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PID control loop tuning for three-port mixing valves within building energy distribution systems—application and assessment of different tuning methods under real operation conditions

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Abstract:

We assess different control loop tuning methods to tackle suboptimal building performance due to suboptimal PID control within building automation systems. Advanced control research for building energy systems is usually conducted either simulation-based or with the help of experiments via test benches. Therefore, it is limited in terms of applicability to real systems. Consequently, we conduct real tuning experiments with different PID tuning methods under real operation conditions within a state-of-the-art building energy distribution system.

We use experimental step response tests to identify transfer functions for different three-port valves. We theoretically specify controlled systems' transmission behaviour by functional diagrams, as well as mathematically describe them via characteristic variables according to Ziegler and Nichols and via fitted transfer functions. In order to ameliorate the actual control quality, we apply different tuning rules and adjustment standards: namely lambda-tuning, absolute value optimum method, symmetrical optimum method, Ziegler and Nichols, optimization on different control quality indicators and cognitive parameterization. For each method-system-combination, we experimentally conduct step experiments to evaluate with reference to control quality.

Our results show an improvement of control quality up to 88%. Controller parameterization based on cognitive parameterization and lambda-tuning are the most effective methods.

By conduction of field experiments under operating conditions, we show how to monitor, evaluate and ameliorate control quality of three-port valves. Therewith, we derive the most effective tuning methods. Further, we conclude that control quality amelioration crucially depends on the applied control tuning method and on knowledge about the behaviour and characteristics of controlled systems.

Keywords:

PID-control, monitoring, controller tuning, building energy systems, application

1. Introduction

Control quality of PID control loops in nowadays-building energy systems is often far from optimal. A reason is that system integrators tune controllers by heuristics, empirics or even not at all. More innovative building automation systems have adaptive tuning methods, which, as we observed in our case, do not provide satisfying control quality neither. Classical mathematical tuning methods, applied to monitored data, can improve control quality following the methodology, which we present in this paper.

Good control quality is important in e.g. building energy systems, HVAC systems and ventilation units [1-3]. Good control quality can lead to little maintenance effort, good energy efficiency and good system demand satisfaction, e.g. appropriate thermal energy flows, thermal comfort, indoor air quality. Bad control quality can mean either oscillatory behaviour of control loops; overshooting behaviour; or permanent control deviation; or a combination of two or three of these characteristics [4]. Oscillatory behaviour leads to higher maintenance efforts due to higher wear and tear in valves, dampers, drives, etc. Overshooting behaviour decreases energy efficiency and the systems demand satisfaction ratio. Permanent control deviation leads either to suboptimal demand satisfaction or even to suboptimal demand satisfaction and bad energy efficiency in parallel.

Control theory literature provides extensive work towards system identification [5], control parameter setting, control parameter setting rules and heuristics, online and offline parameter tuning and adaption methods [6, 7]. Evidently, these concepts also apply for control loops in building energy systems. Researchers conducted several studies, applying different control optimization approaches to different control problems in buildings [1, 3, 8-15]. As research methodology, the vast majority of building control researchers uses simulation studies [1, 3, 8-15]. Simulations provide a flexible experiment set up, meaning e.g. freedom in system size and capacity; they provide flexible boundary conditions, such as ambient temperatures, air/water volume flows etc. However, in general, simulations do not account for uncertainties coming from e.g. users or weather, even though a few attempts are undertaken to incorporate uncertainties. Further, they do not reveille application constraints from real systems, e.g. data exchange speed limitations, computing power of programmable logic controllers, data storage limitations, limitation of data frequency etc. A few building control researchers conduct experiments on test benches, facing a flexible experiment set up planning, flexible boundary conditions and but no uncertainty and no full application constraints [11, 12]. Others use monitoring data from real buildings for validation but do not interact with the building [3, 14]. By contrast, real experiments, so-called field-tests or field experiments, do provide real uncertainty and real constraints towards system application. Field tests have a given experiment set up and given boundary conditions. We believe that there is a lack of building control research demonstration in real buildings equipped with real monitoring systems under constraints of real operation conditions.

In this paper, we assess different control loop tuning methods to tackle suboptimal building performance due to suboptimal PID valve control. We use experimental step response tests to identify transfer functions for different three-port valves. We theoretically specify controlled systems' transmission behaviour by functional diagrams, as well as mathematically describe them via characteristic variables according to Ziegler and Nichols and via fitted transfer functions. In order to ameliorate the actual control quality, we apply different tuning rules and adjustment standards: namely lambda-tuning, absolute value optimum method, symmetrical optimum method, Ziegler and Nichols, optimization on different control quality indicators and cognitive parameterization. For each method-system-combination, we experimentally conduct step experiments to evaluate with reference to control quality.

First, we shortly introduce the applied tuning methods. We present our experiment set up with a focus on theoretical and applied system identification. Going on, we present results for each tuning method. We then integrate and discuss them. Finally, the paper ends with our conclusion and research prospects.

2. Methods

2.1 – Applied tuning-rules and adjustment standards

The determination of controller parameters has taken place according to the adjustment standards of Ziegler and Nichols [16], the method of lambda-tuning by Dahlin [17], the both regulatory optimization criteria absolute value optimum and symmetrical optimum as well as tuning on basis of experimental results and cognitive tuning. All tuning methods have been applied to PI-Controllers.

The well-known controller setting rules have been developed empirical for proportional plants with first order time increase and dead time (FOPDT). Consequently, and as in all other following tuning rules it is assumed that knowledge about the controlled system exists already. The adjustment standards are, inter alia, presented in the original work of Ziegler and Nichols [16].

