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EARLY ANALYSIS OF THE SYSTEM DYNAMICS OF SELF-OPTIMIZING SYSTEMS

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Keywords: system dynamics, conceptual design, self-optimizing systems, costs and benefits

1. Introduction

Self-optimizing (s.o.) systems are systems with inherent partial intelligence. Their bases are mechatronic systems which are characterized by the close interaction of mechanics, electrics/electronics, control and software engineering as well as a rigid control. The integration of cognitive functions (e.g. "share knowledge" or "coordinate behaviour") into mechatronic systems enables self-optimizing systems. The paradigm of self-optimization has been the research subject of the Collaborative Research Centre (CRC) 614 "Self-Optimizing Concepts and Structures in Mechanical Engineering" (www.sfb614.de/en). The work continues in the BMBF-Leading-Edge-Cluster "Intelligent Technical Systems OstWestfalenLippe" (it's OWL). Self-optimization describes the endogenous adaptation of the system's objectives due to changing operation conditions and the resulting autonomous adjustment of system's parameters or system structure and consequently of the system's behaviour. The key aspects and the mode of operation of a self-optimizing system are illustrated in Figure 1a. In order to change its behaviour the system carries out the so called self-optimization process continuously (cf. Figure 1b) [Adelt et al. 2009], [Dumitrescu 2011], [Dumitrescu et al. 2014]. An example for self-optimizing systems is the innovative railway system RailCab. Tests with prototypes and test benches of self-optimizing systems and self-optimizing function modules within the CRC 614 as well as application examples within the innovation projects „itsowl-ReSerW" and „itsowl-Self-X-Pro" of the Leading-Edge-Cluster it's OWL have shown their benefit compared to conventional mechatronic systems [Adelt et al. 2009], [Gausemeier et al. 2013], [Boecker et al. 2014]. The properties of self-optimizing systems also with regard to costs and benefits are influenced by design decisions all over the life-cycle. These design decisions are made within the early development in the conceptual design [Vassholz and Gausemeier 2014]. In addition to the technical parameters, the effectiveness of a system is influenced by organizational parameters [Niemann 2009]. Due to rapidly changing customer requirements, a system has to adapt to these requirements continuously over its whole life-cycle [Damm et al. 2010]. Self-optimizing systems are able to adapt their behaviour to changing environmental conditions during its operation. Therefore on the one hand they are able to adapt to customer needs and thus maximize the benefit. On the other hand they are able to be resource efficient and reduce the costs for operation accordingly. During the conceptual design the potential for self-optimization can be identified [Pook 2011]. The developer has to choose between an mechatronic or a self-optimizing system [Vassholz and Gausemeier 2012]. For this decision, maximization of benefits and minimization of costs over the life-cycle should be in focus [Niemann 2009]. The solution variants differ in these points due to their behaviour during operation. This difference can be attributed to the different dynamic of mechatronic and self-optimizing systems. An approach to analyze the economic efficiency of self-optimizing systems during the conceptual design therefore has to include the dynamic of the system [Vassholz 2014]. Without the simulation of the system dynamics a proper comparison of the benefits during operation will not be possible.

