“Tennessee-Eastman-Process”
Alarm Management Dataset
-
Technical Report

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Abstract

This is a supplementary technical report for the *"Tennessee-Eastman-Process"* (TEP) alarm management dataset. The report starts with a brief overview of the facility, implemented control loops, and used simulation model. Two types of data, namely process and alarm data, were collected from the facility, their underlying data structure is included. The process of developing and implementing suitable alarm thresholds and alarm management techniques is described in detail. Furthermore, all induced abnormal situations and the respective scenario design is presented thoroughly. The report concludes with a detailed description of the dataset structure and layout.

The presented dataset aims to provide a suitable benchmark for the development and validation of alarm management methods in complex industrial processes using both quantitative data and qualitative information from different sources. Unlike real industrial processes, simulation of the TEP allows to design and generate abnormal sequences, which can be repeated and varied without risking the loss of equipment or harming the environment. In addition, as the simulation is supervised, all induced faults and process normalizations are explicitly known and therefore act as a ground truth, facilitating the utilization of external evaluation metrics, e.g., when using cluster analysis.

Changelog

Below is a list of changes to the dataset:

- **v1.2:** Added a set of six ground-truth partitions for the purpose of alarm flood similarity analysis and alarm flood clustering. The ground-truths can be found in Appendix E.
- **v1.1**: Added three tests with steady-state data, i.e., data using the adjusted normal operating mode of the "Tennessee-Eastman-Process" without any external intervention in the process. Each test includes 75 hours of process simulation. During normal operation no alarms are activated, thus the novel three tests only include data of the process variables and manipulated variables.
- **v1.0**: Initial version.

Table of Contents

Index of Figures

Index of Tables

Preliminary Remarks

With the aim of facilitating a better understanding of the herein used terms, the following definitions are given: An ***abnormal situation*** is characterized by *"a disturbance or series of disturbances in a process* […] [EEMUA 191, 2013#]*"*, with a ***disturbance*** being an unwanted deviation of at least one characteristic property, physical quantity or parameter of a system from its desired, normal or defined state [RAM88]. In addition, an abnormal situation is defined by the control system being unable to cope with these deviations, so that an operator intervention is required [ASM, 2009#]. Rather than showing only a small number of disturbances, a typical phenomenon is the plantwide propagation of locally restricted abnormal situations due to causal dependencies throughout the process [WYC+15]. These dependencies require the existence of a connection, i.e., material, energy or information connection [YDS+14]. Disturbances of a certain process variable can now propagate along these connections and thus trigger further deviations in other components. Abnormal situations are therefore not necessarily limited to their place of origin [BCC+07B] [TBB+09] [YDS+14] [CHR15] [WYC+15] [ARR17]. If the resulting deviations of the respective underlying process variables are causing a violation of their defined alarm thresholds, a large number of consecutive alarms can be activated, which are symptoms of a common ***root cause disturbance*** [ROT09] [ISS+09A] [ARR17]. The latter is defined as the underlying cause in a complex cause-and-effect relation from which all effects of the corresponding abnormal situation, i.e., other disturbances, directly or indirectly result. The cause of this root cause disturbance lies beyond the observed system. According to [ASM, 2009#], desired operation goals during an abnormal situation are associated with the gravity of the deviation from a defined target operating region. It can be necessary to bring the process back to a safe state, establish control of the process and/or to return the process to a normal operating state [ASM, 2009#]. Effectual and timely measures against the root cause of an abnormal situation are the key to reach those goals [ROHE04] [WYC+15] [YAGU17] [HCS+17].

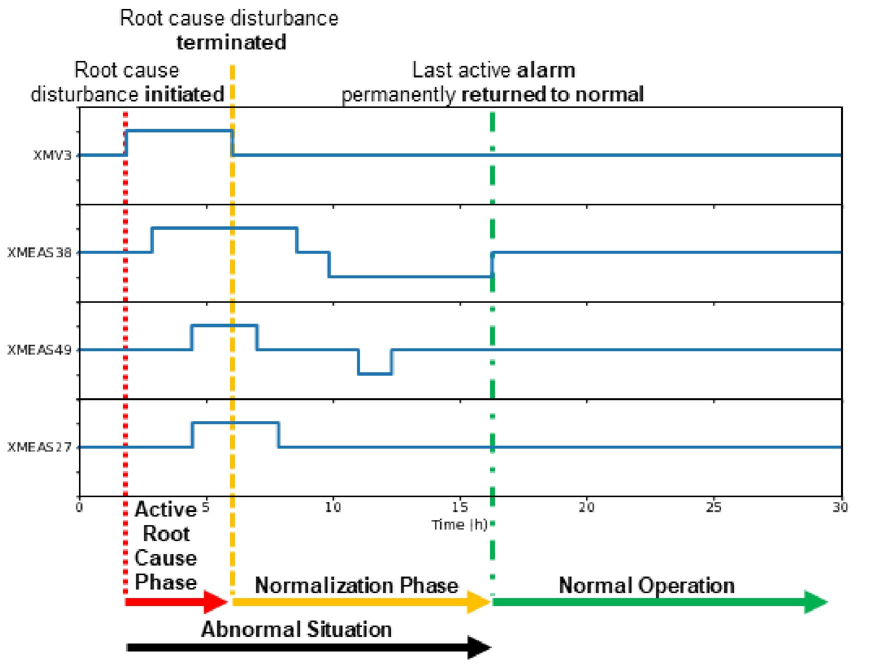

Figure 0.1: Exemplary scenario with an abnormal situation that triggers alarms in four different process variables and additional annotations regarding the structure of an abnormal situation

Based on the alarm timeline described in [ANSI/ISA 18.2, 2016#], this report uses a definition in which an abnormal situation is divided into the following two phases:

1. An ***active root cause*** (ARC) phase.
2. A ***normalization*** phase.

Figure 0.1 shows an exemplary scenario with an abnormal situation that triggers alarms in four different process variables. Total duration of this abnormal situation is represented using a black arrow, whereas the corresponding ARC phase is marked with a red arrow. The latter begins with the ***root cause disturbance*** being ***initiated*** (red-dotted line), in terms of initially affecting the process and starting propagation along causal dependencies. Eventually, the ARC phase ends with the ***termination*** of this root cause, which can be, among other factors, due to random influences or the operator taking effectual and timely action against it (yellow-dashed line). As indicated by the successive yellow arrow, the ***normalization*** phase directly follows the ARC phase. However, this behavior is not a matter of course, as abnormal situations can escalate, eventually resulting in an ***emergency shutdown*** (ESD) or major incident [ASM, 2009#] [ANSI/ISA 18.2, 2016#]. In case of a successful termination of the root cause, normalization of a single process variable is characterized by a two-stage process response [ANSI/ISA 18.2, 2016#], which also applies to the process in its entirety:

1. A process deadtime.
2. A process response delay.

The first one describes a phenomenon in which, despite an effectual and timely operator intervention, the process continues to deviate further from its desired state. The second one describes a time delay during which the process is responding to the operator intervention and process variables are approaching their desired state [ANSI/ISA 18.2, 2016#]. Observations of the TEP and other processes have shown that a plantwide normalization has to propagate throughout the process in a similar way as the initial disturbance propagation. Furthermore, the response of the implemented control system can cause different process variables to show oscillating behavior, thus resulting in recurrent or newly activated alarms during the normalization phase. Due to complex interconnections and causal dependencies, it is possible for a normalization phase to take longer and arise more alarms than the actual ARC phase, which can confuse the operator albeit his reasonable primary intervention and lead to misguided follow-up actions. The difference between the two phases lies within the fact, that the process is able to cope with the remaining deviations within the normalization phase, so that an additional operator intervention is not required. Eventually, a normalization phase results in all meanwhile activated alarms permanently switching back to an inactive alarm state, for as long as no new abnormal situation arises. Figure 0.1 depicts this successive ***normal operation*** with a green-dashed-dotted line and green arrow.