Lambda-Tuning is a particular form of placement of pole points in closed-loop systems. In this tuning rule, the controller parameterization relies on the design parameter λ. In addition, this setting rule is utilized for FOPDT processes [7].

Both the absolute value optimum method and the symmetrical optimum method are based on optimization of the frequency response at open control loop settings. For controlled systems with time delay of n^{th} order the settings for different controllers can be found at [7].

Furthermore, tuning rules adapted to the examined processes have been designed and tested. They are described in equations (1) and (2) and base on the knowledge that, proportional gain X_p is the reciprocal of the transfer factor standardized on the whole setting range [18] and reset time T_n is the duration required to achieve the same alteration as X_p forms immediately.

$$X_p = T_{max} - T_{min} \tag{1}$$

$$T_I = T_g \frac{y_{100\%}}{y_{exp}} \tag{2}$$

Based on all conducted research, controller settings and control quality have been analysed. Thereupon, a cognitive controller parameterization has been implemented and evaluated.

2.2 – Applied indicators for control loop performance

Due to the execution of step response experiments, indicators like rise time and settling time etc. have been examined. Since there is no superior optimization objective, the focus was placed on integral criteria, by which it became an overall aim to minimize these performance indices.

The integral of absolute error (IAE), the integral of squared error (ISE) and the integral of time-multiplied absolute error served as evaluation criteria for control loop performance. The three integral criteria describe control loop quality to different degrees by weighting. While IAE-criterion is neither time-multiplied nor weighted, within the ISE-criterion large control deviations are weighted stronger than small system deviation. By use of the ITAE-criterion control deviations that occur in late time are penalized strongly while early time errors are nearly ignored [19].

3. Experiments

The objects of this study are four three-port mixing valves with heterogeneous size. Valve 1 and 2 have a nominal diameter of 65, their k_{vs} value is 40 m^3/h. The feature sizes of valve 3 are DN 65 and k_{vs} 25 m^3/h of valve 4 DN 50 and k_{vs} 16 m^3/h. The investigated controllers regulate the flow temperatures to different parts of the concrete core activation systems. Controlled variables as well as working set points and regulating variables are monitored and recorded every minute by the monitoring system. The reference and the regulating variables are not only readable but also writeable, which allows both open and closed-loop inspection.

In order to identify the controlled system and evaluate the existing and increased control quality, experiments at the plant and at the control circuit have been conducted.

All experiments took place in a 7000m² multifunctional building for offices, laboratories, and conferences [20]. In previous work, the authors extended the building to a multifunctional demonstration bench for advanced control research in buildings. They integrated a monitoring, control and interface system to deal with the prerequisites for control tuning application in real buildings. Reference [21] provides more details on the demonstration bench.

3.1 – System identification

To specify the system's transmission behaviour theoretically, a functional diagram [22] has been developed. The cause-effect relationships of the subsystems valve-actuator, valve-flow and heat-transfer are analysed separated and brought together in Figure 1.