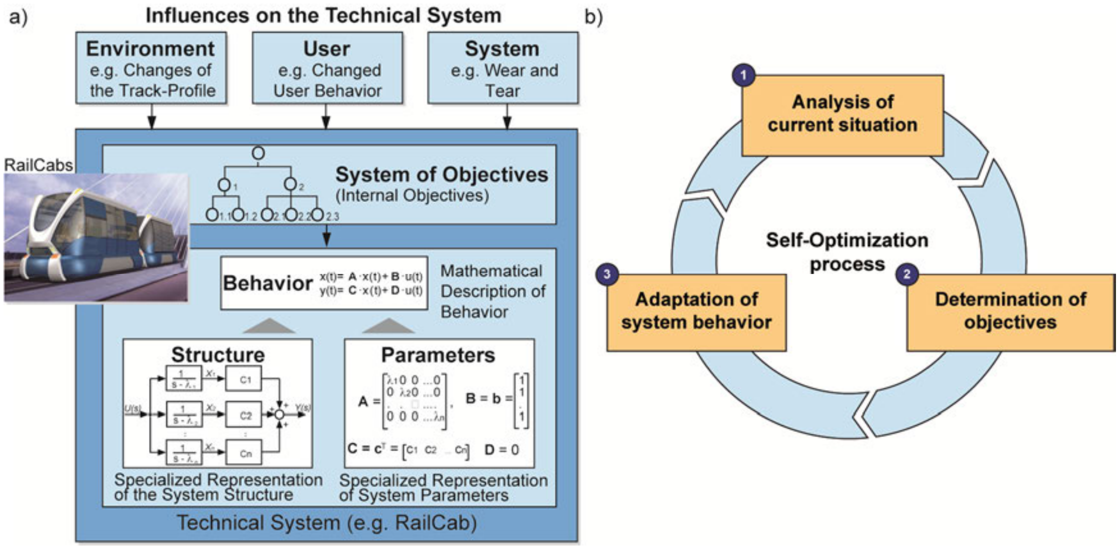

Figure 1. a) Aspects of a self-optimizing system and b) the self-optimization process ([Frank et al. 2004], [Dumitrescu et al. 2014])

In this paper we will present a model-based approach to simulate the dynamic of a mechatronic and self-optimizing systems based on a discipline-spanning system model (cf. [Friedenthal et al. 2012]) during conceptual design. The method allows linking the behaviour with the resulting operating costs subsequently. Furthermore a comparison of the quality of customer requirement fulfillment of the alternative solutions is possible. First we will motivate the method and give an overview of the state of the art in section 2. In section 3 the application example RailCab and its Hybrid Energy Storage System are introduced. In section 4 we will describe the method based on the application example. Finally we will summarize our results and give an outlook in section 5.

2. Challenges for the analysis of the system dynamics in the conceptual design of self-optimizing systems and state of the art

The analysis of the current state of the art shows that there are a lot of approaches for the analysis of costs and benefits of mechatronic systems. One part of the approaches focuses only on the evaluation of costs, e.g., target costing [Dinger 2002], trans-disciplinary target costing for complex mechatronic products [Zirkler 2010] or life-cycle cost estimation [Ehrlenspiel et al. 2007]. Other approaches give priority to both costs and benefits, e.g., value engineering [Bronner and Herr 2006], benchmarking [Kreuz 2002], economic value analysis [Zangemeister 1970], simple point evaluation, weighted point evaluation or the ABC-analysis [Ehrlenspiel 2009]. These approaches do not fulfil the requirements which are set by self-optimizing systems, because they only focus on the system elements and do not take the costs and benefits which result from the interactions between them into account, as shown in [Vassholz and Gausemeier 2012]. For the analysis of complex systems [Bertalanffy 1972] proposes a general procedure with four steps. First the input and output of the system needs to be analysed. In the next step each system element is analysed in order to make a statement about the systems' characteristics. In the third step the interconnections between the system elements and in the last step, the systems behaviour needs to be analysed [Bertalanffy 1972]. Self-optimizing systems are complex systems in the definition of [Ulrich and Probst 1991], because they have a high variety of system elements with changing relations between them. These systems are able to develop new properties during operation and are highly dynamic and variable. Thus, they need to be analysed by the four steps as well. Especially the systems dynamic should be given special attention. In the context of control engineering in particular a analysis of the dynamic of a self-optimizing systems is conducted in order to build the basis for development of its optimization and control strategies. As described in [Kessler et al. 2013] the system model can be used to generate process models to develop the control strategy. On this occasion dynamic models of the system are build. However, a reliable statement about the systems dynamic needed for the development of the control strategy can only be made on very detailed information, for example about the weight of the controlled system. At this time the development is already very proceeded and it is very expensive to abort the development, if the wrong solution alternative has been chosen. The system dynamics approach by [Forrester 1971] enables the simulation of the dynamic of diverse systems. But it does not consider the specicalties of self-optimizing systems: the autonomous changing objectives. [Dumitrescu 2011] provides a Target-Priority-Matrix to clarify the changes of the priority of the objectives of self-optimizing systems. This approach does not take into account the changes of the system state over time. Therefore a method is needed to analyse the system dynamics of the self-optimizing system very early in the conceptual design based on an abstract describtion level.