1 Overview

1.1 Tennessee-Eastman-Process

Since initial publication of the *"Tennessee-Eastman-Process"* (TEP) by Downs and Vogel in 1993, as *"a plant-wide industrial control problem* [DoVo93]", it has become accepted as a benchmark case study in process automation of chemical plants [BRJ15] [Arr17]. The TEP is based on an actual plant and therein-running processes of the *"Eastman Chemical Company"* (Tennessee, United States of America) [DoVo93]. Its persistent academic relevance is emphasized by means of different publications in the field of fault detection and identification [YDS+14] [Arr17], alarm management [TBB+09] [YaGu17] [Arr17] [HSC18] or parametrization of control loops and structures [McYe94] [Luy96] [Ric96].

Figure 1.1 shows the piping and instrumentation diagram (P&ID) of the TEP according to [DoVo93], [BRJ15] and [Arr17]. Considering the plant and process hierarchy described in [ANSI/ISA 88, 1995#] and [ANSI/ISA 95, 2010#], which was initially developed for batch processes but according to [SUT+18] can also be applied to continuous processes, the TEP can be separated into five main equipment modules [DoVo93] [Arr17]:

- One two-phase chemical reactor (***R003***)
- One condenser (***C115***)
- One vapor-liquid-separator (***S102***)
- One stripper (***E005***)

- One reboiler (***G111***)

Furthermore, the following control and equipment modules, placed along material connections (pipes) between the aforementioned components, are part of the TEP [DoVo93] [Arr17]:

- 11 (pneumatic) valves (***V160-V170***)
- Two pumps (***P101*** and ***P102***)
- One compressor (***K100***)

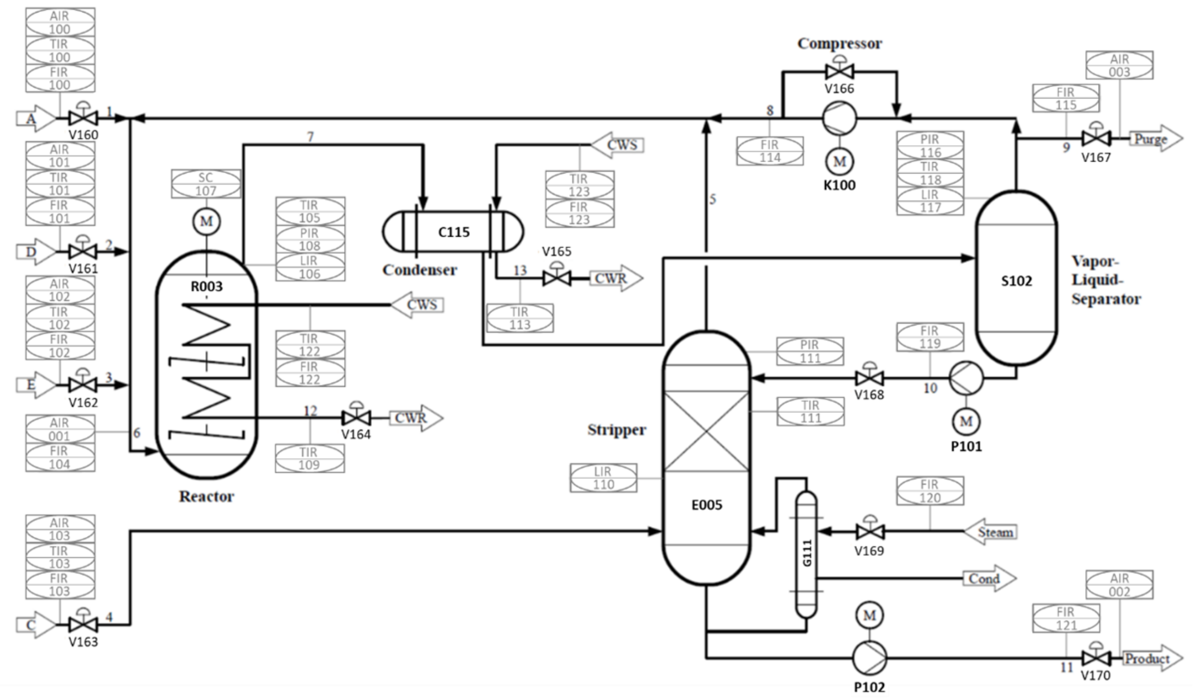

Figure 1.1: P&ID of the TEP ([DoVo93], [BRJ15] and [Arr17])

The P&ID in Figure 1.1 displays the extended process by [BRJ15] and adapted tags by [Arr17]. A total of 73 process variables (PV) of types flow (F), pressure (P), temperature (T), level (L) and chemical component concentration (A) as well as 12 manipulated variables (MV) are observed and measured [BRJ15] (a detailed table of all PVs and MVs can be found in Section 2).
Eight different chemical components (A-H) are part of the TEP. Gaseous reactants ***A***, ***C***, ***D*** and ***E*** are fed to the reactor via correspondent inlets (***V160-V163***), which also contain a small amount of inert gas ***B***. Liquid products ***G*** and ***H*** exit the stripper base and are transferred to subsequent units and process cells via outlet valve ***V170***. Liquid by-product ***F*** is purged from the TEP using outlet valve ***V167***. Furthermore, four auxiliary streams follow the purpose of transporting thermal energy into and out of the TEP (Steam and chilled water). A detailed description of process operations and steps can be found in [DoVo93].

1.2 Control Structure

According to simulation results presented in [MUS18] the TEP is highly instable and tends to exceed or go below set emergency shutdown thresholds after a runtime of approximately one hour. Hence, a suitable control structure has to be implemented. [Ric96] describes a control structure, which consists of 17 control loops and two additional override loops. This control structure is used for the TEP simulation model of this dataset Three unique features of [Ric96] are:

1. The reactor pressure is controlled by using the relatively low purge flow.
2. The production rate controller sets ratio controller set points on all feeds, purge and liquid flows.
3. The reactor level is controlled by setting the separator temperature controller, which controls the cooling water supply to the condenser [Luy96].

Figure 1.2 gives an overview of the implemented control loops described in [RIC96]. The following controller types are used:

- ***LC:*** Liquid level control
- ***PC:*** Pressure control
- ***TC:*** Temperature control
- ***FC:*** Flow control
- ***CC:*** Component concentration control
- ***RC:*** Ratio control

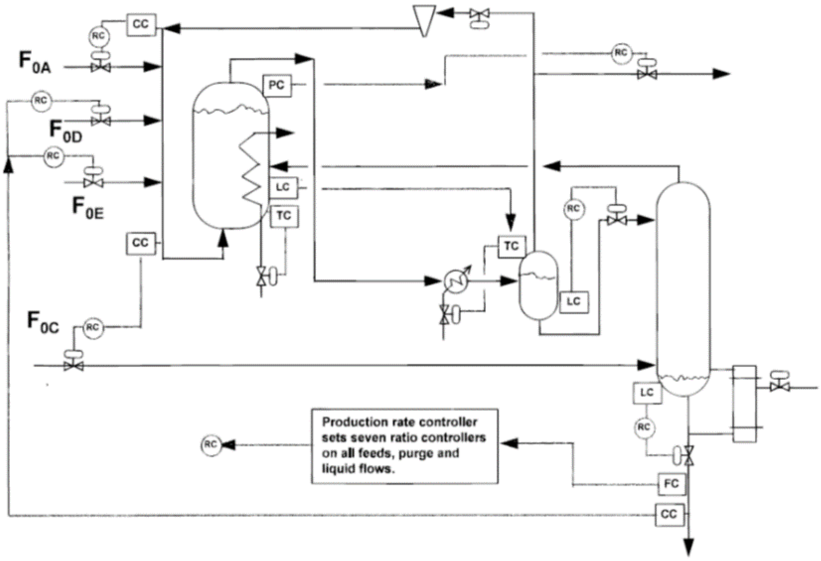

Figure 1.2: Control structure of the TEP as described in [RIC96] ([LUY96])