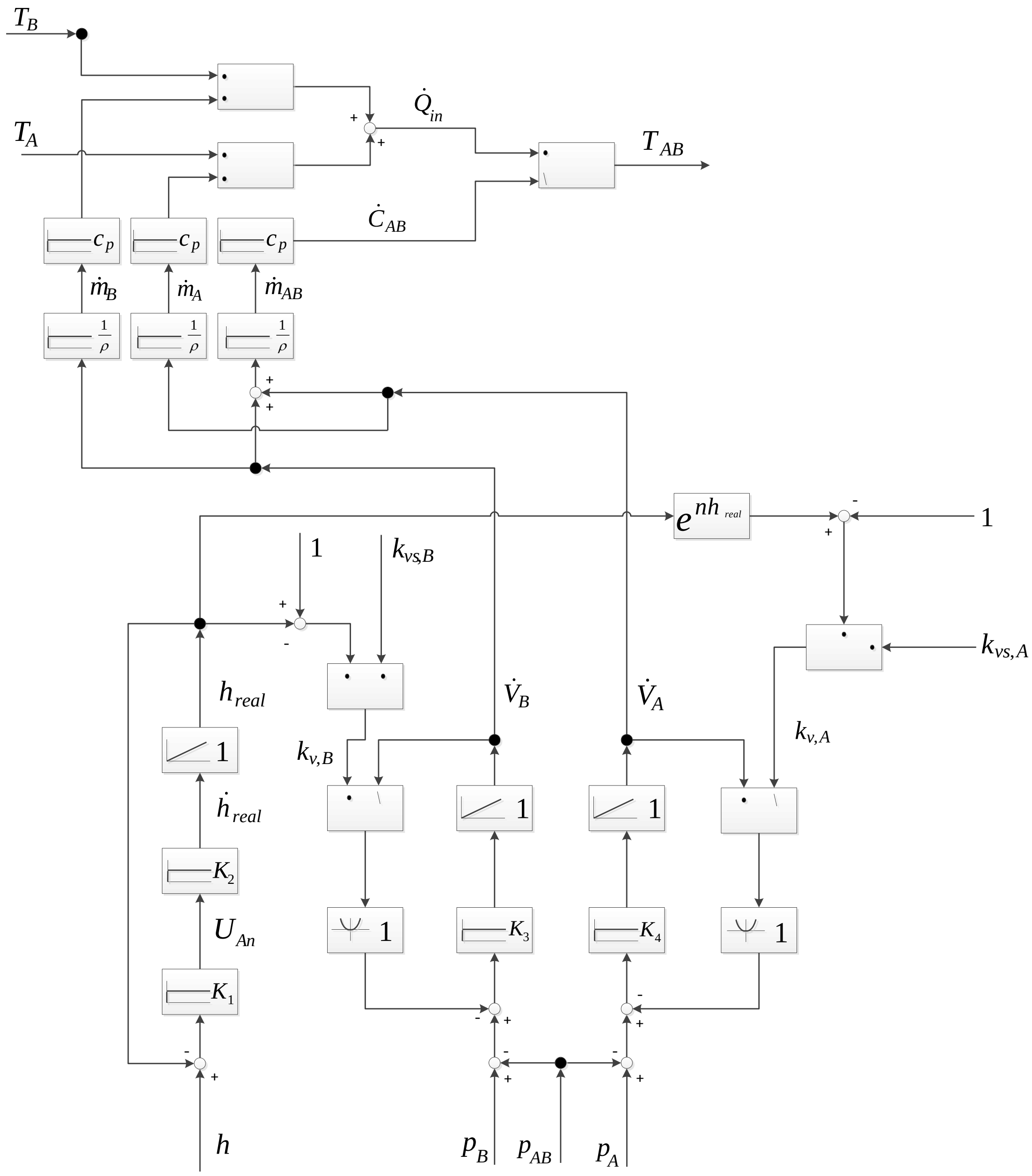

Figure 1: Functional diagram of the controlled system

The subsystem valve-actuator is described by equation (3). Input variable is the signal for valve opening h, output variable is the real valve opening h_{real}.

$$\frac{1}{K_1 K_2}\,\dot{h}_{real} + \dot{h}_{real} = h \tag{3}$$

By means of formulae for the flow coefficient, k_v, and the k_{vs} value [23] the subsystem valve-flow is described:

$$\ddot{V} + \frac{K_3}{k_v^2}\,\dot{V}^2 = K_3 \Delta p \tag{4}$$

Subsystem heat-transfer is determined by an energy balance, equation (5) describes energy conservation at the valve. Output variable is among others the control variable flow temperature T_{AB}.

$$\dot{m}_{AB}\, c_p\, T_{AB} = \dot{m}_A\, c_p\, T_A + \dot{m}_B\, c_p\, T_B \tag{5}$$

From the equations it is deduced, that the subsystems valve-actuator and valve-flow can be summarized as PT_1-elements, the subsystem heat-transfer as P-element. Combined to series connection, PT_2 transmission behaviour for the whole controlled process is concluded.

To verify theory and identify the controlled system mathematically various experiments were conducted. The adjustment range was defined by hysteresis and volume flow experiments. The dynamics of different-three-port valves were examined by experiments on valve velocity. To specify transmission behaviour step experiments on the controlled system were realized.

The optimal setting range $y_{100\%}$ has been determined experimentally. Therefore, upper and lower boundary values wherein the regulating variables operate have been set. By default, the boundaries for the valve opening were 0% and 100%, which was the expected adjustment range. The validation of these values took place via experiments on the dependency of the volume flow on the valve opening and hysteresis measurements. If response characteristics had been different from anticipated, the setting range has been adjusted. By this adjustment, setting points are reached faster because the controller doesn't work at setting range parts, wherein changes in the regulating variable have no effect on the controlled variable.

The open loop behavior was analyzed by step response tests. To ensure static conditions, as it is required that step response experiments take place from a point of rest, the valve opening, the volume flow and thus, also the flow temperature were held constant before the step occurs. From this resting position the valve opened and the reaction on the flow temperature was observed. The results served to describe the transmission behavior by a three-parameter model. If the observed process can be approximated by an FOPDT model, the three describing parameters are the static gain K, the time constant T and the dead time L [6].

$$G(s) = \frac{K}{1 + sT} e^{-sL} \tag{6}$$

Furthermore, the results have been used to fit a transfer function for a second order model.

$$G(s) = \frac{K}{(1 + sT_1)(1 + sT_2)} \tag{7}$$

Having these models fitted for each valve and with graphical analysis of the step responses' graphs, all prerequisites for the used control tuning methods are available.

3.2 – Control quality

The existing controller parameters as well as the parameters arising from the application of different tuning rules were tested in closed-loop operation. Hence the actual control quality could be evaluated by the introduced integral time criteria.

In order to ameliorate the existing controller performance, the parameters arising from the application of different tuning rules were tested on closed-loop system. All used parameters resulted from implementation of the tuning-methods and adjustment standards introduced in chapter 2.1 on the established transfer functions (chapter 3.1). By use of IAE-, ISE- and ITAE-criterion control quality could have been valued and compared with actual control quality. This experiment has been conducted for most method-system-combinations.

However, not all method-system-combinations could have been tested. Trying to apply, beside the proportional gain X_p and the reset time T_n, also a derivative time T_v, technical constraints have been found. Within the controller software the setting of a derivate time, which is more than three times smaller than the integral time, was not allowed. This constraint conflicts with the calculated parameters for a PID controller by Ziegler and Nichols and by lambda-tuning (see Appendix A).

4. Results

4.1 – Actual controller parameterization

Considering the control results of the step experiments with standard control parameters, we make the following observations.

At valves 1 and 2 the control variable approaches to the set point very slow without overshoot (aperiodic sequence). After reaching the reference variable the control process is influenced by the disturbance variable. The controller cannot reduce the periodical control deviation.

Valve 3 shows a quick response time followed by some over and undershoot. Also after settling the periodical influence of disturbance variable cannot be eliminated.

An aperiodic approaching of the set point can be observed at valve 4. The following control process is determined by oscillations of high amplitude.