3. Application example "Hybrid Energy Storage System of RailCab"

The innovative railway system RailCab consists of autonomous vehicles which supply transport for both passengers and cargo. RailCabs drive on demand and not by schedule. The RailCabs act in a proactive way, e.g. in order to reduce the required energy by forming convoys. The RailCab modules drive and braking system, spring and tilt system, energy management as well as the cooperation of these modules are based on the paradigm of self-optimization. Central element of the RailCab is its self-optimizing energy management, which enables the optimum power distribution for the function modules. The RailCab's propulsion system is realized by a double-fed linear drive. The maximum power transmission is approximately proportional to the provided driving power. In specific situations, for example slight inclines, the energy demand of the on board supply system cannot be fully covered by the linear drive's power transmission [Boecker et al. 2014]. To ensure a sufficient power supply continuously, the Hybrid Energy Storage System (HES) has been developed (Figure 2). It consists of nickel metal hydride (NiMH)-batteries for long term energy storage and double layer capacitors (DLCs) to buffer power peaks. To ensure the efficient operation of the HES, a self-optimizing operation strategy is required which pretends the specific power of the available energy storages depending on the situation. On this occasion especially the power losses and the system's power reserve, i.e. the potential to submit and store electrical power, have to be minimized [Romaus et al. 2009]. Through integration of cognitive functions, a self-optimizing calculation of the power distribution for the two power storages is enabled [Dumitrescu et al. 2011]. The application of self-optimization allows an ideal operation strategy [Romaus et al. 2009]. The test bench of the HES has demonstrated the potential for self-optimization impressively. Compared to a pure battery system the weight of the energy storage has been reduced by 30 % and at the same time the power density has been increased by more than 70 % through self-optimization [Romaus 2013]. These savings can be attributed to the self-optimizing energy management and the resulting improved dynamic of the system. The example shows that the benefits of self-optimization can be demonstrated impressively based on prototypes and test benches. During the conceptual design it is necessary to identify the favourability of the self-optimizing system to support the decision for a solution alternative. The following method has been developed retrospective based on HES.

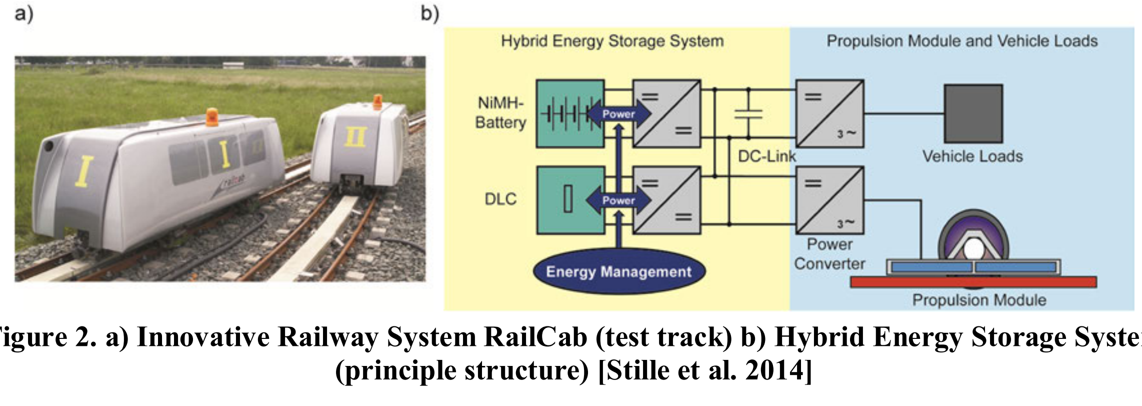

Figure 2. a) Innovative Railway System RailCab (test track) b) Hybrid Energy Storage System (principle structure) [Stille et al. 2014]