1.3 Simulation Model and Operating Mode

Based on the original TEP FORTRAN simulation model [BRJ15] presented a revised MATLAB-Simulink model, which can be accessed and downloaded online via the "*Tennessee Eastman Challenge archive*"*:*

http://depts.washington.edu/control/LARRY/TE/download.html
Version: 23. January 2015 (MultiLoop_mode1.mdl Version 1.3.3)

This TEP simulation model was used for this dataset, in order to generate artificial alarm and process data in several tests and with specific abnormal situations.

Table 1.1: Parameter setting for the model structure flag [BRJ15]

Bit	Description	Value
0	Additional measurement points	1
1	Monitoring outputs of the values subjected to random variations	0
2	Monitoring outputs of the reaction and process	0
3	Monitoring outputs of the component's concentration	0
4	Deactivation of measurement noise switch	0
5	Random generator uses different state variables for the process disturbances and measurement noise	1
6	Solver-independent calculation of the process disturbances	1
7	Disturbances are scaled by the value of the activation flags	1
15	Reset of the model to the original structure, including the adaption of the program flow of the model to the program flow of the simulation	0

Besides additional process measurements and disturbances the revised model allows for the random number generator to use "[…] *different state variables for the process disturbances and measurement noise* [BRJ15]". The initial generator seed is part of the scenario documentation. Table

1.1 shows the configured parameter setting for the model structure flag, which is used to define relevant parts of the simulation's output and calculation [BRJ15].
As described in [DoVo93] the TEP can be operated using different operating modes. Figure 1.3 shows the adjusted normal operating mode of the TEP simulation model, which uses the control structure from [Ric96] and additional process measurements from [BRJ15]. The red-labelled steady-state values were derived by analyzing the average of all 85 variables over a 150-hour simulation without process disturbances or measurement noise. It can be seen that neither the compressor recycle nor the stripper steam supply are used in this model, as both corresponding valves are permanently closed. In addition, the agitator inside the reactor is constantly set at a relative speed of 100%. A detailed overview of all measured and manipulated variables can be found in the following section.

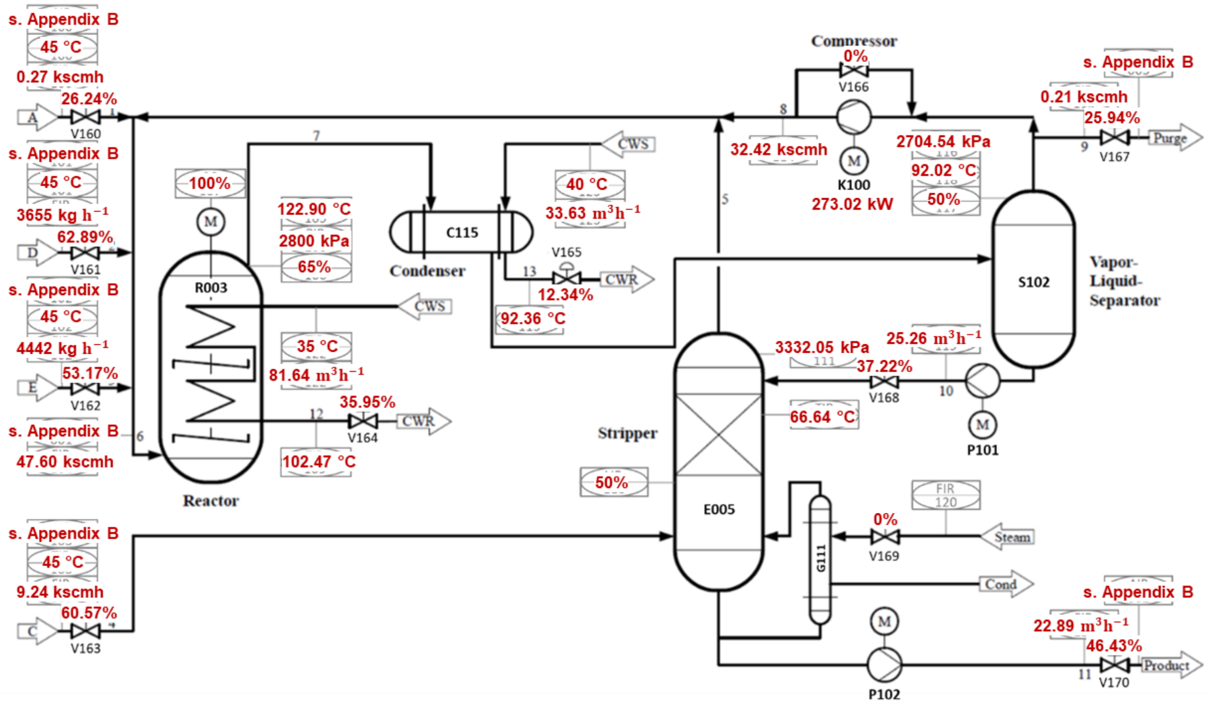

Figure 1.3: Adjusted normal operating mode of the TEP [Ric96] [BRJ15]

2 Measurement Availability

2.1 Measurement Specifications

Table 2.1 shows the availability of data sources for each of the conducted tests of this dataset. The sampling rate for all measured variables was set to 0.1Hz (approx. 0.0028h or 10s) and corresponding time stamps, measured in hours, were saved in a distinct file. Instead of discrete event logs, alarm data is made available as a continuous quantitative data stream with values for HIHI- (2), HI- (1), LO- (-1) and LOLO-Alarms (-2) as well as the inactive alarm status (0).

Table 2.1: Data availability

Measured Variable	Sampling Rate	Availability	File Name
Process Variables (XMEAS)	0.1 Hz	Continuous	SIMOUT.xlsx
Manipulated Variables (XMV)	0.1 Hz	Continuous	XMV.xlsx
Time	0.1 Hz	Continuous	TOUT.xlsx
Alarm Variables	0.1 Hz	Continuous	ALARMS.xlsx

2.2 Process Variables

The available PVs are listed in Table 2.2 with their corresponding sensor type as well as tag, description and unit.