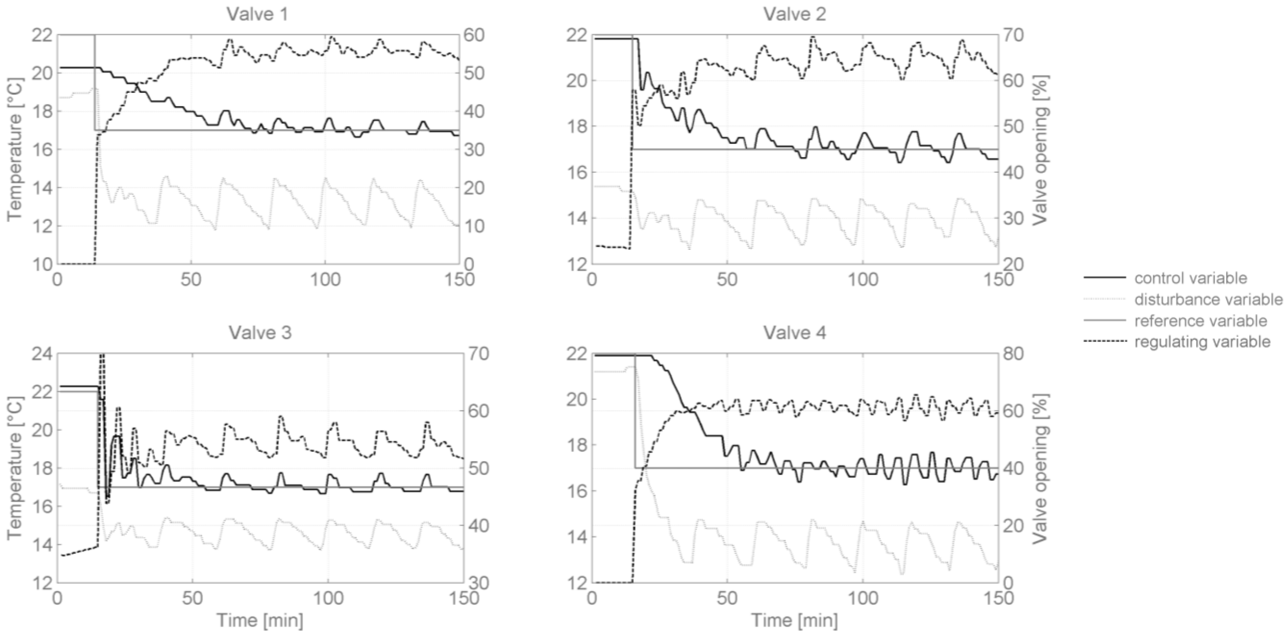

Figure 2: Step response with actual controller parameterization

In Figure 3 the typical trend of the main disturbance variable is shown. Considering wavelength and amplitude, its periodical behaviour is similar for the following experiment. Therefore, further presentation of the disturbance variable within the following figures has been omitted.

4.2 – Ziegler and Nichols

The following step responses are the result of application of the control parameters by Ziegler and Nichols.

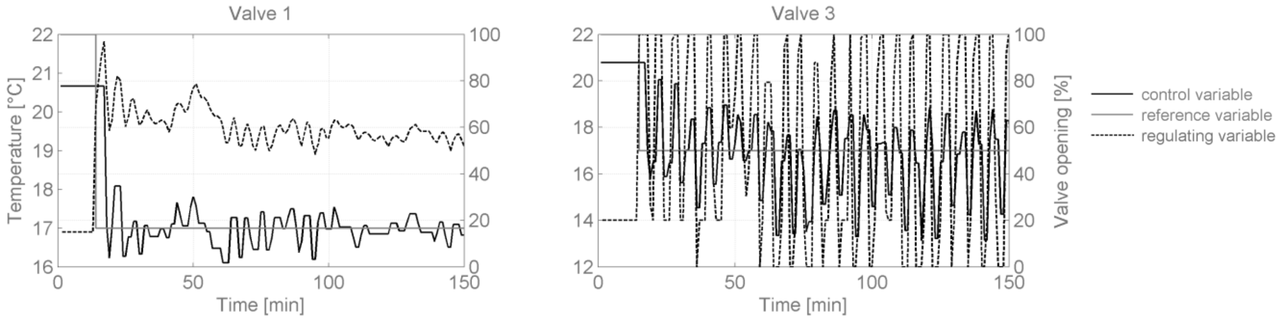

Figure 3: Step response with controller parameterization by Ziegler and Nichols

The control process around valve 1 is characterised by a quick response time and a remaining oscillation around working set point. Compared to the standard parameters both the proportional gain and the integral time have been reduced. Therefore, control is more dynamic and stability margin is smaller. IAE- and ISE-criterion can be ameliorated due to quick response and small amplitudes.

Valve 2 shows a slow approach to reference variable and a significant impact from disturbance variables. While IAE- and ISE-values are comparable with their values at standard parameters, ITAE-criterion deteriorates on account of persistently high system deviations.

At the valves 3 and 4, after the step signal, the system is still predominated by oscillation, due to external oscillation, see disturbance variable in Figure 2. This position at the margin of stability affects all integral criteria negatively.