4. Method for the early analysis of system dynamics of self-optimizing systems

The method for the early analysis of system dynamics of self-optimizing systems is part of the conceptual design of self-optimizing systems (cf. [Gausemeier and Vassholz 2014], [Vassholz 2014]) and is based on the concept of system dynamics developed by [Forrester 1972]. The concept allows the simulation of the system dynamics based on causal and logical relationships, as well as on equations [Forrester 1972]. It is very well suited for the analysis based on a low level of knowledge and a high abstraction level during the early conceptual design. Figure 3 illustrates the method for the analysis of the dynamic behaviour based on a phase and milestone diagram. Input for the method is the system model of the mechatronic and the self-optimizing system described by the specification technique CONSENS (CONceptual design Specification technique for the Engineering of complex Systems). The system model consists of eight interrelated aspects: environment, application scenario, requirements, functions, active structure, behaviour, shape and system of objectives [Gausemeier et al. 2009]. Result of the conceptual design is the validated system model of the solution alternative which will be concretised. The difference between the model of a mechatronic and a self-optimizing system is applicably the aspect system of objectives, which is self-optimization specific [Gausemeier et al. 2009]. In the following subsections each phase will be described based on the application example HES.

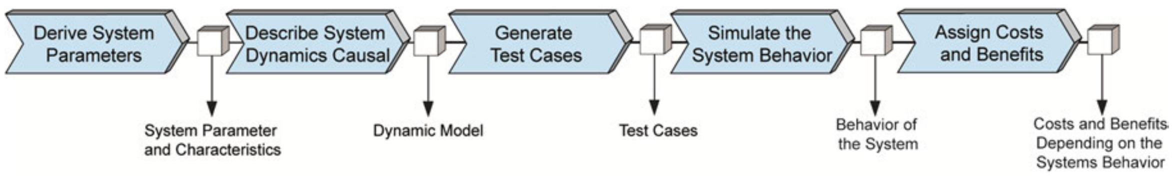

Figure 3. Process model for analysis of the system dynamics

4.1 Derive system parameters

In order to represent the self-optimization process (cf. Figure 1a) and simulate the system dynamics the system model for HES needs to be analysed regarding the following parameter: external influences, control variables and the system's objectives. Figure 4 gives an overview of the aspects of the system model, the resulting parameter for the simulation as well as their characteristics exemplary.