Table 2.2: Process variables

XMEAS-Nr.	Type	Tag [ARR17]	Description	Unit
1	FIR	100	Flow Feed A	kscmh
2	FIR	101	Flow Feed D	kg h^{-1}
3	FIR	102	Flow Feed E	kg h^{-1}
4	FIR	103	Flow Feed C	kscmh
5	FIR	114	Flow Compressor Re-Cycle	kscmh
6	FIR	104	Flow Reactor Feed	kscmh
7	PIR	108	Pressure Reactor	kPa gauge
8	LIR	106	Level Reactor	%
9	TIR	105	Temperature Reactor	°C
10	FIR	115	Flow Purge	kscmh
11	TIR	118	Temperature Separator	°C
12	LIR	117	Level Separator	%
13	PIR	116	Pressure Separator	kPa gauge
14	FIR	119	Underflow Separator	m^3 h^{-1}
15	LIR	110	Level Stripper	%
16	PIR	111	Pressure Stripper	kPa gauge
17	FIR	121	Underflow Stripper	m^3 h^{-1}
18	TIR	111	Temperature Stripper	°C
19	FIR	120	Flow Stripper Steam	kg h^{-1}
20	K	100	Compressor Work	kW
21	TIR	109	Temperature Cooling Water Outlet Reactor	°C
22	TIR	113	Temperature Cooling Water Outlet Condenser	°C
23-28	AIR	001	Concentration Reactor Feed (Materials A to F)	mol%
29-36	AIR	003	Concentration Purge (Materials A to H)	mol%
37-41	AIR	002	Concentration Underflow Stripper (Materials D to H)	mol%
42	TIR	100	Temperature Feed A	°C
43	TIR	101	Temperature Feed D	°C
44	TIR	102	Temperature Feed E	°C
45	TIR	103	Temperature Feed C	°C
46	TIR	122	Temperature Cooling Water Inlet Reactor	°C
47	FIR	122	Flow Cooling Water Inlet Reactor	m^3 h^{-1}
48	TIR	123	Temperature Cooling Water Inlet Condenser	°C
49	FIR	123	Flow Cooling Water Inlet Condenser	m^3 h^{-1}
50-55	AIR	100	Concentration Feed A (Materials A to F)	mol%
56-61	AIR	101	Concentration Feed D (Materials A to F)	mol%
62-67	AIR	102	Concentration Feed E (Materials A to F)	mol%
68-73	AIR	103	Concentration Feed C (Materials A to F)	mol%

Measurement of chemical component concentration includes the following sampling frequencies and dead times:

- ***XMEAS 23-36***: 0.1h sampling frequency and 0.1h dead time
- ***XMEAS 37-41***: 0.25h sampling frequency and 0.25h dead time
- ***XMEAS 50-73***: 0.1h sampling frequency and 0.1h dead time

"The analyzer sampling frequency is how often the analyzer takes a sample of the stream. The dead time is the time between when a sample is taken and when the analysis is complete. For an analyzer with a sampling frequency of 0.1 h and a dead time of 0.1 h, a new measurement is available every 0.1 h and the measurement is 0.1 h old [DoVo93]."

2.3 Manipulated Variables

The available MVs are listed in Table 2.3 with their corresponding sensor type as well as tag, description and unit. ***XMVs 5, 9*** and ***12*** are kept constant using the control strategy described in [Ric96].

Table 2.3: Manipulated variables

XMV-Nr.	Type	Tag [ARR17]	Description	Unit
1	V	161	Valve Position Feed D	%
2	V	162	Valve Position Feed E	%
3	V	160	Valve Position Feed A	%
4	V	163	Valve Position Feed C	%
5	V	166	Valve Position Compressor Re-Cycle	%
6	V	167	Valve Position Purge	%
7	V	168	Valve Position Underflow Separator	%
8	V	170	Valve Position Underflow Stripper	%
9	V	169	Valve Position Stripper Steam	%
10	V	164	Valve Position Cooling Water Outlet Reactor	%
11	V	165	Valve Position Cooling Water Outlet Condenser	%
12	SC	107	Agitator Setting Reactor	%

2.4 Process Connectivity Information

Material and energy connections can be retrieved from the P&ID [DoVo93] [BRJ15] [ARR17]. Information connections are described in the control structure of the TEP [RIC96] [LUY96].

2.5 Alarm Thresholds and Data

The following formula describes calculation of the alarm variable $x_a(t)$ of a process variable x (following [LCG+19]):

$$x_a(t) = \begin{cases} 2, & if\ x(t) \geq x_{tp_{HIHI}} \\ 1, & if\ x(t) \geq x_{tp_{HI}}\ and\ x(t) < x_{tp_{HIHI}} \\ -1, & if\ x(t) \leq x_{tp_{LO}}\ and\ x(t) > x_{tp_{LOLO}} \\ -2, & if\ x(t) \leq x_{tp_{LOLO}} \\ 0, & else \end{cases} \tag{2.1}$$

With $x(t)$ describing the value of a process variable x at the time t and $x_{tp_{HIHI}}, x_{tp_{HI}}, x_{tp_{LO}}$ as well as $x_{tp_{LOLO}}$ representing corresponding alarm activation thresholds. It allows an unambiguous definition of the effective alarm state, so that only one of the aforementioned conditions can be active at any given time.

Parametrization and implementation of suitable alarm thresholds and alarm management techniques for all relevant PVs and MVs will be discussed in the following section.

3 Alarm Management

3.1 Alarm Design – [MALI17] [KIR19]

Despite the fact that TEP simulations have been subject of different alarm management studies, e.g. [TBB+09], [YAGU17], [ARR17], [HSC18] and [XWY20] the systematic parametrization and implementation of suitable alarm thresholds and alarm management techniques have been mostly disregarded to date.

Table 3.1: Process operating constraints [DoVo93]

Process Variable	Normal Operating Limits		Shutdown Limits	
	Low Limit	High Limit	Low Limit	High Limit
Pressure Reactor	-	2895kPa	-	3000kPa
Level Reactor	50%	100%	10%	112%
Temperature Reactor	-	150°C	-	175°C
Level Separator	30%	100%	10%	130%
Level Stripper	30%	100%	15%	120%

In [XWY20] a set of 33 alarm thresholds is presented. These alarm thresholds are partly set inside the normal operating limits as defined by [DoVo93], which also apply to the adjusted normal operating

mode described [RIC96]. Hence, corresponding alarms do not necessarily indicate an abnormal situation.
A set of calculation formulas and corresponding alarm thresholds can be found in [MALI17]. This set was extended in [KIR19]. Considering both publications a total amount of 25 PVs and five MVs are implemented with HI- and LO-Alarm thresholds. The following rules were used to generate suitable alarm thresholds:

1. Normal operating limits defined in [DOVO93] (s. Table 3.1) are implemented as HI- and LO-Alarm thresholds.
2. Full closing and full opening of manipulated valves are implemented as LO- ($x_{tp_{LO}} = 0\%$) and HI-Alarm thresholds ($x_{tp_{HI}} = 100\%$).
3. Alarm thresholds for other process variables are calculated using the following formulas (with $\bar{x}$ as the steady-state value of PV x):

$$x_{tp_{HI}} = \bar{x} + 0.1\bar{x} \tag{3.1}$$
$$x_{tp_{LO}} = \bar{x} - 0.1\bar{x} \tag{3.2}$$