4.3 – Lambda-tuning

We consider the control results of the step experiments parameters by lambda-tuning:

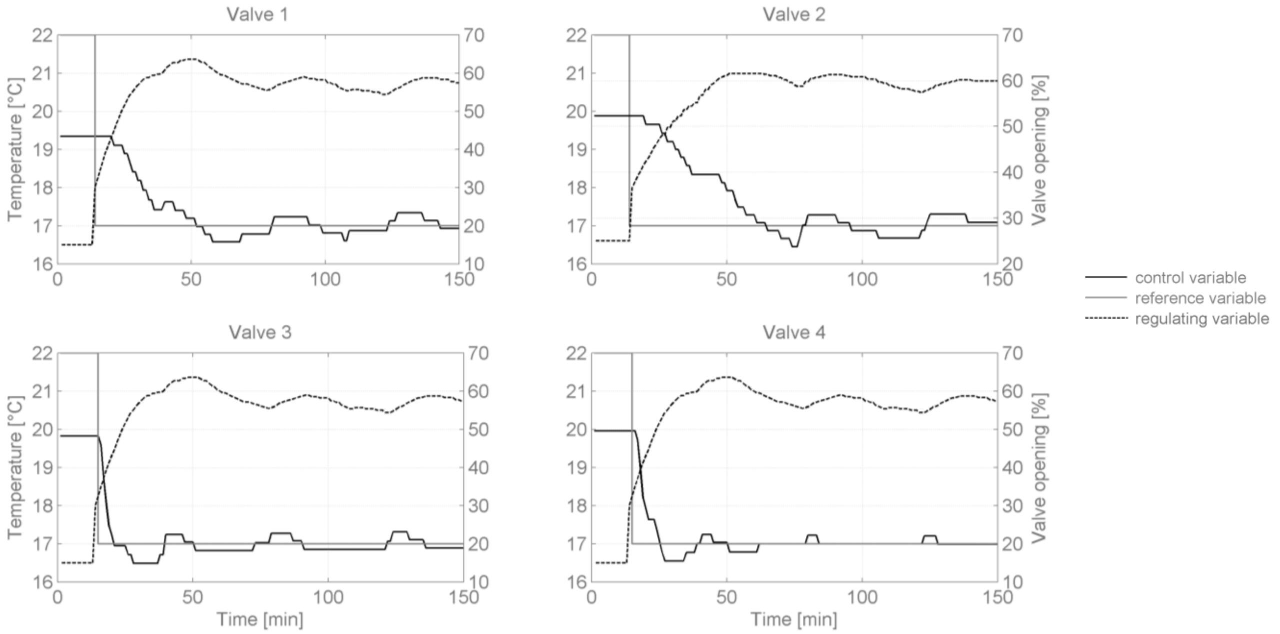

Figure 4: Step response with controller parameterization by means of lambda-tuning

The control variable at valves 1 and 2 needs a long rise time. The disturbance variable causes system deviations. These are small for valve 1 and bigger for valve 2, as a result integral criterion at valve 1 can meliorated, at valve 2 they are comparable with standard control quality.

We observe very dynamic control and high control accuracy for valve 3. Considering the control parameter control performance is much better than the expected controller operation near stability margin. All quality criterions change for the better.

Also at valve 4 we monitor only minimal control deviations after a short rise time. Control quality improves many times over standard quality.

4.4 – Absolute value optimum

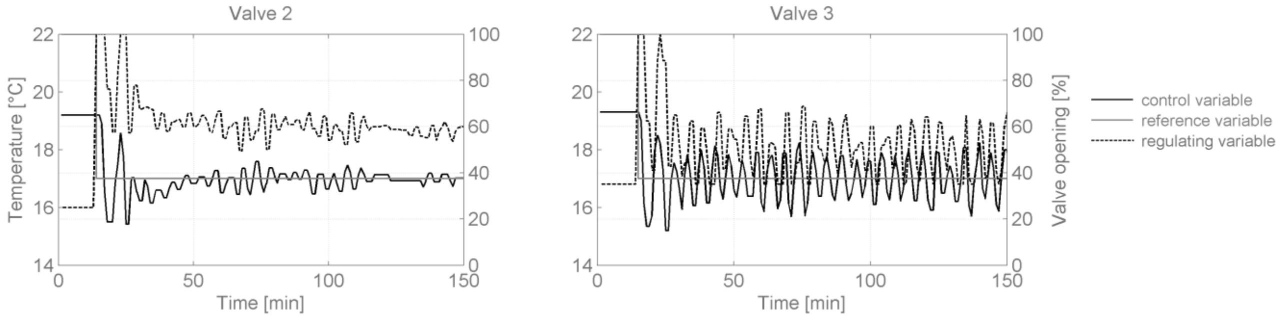

Figure 5: Step response with controller parameterization by absolute value optimum method

Since the proportional gain for every controller was largely decreased by absolute value optimum method, we expect oscillation behaviour for all valves. Observing the experimental results, very dynamic control and permanent oscillations show that our expectations have been met.

Due to a quick response time, compared with standard rise time, ISE- and IAE-criteria for valve 1 improve. The strong and lasting vibration causes a worse ITAE value.

As control deviation is small for valve 2 control quality increases within this system.

Moreover, we monitor high system deviations for the valves 3 and 4, which lead to a decreased control quality within these systems for the IAE- und ITAE-criteria.

4.5 – Symmetrical optimum

With the symmetrical optimum method we generate the same values for the proportional gain X_p and likewise values for the integral time T_n. Therefore, we observe very similar results to the absolute value optimum method.