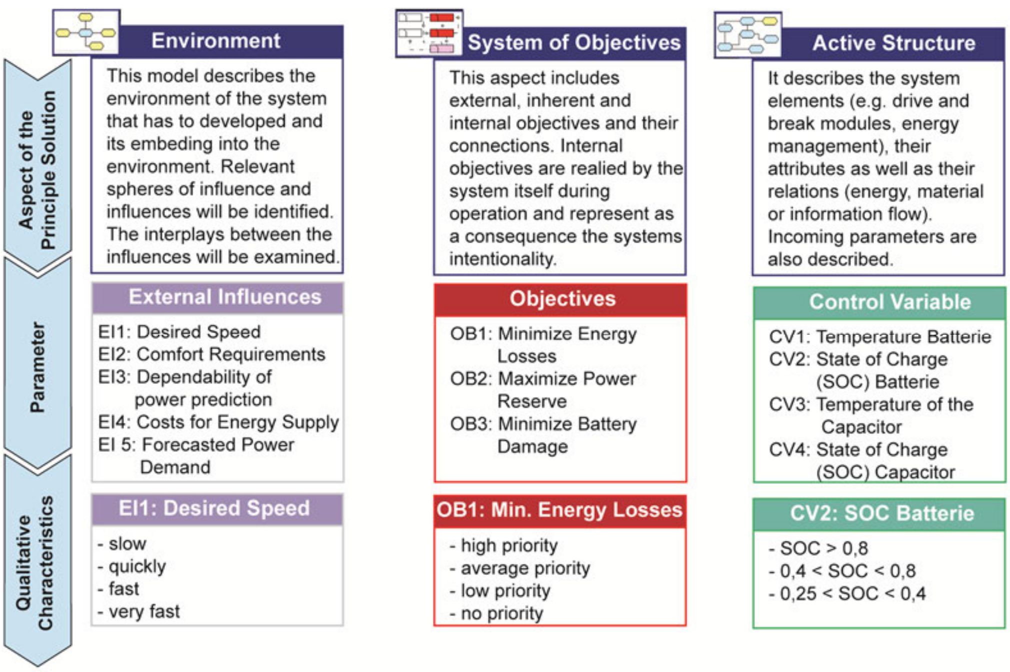

Figure 4. Process model for analysis of the system dynamics

External influences result from the flows in the aspect environment. In case of HES the external influences which need to be considered are desired speed (EI1), comfort requirements (EI2), dependability of power prediction (EI3), costs for energy supply (EI4) and forecasted power demand (EI5). Based on the active structure the systems inherent influences on the objectives as well as the control variables can be identified. The inherent influences are the temperature and state of charge (SOC) of battery (CV1, CV2) and capacitor (CV3, CV4) The system of objectives supplies the objectives: minimize energy losses (OB1), maximize power reserve (OB2) and minimize battery damage (OB3). For each parameter characteristics are determined. Since the analysis of the HES is done in an early stage during the conceptual design, these characteristics are qualitative. For instance priority of the objective "minimize energy losses" can be qualitative low, high, very high or no priority (based on [Dumitrescu 2011]). In this phase the first two steps of the recommended analysis methodology for complex systems by [Bertalanffy 1972] are covered. To be able to simulate the self-optimization process the interconnections of the parameters need to be analysed as described in the following section.

4.2 Describe system dynamics

In order to simulate the self-optimization process the interplay of the parameters in this process and the dynamic of the system, needs to be described: In case that the external influences of the environment on the system changes, the change of the priority of the system's objectives can be necessary. The objectives of the system are also influenced by themselves and the current system state. The system state can be influenced by the environment due to disturbing values. The self-optimizing system determines its objectives, if necessary. This leads to a changed reference value for the system's control strategy. The deviation between reference value and measured system state can change the control variable and therefore the behaviour of the system.

As [Bertalanfy 1972] suggests we use a matrix-based approach to describe these circumstances. Figure 5 shows exemplary two derived parameter and their attributes for each aspect. In matrix 1 (external influence vs. external influence) we conduct a consistency analysis of external influences, to be able to generate test cases in the following step (cf. section 4.3 and step 1 of Figure 1b). The adaptation of the system's objectives due to changes in the environment (phase 2 of Figure 1b) are described by matrix 2 (external influence vs. objectives). External influences can also be disturbing and have direct influence on the control variable. The effects of these influences are described in matrix 3 (external influence vs. control variable). The change from one state to another is connected to different effort for the system. The effort to change from one weighting of the objective to another is analysed in matrix 4 (objectives vs. objectives). The adaptation of the system due to changing system objectives (phase 3 of Figure 1b) is described by matrix 5 (objectives vs. control variable). Matrix 6 (control variable vs. objective) shows the influence of the system state to the system of objectives. For example, in case of a low SOC of the battery the objective “maximize power reserve” will get the highest priority to be able to ensure a secure operation of the system. Matrix 7 (control variable vs. control variable) establishes a relationship between different system states. Since the described relationships are very complex, the simulation of the behaviour is supported by a software-tool.

In the next step a simulation model for HES is build within the visual modelling tool Vensim©. The tool can be used to conceptualise, simulate, and analyse models of dynamic systems. The simulation models can be build by causal loop or stock and flow diagrams [Vensim 2007]. Figure 6 presents the model of HES in the Vensim© editor. It describes the relationships between parameters and their behaviour. The description can be either physically and formula based, e.g., the power of HES can be described by the sum of power supplied by battery and capacitor, or qualitatively. The qualitative description is used for relationships and behaviour which cannot be described formula based in this early stage due to a lack of information. An example is the selection of the Pareto optimum. During operation of the real system, this will be done by a selection heuristic based on Pareto sets. However, the generation of the needed Pareto sets requires detailed dynamic models and parameters which are not known in this early stage. The RailCab with its HES is represented under i) by the system elements and their relationships. The battery, the capacitor as well as the board net of the RailCab are fed by the linear motor. The state of charge (SOC) of the battery and capacitor increases exponentially.