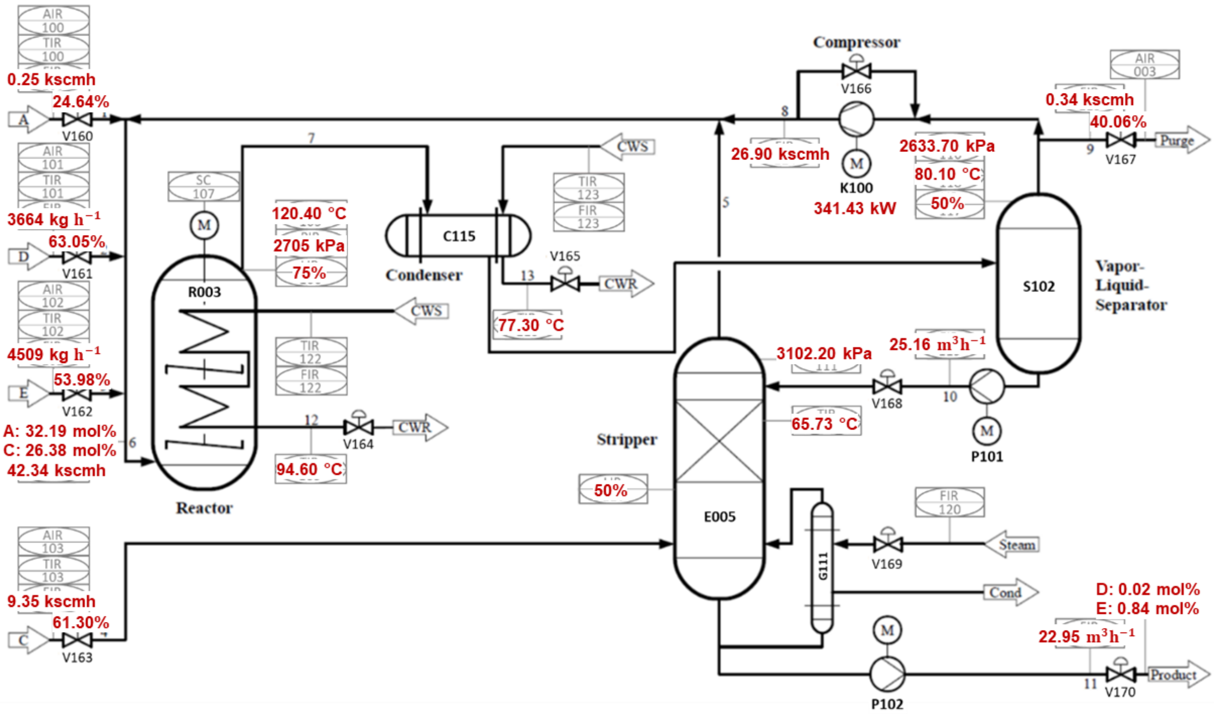

Figure 3.1: Normal operating mode 1 ("Base Case") of the TEP according to [DOVO93], [MALI17] and [KIR19]

Figure 3.1 shows the steady-state values of the 25 PVs and five MVs, which have been implemented with alarm thresholds in [MALI17] and [KIR19], for normal operating mode 1 (“*Base Case*”) according to [DOVO93], [MALI17] and [KIR19]. Table **3.2** shows all alarm thresholds defined in [MALI17] and [KIR19]. Operating limits described in [DOVO93] are marked with *.

Table 3.2: Alarm thresholds used in [MALI17] and [KIR19]

ID	Type	Tag [ARR17]	Description	HI-Alarm	Normal	LO-Alarm	Unit
XMEAS 1	FIR	100	Flow Feed A	0.26	0.25	0.24	kscmh
XMEAS 2	FIR	101	Flow Feed D	3735.00	3664.00	3589.00	kg h-1
XMEAS 3	FIR	102	Flow Feed E	4599.00	4509.00	4419.00	kg h-1
XMEAS 4	FIR	103	Flow Feed C	9.54	9.35	9.16	kscmh
XMEAS 5	FIR	114	Flow Compressor Re-Cycle	27.44	26.90	26.36	kscmh
XMEAS 6	FIR	104	Flow Reactor Feed	43.19	42.34	41.49	kscmh
XMEAS 7	PIR	108	Pressure Reactor	2895.00*	2705.00	0.00	kPa gauge
XMEAS 8	LIR	106	Level Reactor	100.00*	75.00	50.00*	%
XMEAS 9	TIR	105	Temperature Reactor	150.00*	120.40	0.00	°C
XMEAS 10	FIR	115	Flow Purge	0.375	0.337	0.303	kscmh
XMEAS 11	TIR	118	Temperature Separator	81.70	80.10	78.50	°C
XMEAS 12	LIR	117	Level Separator	100.00*	50.00	30.00*	%
XMEAS 13	PIR	116	Pressure Separator	2686.37	2633.70	2581.03	kPa gauge
XMEAS 14	FIR	119	Underflow Separator	25.66	25.16	24.66	m³ h-1
XMEAS 15	LIR	110	Level Stripper	100.00*	50.00	30.00*	%
XMEAS 16	PIR	111	Pressure Stripper	3164.24	3102.20	3040.16	kPa gauge
XMEAS 17	FIR	121	Underflow Stripper	23.41	22.95	22.49	m³ h-1
XMEAS 18	TIR	111	Temperature Stripper	67.05	65.73	64.42	°C
XMEAS 20	K	100	Compressor Work	348.26	341.43	334.60	kW
XMEAS 21	TIR	109	Temperature Cooling Water Outlet Reactor	96.49	94.60	92.71	°C
XMEAS 22	TIR	113	Temperature Cooling Water Outlet Condenser	78.84	77.30	75.75	°C
XMEAS 23	AIR	001	Concentration Reactor Feed Material A	35.41	32.19	28.97	mol%
XMEAS 25	AIR	001	Concentration Reactor Feed Material C	29.02	26.38	23.74	mol%
XMEAS 37	AIR	002	Concentration Underflow Stripper Material D	0.022	0.02	0.018	mol%
XMEAS 38	AIR	002	Concentration Underflow Stripper Material E	0.92	0.84	0.76	mol%
XMV 1	V	161	Valve Position Feed D	100.00	63.05	0.00	%
XMV 2	V	162	Valve Position Feed E	100.00	53.98	0.00	%
XMV 3	V	160	Valve Position Feed A	100.00	24.64	0.00	%
XMV 4	V	163	Valve Position Feed C	100.00	61.30	0.00	%
XMV 6	V	167	Valve Position Purge	100.00	40.06	0.00	%

The aforementioned alarm thresholds have been used to calculate alarm variables for three 75-hour simulations using the TEP model described in section 1 (adjusted normal operating mode). Figure 3.2 illustrates one of the resulting alarm-burst-diagrams showing a high average and maximum alarm activation rate per 10 minutes.

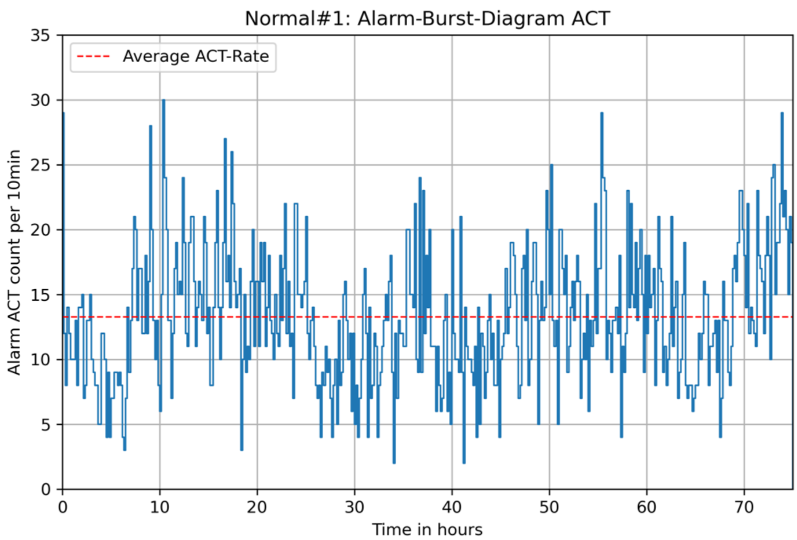

Figure 3.2: Alarm-burst-diagram for normal operating mode using alarm thresholds from [MALI17] and [KIR19]

Analyzing the respective alarm count in Figure 3.3 and respective amount of time in an active alarm state in Figure 3.4, one can identify that mostly ***XMEAS 1, 3, 4, 14, 17*** and ***37*** are responsible for high alarm rates and that 11 other PVs are in alarm condition all the time. Furthermore, it can be diagnosed, that only those PVs are showing poor alarm behavior, where the alarm threshold was calculated using the formulas (3.1) and (3.2) from [MALI17].

