucial for the correct choice of simulation tools. An example would be the classification of the simulative problem to simulate the fluid flow as shown in. The qWSM is not developed to perform the simulation itself but to provide knowledge to describe the simulation problem.

Furthermore, the qWSM can be used as a multiphysical modelling tool, linking physical domains such as solid, fluid and electric domain and coupling them, only using the balance of conservation variables. By enabling multiphysical modelling, three-dimensional volumes can contain multiple working spaces in multiple domains, broadening the scope of application to generate knowledge in the K Space.

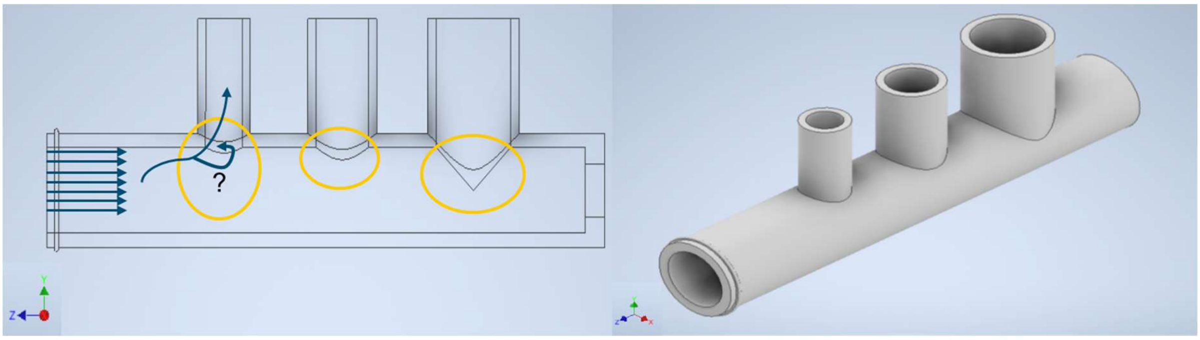

Figure 9 Shape of the flow (left); Designed Prototype (right)

Further research is required to develop a comprehensive set of rules for using the qWSM and to provide accumulated expert knowledge for multiphysical modelling. The authors intend to perform the necessary research to further develop the qWSM to a powerful tool for developers.

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