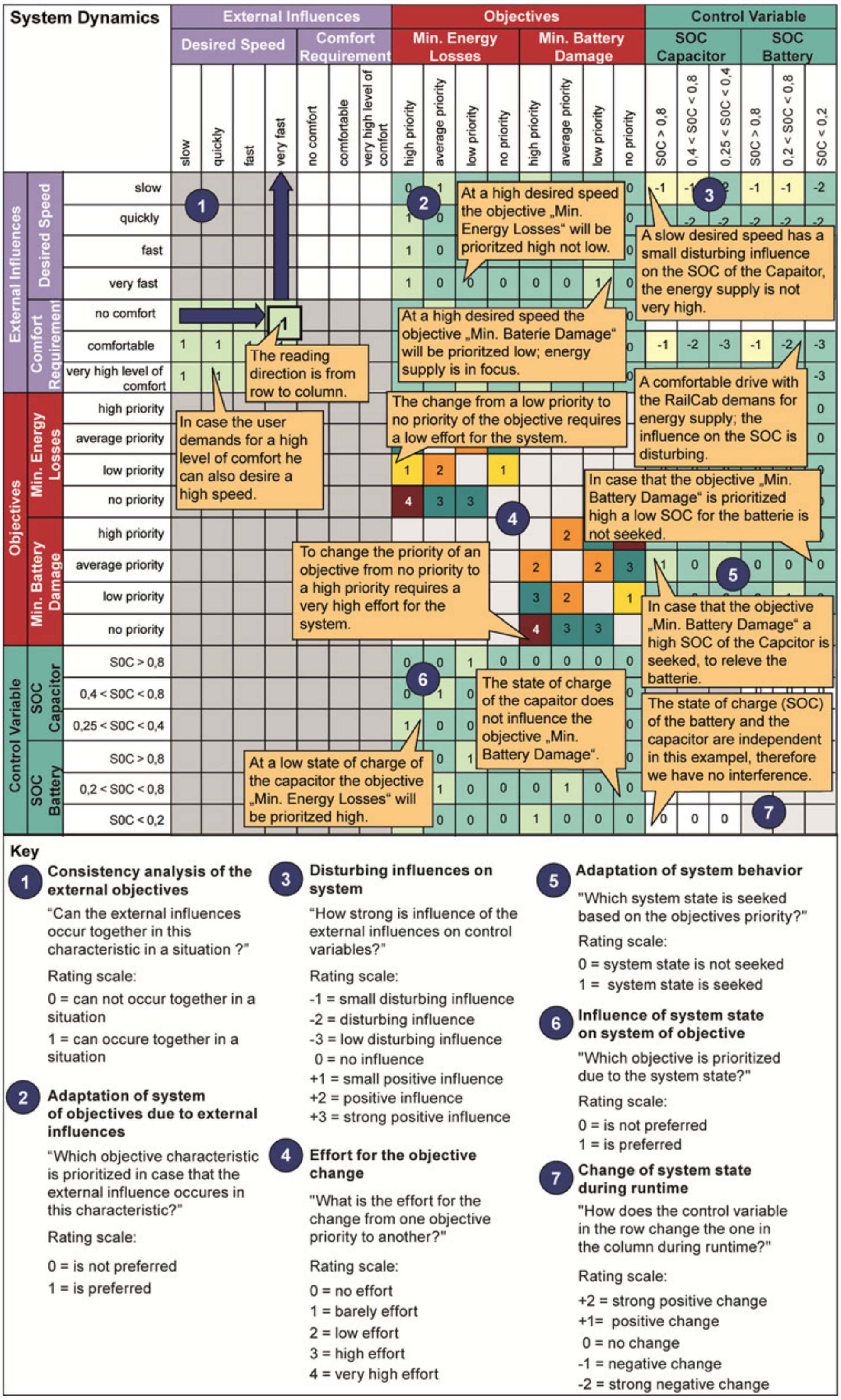

Figure 5. Matrices for the description of system dynamics [Vassholz 2014]

For the simulation we simplified the physical model. The information processing of a self-optimizing system is realized by a three layer architecture called Operator Controller Module (OCM) (cf. [Adelt et al. 2009]). On the cognitive level of the OCM the weighting of the system's objectives is conducted. This process takes place based on the current state of the systems under iii) as well as the systems state. The external influences are integrated under iv) into the simulation model. The relationships between the elements have already been described in Figure 5.