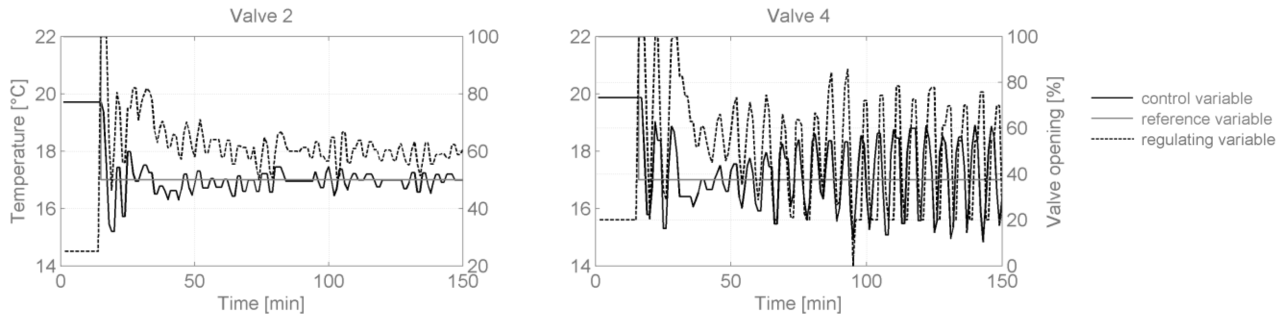

Figure 6: Step response with controller parameterization by symmetrical optimum method

At valve 1 we observe an oscillation of high frequency and constant amplitudes. Because of a quick rise the ISE-criterion can be meliorated, the other criteria worsen.

Since X_p and T_n are higher than for the other valves, the control deviation for valve 2 can be reduced. Compared with the slow and disturbance-influenced standard control quality, all performance indicators amend.

Due to predominant oscillation of the controlled variable in zone 3 and 4, IAE and ITAE values increase, videlicet changes for the worse. The observed amplitudes are 34% of step size at zone 3 and 43% at zone 4. Only ISE-criterion improves, because of the accelerated control.

4.6 – Experimental tuning

The following step responses are the result of application of the control on basis of experimental results.

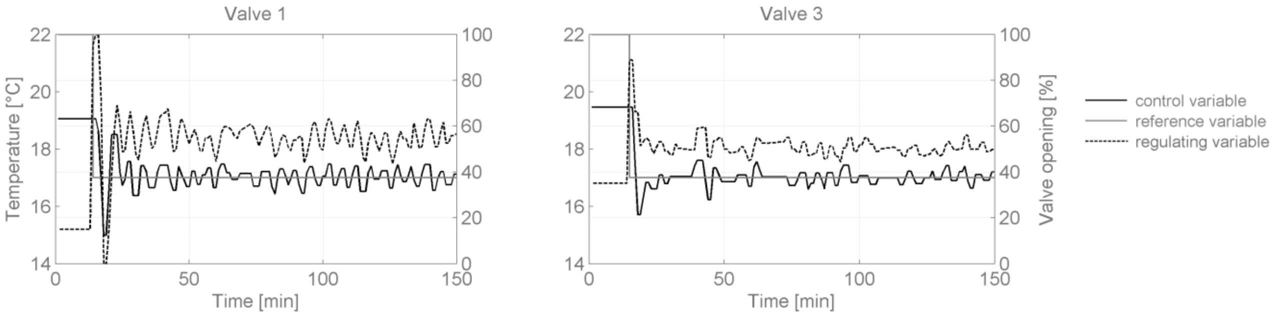

Figure 7: Step response with controller parameterization on basis of experimental results

As expected with low controller parameters, we observe a quick response with one over- and one undershoot for valve 1. A permanent oscillation with small amplitude trails. Although there is no closed-loop stability, caused by dynamic control and small deviations we register a significantly meliorated control quality.

Also for valve 2 and 3 quick adjustments minimize the three integral criteria. In system 3 we monitor an intermittent occurrence of no or very less control error.

Larger oscillation amplitudes are found at valve 4. A possible explanation could be, that due to the higher T_n in system 4, control deviation can't be controlled quick enough. Nevertheless IAE, ISE and ITAE values decrease compared with the standards.