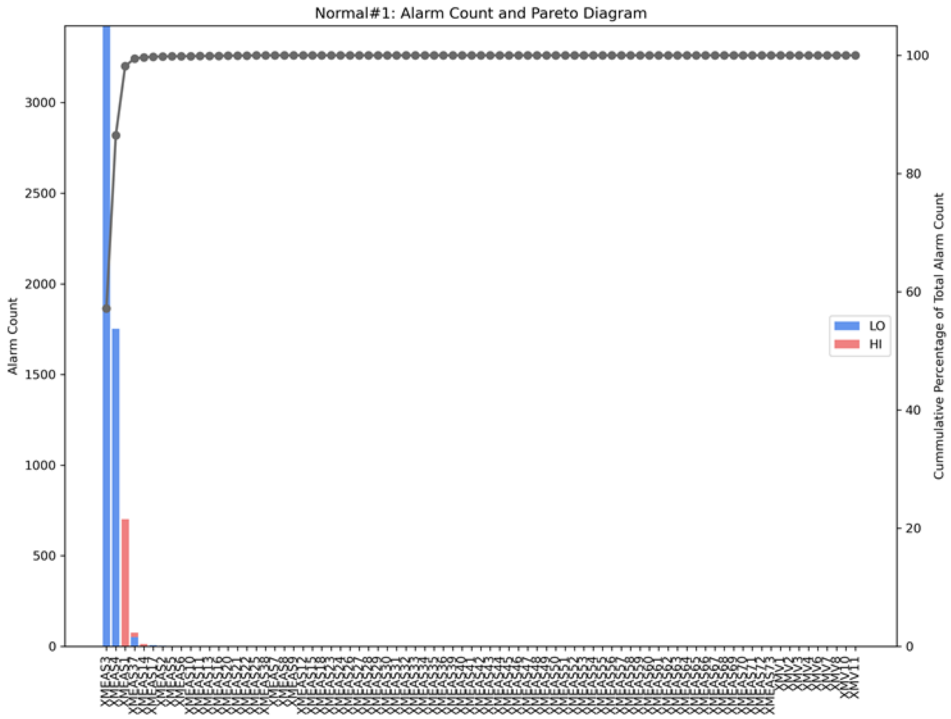

Figure 3.3: Alarm count and pareto diagram for normal operating mode using alarm thresholds from [MALI17] and [KIR19]

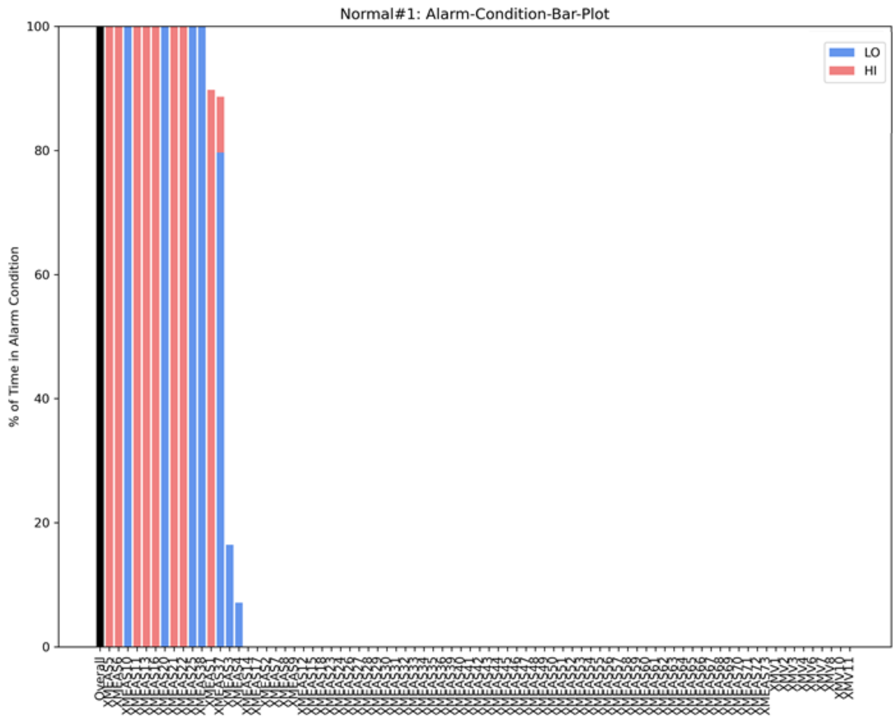

Figure 3.4: Alarm-condition-bar-plot for normal operating mode using alarm thresholds from [MALI17] and [KIR19]

Figure 3.5 shows the high-density alarm plot (top) and corresponding time-trend plots of a selection of PVs (bottom). ***XMEAS 1*** and ***3*** tend to demonstrate chattering alarm behavior, whereas ***XMEAS 14*** and ***17*** both show fleeting alarms. In the case of ***XMEAS 37*** alarm thresholds are placed too narrow and are shifted compared to the steady-state value.

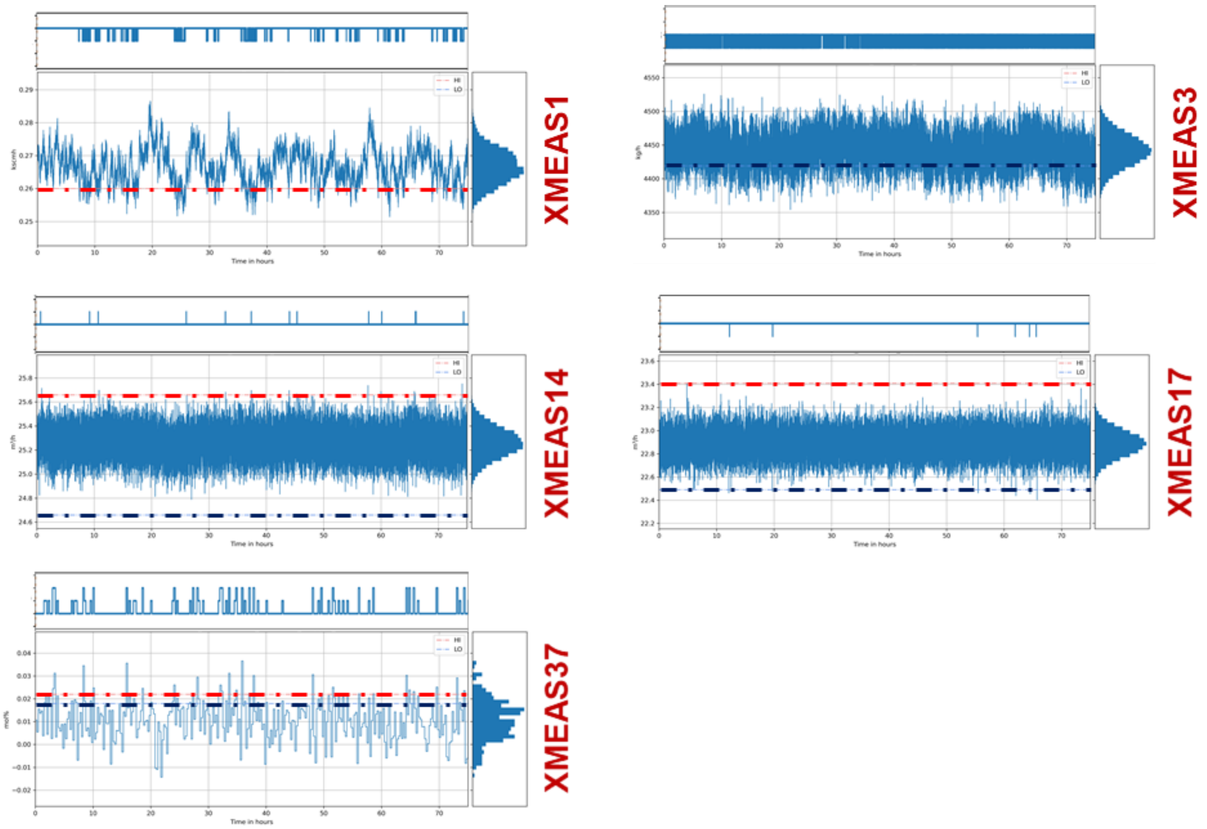

Figure 3.5: High-density alarm plot (top) and time-trend plots (bottom) of assorted XMEAS for normal operating mode using alarm thresholds from [MALI17] and [KIR19]