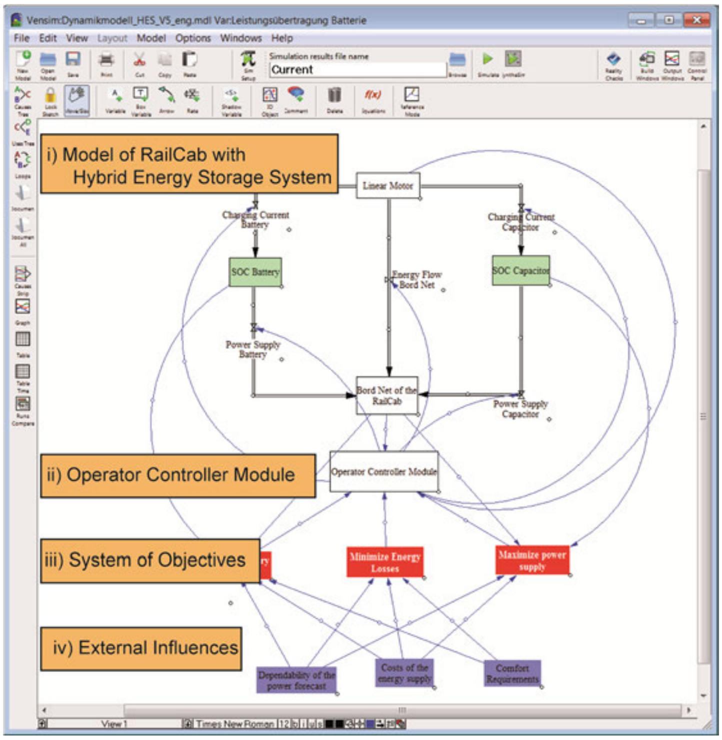

Figure 6. Model of dynamic system of Hybrid Energy Storage System in Vensim© editor

4.3 Generate test cases

In this step the life-cycle of HES is represented by test cases consisting of different operating situations. For this, the situation of the aspect application scenario is formalized. In matrix 1 (external influences vs. external influences) the consistency of the characteristics of the external influences is analysed (cf. Figure 5). For example a high demanded speed and a high demanded comfort by the user can occur in one situation. Different operating situations are derived from this matrix, consisting of a combination of characteristics of the external influences. These are clustered by similarity and assigned to the application scenarios, which describe the same situation during the life-cycle of the system. For example, the RailCab is on an even track, the user wants to drive fast and comfortable, the power supply from the linear drive is sufficient and the dependability of the power supply prediction is high. Afterwards a sequence of application scenarios is generated and each one is provided with a time stamp describing its duration. Thus test cases which represent the life-cycle of HES result. For this step the clustering algorithm of the scenario technique has been adapted [Gausemeier and Plass 2014].

4.4 Simulate system behaviour

For these test cases the dynamical behaviour of the system is simulated using the simulation model (cf. Figure 6). As decision basis for the simulation model the matrices (cf. Figure 5) are integrated in form of lookup tables. During the simulation the self-optimization process (cf. Figure 1a) is continuously conducted as follows:

1. **Analysis of current situation**: The self-optimization process is initiated, either in case that the situation and therefore the external influences, or the system state changes. The external influences vary by changing the situation during a test case. The associated state vector for the external influences is given by the current application scenario which sets the values for the external influences in the simulation model (Figure 6, (iv)). Furthermore it is examined whether this change leads to a direct change of the systems state because of disturbance variables (Figure 5, matrix 3 (external influences vs. control variable)). The other case occurs

for example when capacity of battery of RailCab switches from one state to another, due to energy consumption of the system. The current state of the system results from the values of HES model (i).

2. **Determination of objectives:** The next step is to determine the objectives of the system. The priority of the objectives depends on external influences (iv), the system state (i) and the current priority of the objectives (iii). Each characteristic in the matrices (Figure 5, matrix 2, 6, 4) demand a certain priority (h = high, m = medium, l = low, n = none) of the objectives. Out of these demands the "Pareto optima" for every objective prioritization is chosen and results in the state vector $\overrightarrow{O}_{desired}$ for the new objectives. In this case the "Pareto optima" is chosen by the average of the resulting demands as shown in Equation 1.

$$\overrightarrow{O}_{desired} = \begin{pmatrix} \text{Minimize Energy Losses} \\ \text{Minimize Battery Damage} \\ \text{Maximize Power Resource} \end{pmatrix} = \begin{pmatrix} (2*h)+(3*m)+(2*l) \\ (1*h)+(5*m)+(1*l) \\ (3*h)+(4*m)+(1*l) \end{pmatrix} = \begin{pmatrix} \text{medium} \\ \text{medium} \\ \text{high} \end{pmatrix} \quad (1)$$

3. **Adaptation of system behaviour:** The alteration of the system of objectives for the system, demands a change of systems behaviour. Figure 5, matrix 5 presents the influence of the control variables by priority of objectives. The new state vector of the system can be taken and the system switches to another operation mode. For example, the weighting of the power supply of the three energy sources for the board net can change.