4.7 – Cognitive tuning

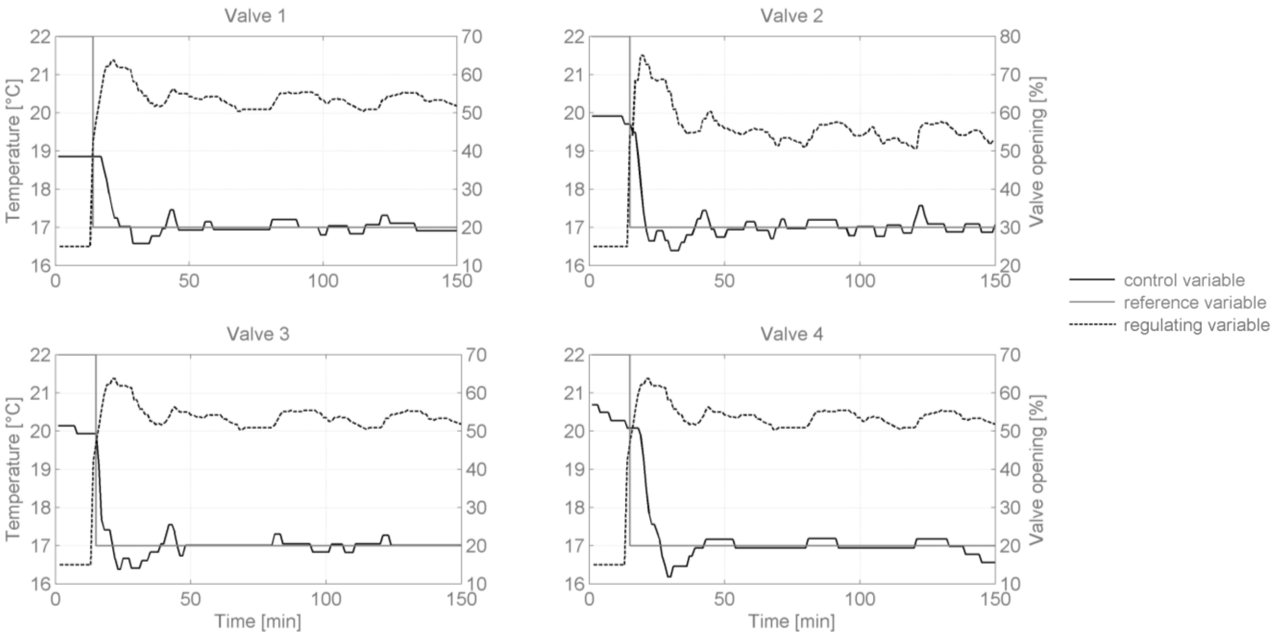

Figure 8: Step response with cognitive controller parameterization

The control results of parameters by cognitive tuning show a coexistence of robustness and dynamic behaviour. For each of the four considered valves, we achieve a small rise time and small control deviations. At valves 1, 2 and 4 there is very little influence of the main disturbance variable, at valve 3 there is nearly no. Control quality is optimised by minimizing of its integral criteria IAE, ISE and ITAE.

5. Discussion

We assess the applied tuning rules and adjustment standards on basis of a direct comparison of the control quality. For this purpose we contrast the specific values for the integral criteria IAE, ISE and ITAE. The actual control quality serves as the reference for evaluation and is set to the value 1 in Figure 9. The other control quality results are pictured normalized to this reference.

We succeed in improving control quality for valve 1. We achieve minimized results in all integral criteria for controller parameterization by lambda-tuning, tuning on base of experimental results and cognitive tuning. For lambda tuning the controller dynamics is slow and influences of the disturbance variable is impeded. Within experimental tuning the controller responds fast, however the system oscillates. The cognitive parameterized control circuit shows the desired compromise between dynamics and impeding of disturbances. We get a maximum improvement by 71% for IAE value, 88% for ISE value and 59% for ITAE value.

We show that control quality for valve 2 is increased by several alternative settings. Good control results can be achieved with the absolute value optimum method, the symmetrical optimum method and tuning on base of experimental results. However, the control loops with these parameters have a disposition to oscillate with low amplitudes. Further away from stability margin, but influenced more by disturbances are the control results within application of cognitive tuning. We minimize IAE criterion by 67%, ISE criterion by 85% and ITAE criterion by 61%.

We achieve improved controller settings for valve 3 with lambda-tuning, tuning on base of experimental results and cognitive tuning. For the first- and last-mentioned we monitor a fast rise time and little influences of the disturbance variable, whereas experimental tuning induces fast control dynamics with little oscillating amplitudes. In terms of the criteria values the best control quality results from cognitive tuning. We improve control quality, measured by integral criteria, by 67%, 84% and 75 %.

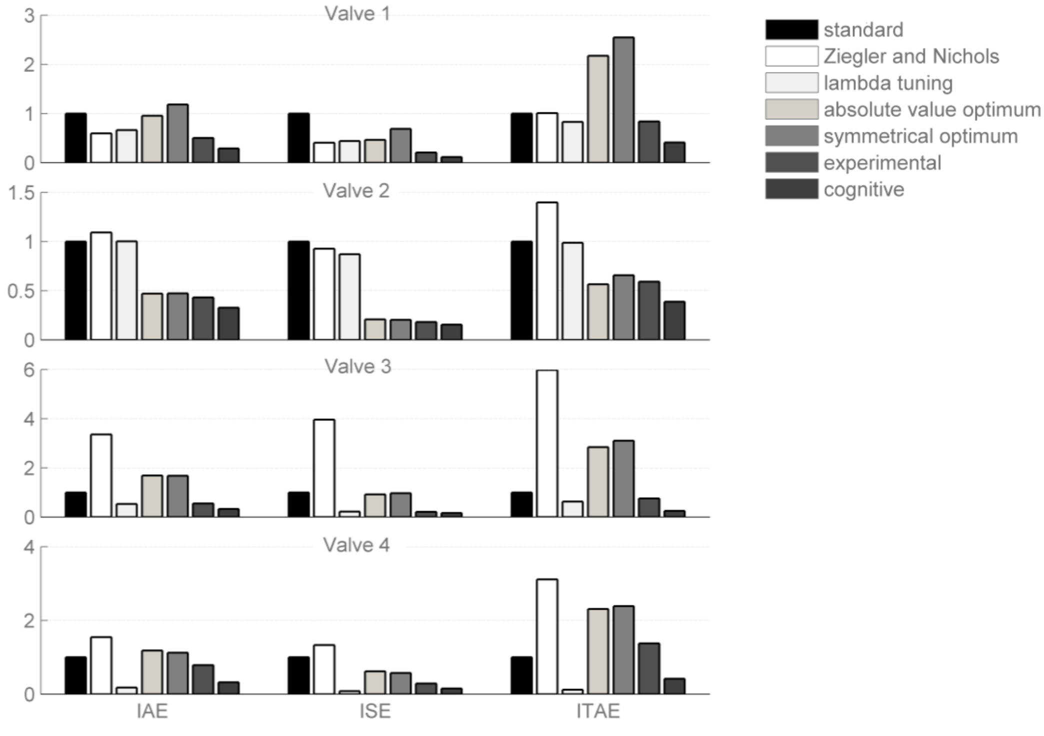

Figure 9: Comparison of control quality within application of different tuning rules

For valve 4 we increase control quality in all criteria with lambda-tuning and cognitive tuning. The monitored control results show quick rise times and a good performance in reducing disturbances and deviation errors. We achieve the best control results by means of lambda-tuning. The IAE criterion is ameliorated by 82%, the ISE criterion by 92% and the ITAE criterion by 88%.