In conclusion, alarm thresholds from [MALI17] and [KIR19] are inadequate and cannot be directly adopted to the used TEP simulation model. Hence, they need to be adapted to the adjusted normal operating mode described in [BRJ15] and [RIC96], to meet the target of no alarm activations during normal operations [IEC 62682, 2014#]. In the following, several revision steps are conducted to work towards this goal. This procedure is based on the iterative rationalization step of the alarm management life-cycle described in [ANSI/ISA 18.2, 2016#].

3.2 Alarm Design – 1st Revision

According to [RIC96] normal operating and emergency shutdown limits defined in [DOVO93] also apply to the herein used adjusted operating mode, therefore are the corresponding alarm thresholds kept. Alarm thresholds for manipulated valves are adopted from [MALI17] and adapted for the remaining valves. Regarding all other PVs alarm thresholds are calculated using the formulas presented in [MALI17] (s. Formulas 3.1 and 3.2) with steady-state values of the adjusted normal operating mode as described in [RIC96] and [BRJ15]. For ***XMVs 5, 9*** and ***12*** as well as ***XMEAS 19*** no alarm thresholds are designed as these variables have no influence on the herein used TEP model. Appendix A displays steady-state values of the adjusted normal operating mode compared to the *"Base Case"*.
Some of the chemical component concentration PVs show a steady-state value of nearly 0mol% (19 PVs) or almost 100mol% (three PVs). The implemented measurement noise generator is not limited to physically valid values, thus the concentration of a certain component can reach values below 0mol% and above 100mol%. Hence, affected PVs are implemented with a HI-Alarm threshold of 1.00mol% and a LO-Alarm threshold of -1.00mol%. Furthermore, threshold values for HI-Alarms greater than 100mol% are considered valid. Appendix B shows the resulting alarm thresholds of this first revision.

To the best of the author's knowledge no HIHI- or LOLO-Alarm threshold have been explicitly defined in TEP-related publications. According to industrial practice (statement at the *"IFAC-V 2020 Industrial Alarm Monitoring Workshop"*), emergency shutdown limits can be implemented as HIHI- and LOLO-Alarms, in order to serve as an information towards the operator. Table 3.3 shows HIHI- and LOLO-Alarm thresholds for the TEP based on emergency shutdown limits defined in [DoVo93] (s. Table 3.1).

Table 3.3: HIHI- and LOLO-alarm thresholds 1st revision

ID	Type	Tag [Arr17]	Description	HIHI-Alarm	HI-Alarm	Normal	LO-Alarm	LOLO-Alarm	Unit
XMEAS 7	PIR	108	Pressure Reactor	3000.00	2895.00	2800.00	0.00	-	kPa gauge
XMEAS 8	LIR	106	Level Reactor	112.00	100.00	65.00	50.00	10.00	%
XMEAS 9	TIR	105	Temperature Reactor	175.00	150.00	122.90	0.00	-	°C
XMEAS 12	LIR	117	Level Separator	130.00	100.00	50.00	30.00	10.00	%
XMEAS 15	LIR	110	Level Stripper	120.00	100.00	50.00	30.00	15.00	%

In a next step, the revised alarm thresholds are applied to the normal operating mode simulation described in section 3.1. Figure 3.6 shows the resulting alarm-burst-diagram. Despite a higher number of configured alarm thresholds, a reduced average and maximum alarm rate was achieved.

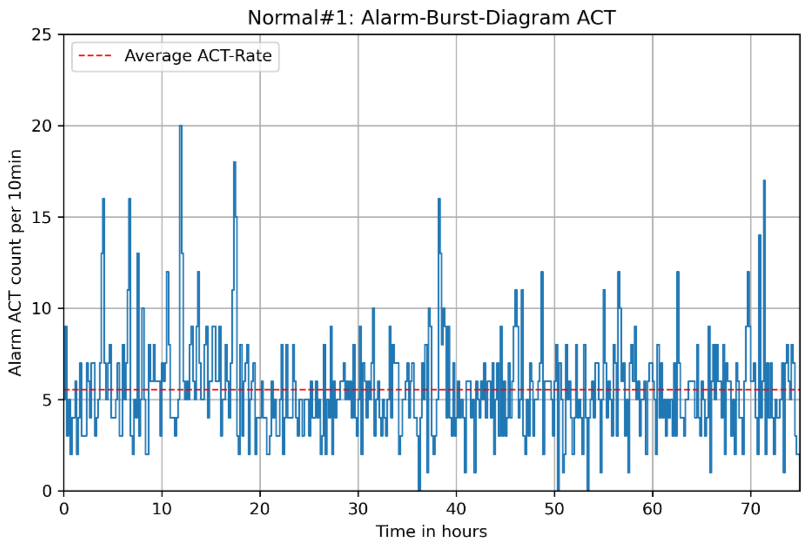

Figure 3.6: Alarm-burst-diagram for normal operating mode using alarm thresholds from 1st revision

Figure 3.7 and Figure 3.8 illustrate that solely ***XMEAS 10, 32, 39, 49*** and ***69*** are responsible for the high alarm count. Furthermore, simultaneous occurrence of HI- and LO-Alarms of a respective PV during simulation can be interpreted as a possible indicator for alarm thresholds that are designed too narrow around the steady-state value. Figure 3.9 (Subplots a to d) shows time-trend plots of relevant PVs. It can be seen that the assumption of too narrow alarm thresholds can be confirmed. Deeper analysis has to be conducted to distinguish between chattering and fleeting alarms. Subsequently suitable alarm management techniques have to be selected and implemented in order to reduce these nuisance alarms.