Since system behaviour can change during operation, e.g., by energy consumption, the continuous operation of the system is simulated as well. For this we simplified the physical behaviour of the components. Figure 7 shows an example for the development of the SOC for the capacitor during a test case. The result shows, that the graph for the self-optimizing systems has less deviation from the optimal SOC than the mechatronic one. For example the capacitor charges exponentially. The highest state of charge is "1" and the lowest possible is "0". When the system state changes to another mode the self-optimization process is initiated again. For the charging of the capacitor this is the case, if its state of charge exceeds for example the value "0.8". The presented procedure is conducted for all scenarios of the test cases. The respective priority of the objectives as well as the system state is recorded by the simulation tool. For the conventional mechatronic system the simulation is conducted in a similar way, except that the changes of objectives are limited to the defined control strategies. Therefore, the adjustment of objectives described earlier is obsolete and a different system behaviour results. Result of the simulation is the development of the SOC during the test cases.

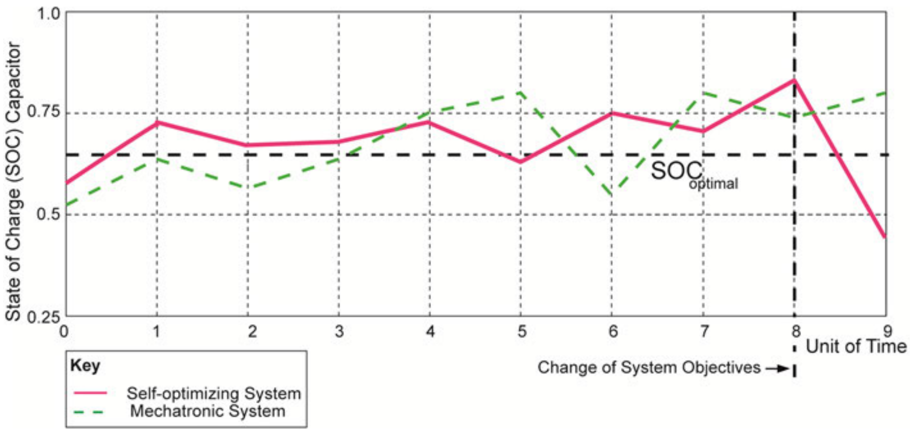

Figure 7. Exctract of simulation results for the SOC of the capacitor in one test case

4.5 Allocation of costs and benefits

The simulation results show the behaviour of the self-optimizing system as well as the mechatronic systems during operation. A comparison regarding the energy efficiency is already possible based on these results. In this step we assign operation costs in monetary units to the results. By this a comparison of the operating costs is possible. Furthermore, the results show how well the customer requirements have been fulfilled during operation and therefore provide information about the received benefit of the customer.

5. Conclusion and outlook

The method presented above allows the early analysis of the dynamic behaviour of a self-optimizing and a mechatronic system. For the application example we are able to compare the load cycles of battery and capacitor and the power transfer to the RailCab's board net over time of both systems. The comparison with the results of the test bench [Romaus 2013] showed the same tendency, when taking the degree of abstraction of our simulation model into account. Without this simulation the estimation of the systems benefit during operation would not be possible. Based on the results a decision for one solution alternative that minimizes the operation costs and maximizes the customer benefit is possible. The development of the simulation model is time consuming. In further research we have to analyse how to support the developer by building the simulation model. For example matrix No. 2 could be filled in automatically based on the Target-Priority-Matrix by [Dumitrescu 2011] which is filled in earlier in the conceptual design (cf. [Vassholz and Gausemeier 2014]).

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