Considering the cumulated control quality separated by the three integral criteria, we provide a ranking of the applied tuning methods. By means of the overall IAE and ISE values lambda-tuning, optimization on different control quality indicators and cognitive optimization are the best tuning methods, in increasing order. For the entire ITAE criterion lambda-tuning shows better results than optimization on different control quality indicators, but as well cognitive optimization turns out as the best tuning method.

6. Conclusion

We have tuned three-port mixing valves in a state-of-the-art building energy system having a state-of-the-art building automation system with adaptive PID control loop tuning. Initially, we found that control quality was in a not acceptable status. We conducted open loop system identification experiments and tuned the controllers according to different classical methods. Finally, we compared and discussed the results.

We find that classical tuning can ameliorate the control quality for three-port mixing valve controllers. Further, we show that cognitive tuning, meaning tuning based on our experience, still reaches the best control qualities. Lambda tuning and experimental tuning follow. We assume even better results, if the data logging resolution, which is not capable of logging more than one value per second, would not have limited the system identification accuracy.

Going on, we want to compare classical and innovative, e.g. adaptive tuning, methods applied to different typical control loops in building energy systems. Therefore, we will implement automated offline and online system identification. Finally, we want to develop a methodology how to monitor a building energy system and tune its control loops. The development of this methodology will take place under real operation conditions with special focus of applicability and nowadays building automation systems.

Nomenclature

$\dot{C}$	capacity flow, W/K
c_p	specific heat, J/(kg K)
h	signal for valve opening, %
h_{real}	real valve opening, %
K	static gain
	absolute term
k_v	flow coefficient, m^3/h
k_{vs}	designed k_v value at the rated travel, m^3/h
L	dead time, s
$\dot{m}$	mass flow, kg/s
p	pressure, bar
$\dot{Q}$	heat flow, W
s	Laplace’s complex variable
T	temperature, °C
	time constant, s
T_g	equalization time, s
T_n	reset time, s
U_{an}	driving voltage, V
V	volume flow, m^3/h
X_p	proportional gain
$y_{100\%}$	effective setting range
y_{exp}	setting range within an experiment

Greek symbols

Δ difference

λ tuning parameter lambda

ρ density, kg/m^3

Subscripts

A valve port A

B valve port B

AB valve port AB

min minimum

max maximum

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Appendix A

Table A.1. Controller parameters by different tuning methods

Valve	Parameter	Standard settings	Ziegler & Nichols (PI)	Ziegler & Nichols (PID)	Lambda-Tuning (PI)	Lambda-Tuning (PID)	Absolute value optimum	Symmetrical optimum	Experimental Tuning	Cognitive Tuning
Valve 1 (DN 65 k_{vs} 40)	X_p	16,00	8,46	6,35	28,07	25,13	3,29	3,29	6,00	16,00
	T_n [s]	729,00	215,78	129,60	194,40	151,80	652,88	416,23	123,25	124,00
	T_v [s]			32,40		23,61				
Valve 2 (DN 65 k_{vs} 40)	X_p	16,00	15,84	11,88	34,03	21,37	4,81	4,81	7,00	16,00
	T_n [s]	729,00	351,65	211,20	316,80	178,80	553,51	569,26	91,50	92,00
	T_v [s]			52,80		30,67				
Valve 3 (DN 65 k_{vs} 25)	X_p	16,00	2,57	1,93	12,14	12,87	4,62	4,62	7,00	12,00
	T_n [s]	729,00	141,86	85,20	127,80	133,20	90,60	170,40	117,78	120,00
	T_v [s]			21,30		17,25				
Valve 4 (DN 50 k_{vs} 16)	X_p	16,00	2,18	1,94	11,74	13,03	3,93	3,93	9,00	20,00
	T_n [s]	729,00	151,85	91,20	136,80	159,00	113,40	182,40	181,44	120,00
	T_v [s]			22,80		18,98				

Table A.1. Controller parameters by different tuning methods

Valve	Criterion	Standard Parameters	Ziegler and Nichols	Lambda-Tuning	Absolute value optimum	Symmetrical optimum	Experimental Tuning	Cognitive Tuning
Valve1 (DN 65 k_{vs} 40)	IAE	107,30	63,62	71,23	102,53	126,75	53,73	30,75
	ISE	194,79	78,49	85,54	90,63	134,19	39,83	22,50
	ITAE	3676,50	3696,34	3045,12	7981,90	9368,10	3083,09	1503,59
Valve 2 (DN 65 k_{vs} 40)	IAE	105,81	115,32	106,04	49,77	50,08	45,70	34,54
	ISE	197,78	182,93	172,05	40,85	39,98	35,97	30,57
	ITAE	4337,94	6055,94	4278,60	2448,29	2851,80	2562,86	1675,63
Valve 3 (DN 65 k_{vs} 25)	IAE	68,76	230,36	36,25	116,10	115,40	37,82	22,61
	ISE	119,24	471,43	25,76	109,94	115,76	25,15	19,10
	ITAE	3193,21	19083,43	1996,33	9081,60	9898,40	2388,58	801,51
Valve 4 (DN 50 k_{vs} 16)	IAE	157,40	350,05	27,95	186,43	176,56	124,09	50,31
	ISE	430,39	1086,53	35,76	265,83	247,32	123,67	64,92
	ITAE	6492,86	26512,27	780,79	14990,90	15484,99	8944,24	2713,08