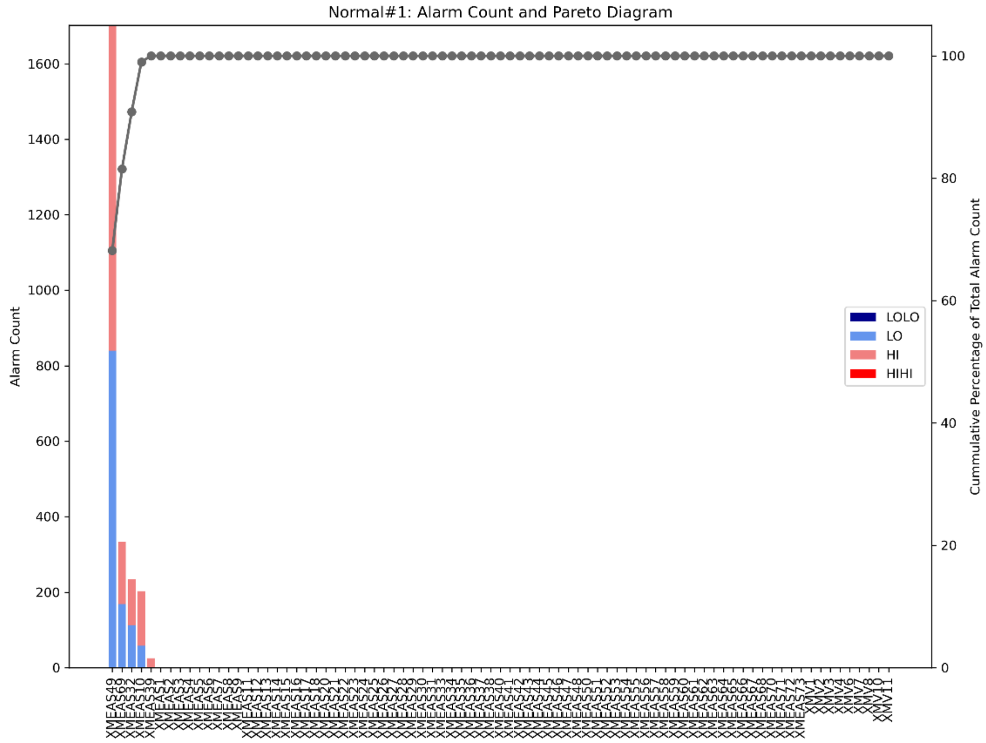

Figure 3.7: Alarm count and pareto diagram for normal operating mode using alarm thresholds from 1st revision

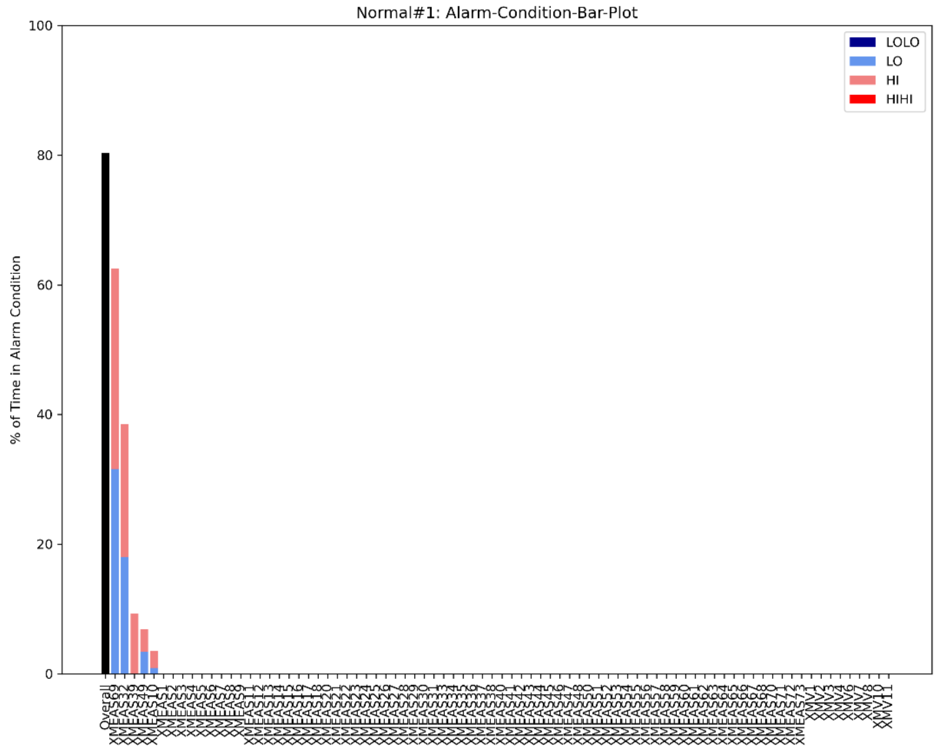

Figure 3.8: Alarm-condition-bar-plot for normal operating mode using alarm thresholds from 1st revision

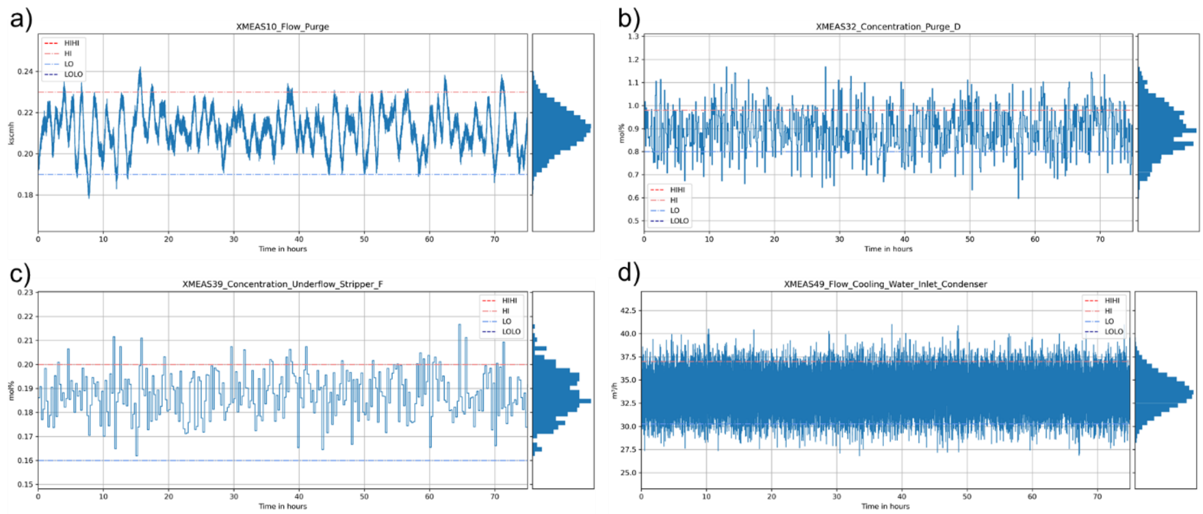

Figure 3.9: Time-trend plots of assorted XMEAS for normal operating mode using alarm thresholds from 1st revision: a) XMEAS 10, b) XMEAS 32, c) XMEAS 39, d) XMEAS 49

[KON13] describes two types of chatter-indices. Based on the time difference between two alarm instances of same type and PV (OFF-ON-Run Length or alarm interval [HOHA10]) tendency of chattering behavior can be calculated using the following formula:

$$\Psi = \sum_{r \in \mathbb{N}} P_r \frac{1}{r} \tag{3.3}$$

$$\text{with: } P_r = \frac{n_r}{\sum_{r \in \mathbb{N}} n_r}, \forall r \in \mathbb{N} \tag{3.4}$$

$\mathrm{n_r}$ describes the alarm count for a specific OFF-ON-Run-Length r and $\sum \mathrm{n_r}$ describes the total count of alarms minus one (the last alarm has per definition no OFF-ON-Run-Length). [KON13] uses a sampling rate of 1s. In order to meet the herein used 10s rate, it is necessary to multiply the calculated chatter-index with a factor of 10. Ψ can take values between 0 (no chattering) and 1 (only chattering). Ψ=1 applies to the case, where all alarms show an OFF-ON-Run-Length of 10s.
Alarms with an OFF-ON-Run-Length greater than a threshold τ are not included in calculating the modified chatter-index. Following recommendations from [KON13] values of 300s (5min) and 600s (10min) are considered for τ. The modified chatter-index can be calculated using the following formula [KON13]:

$$\Psi_\tau = \sum_{r \in \mathbb{N}} P_r \frac{1}{r} \tag{3.5}$$

$$\text{with: } P_{r,\tau} = \begin{cases} \frac{n_r}{\sum_{r=1}^{r=\tau} n_r}, & \forall r \in \{1,2,3 \ldots \tau\} \\ 0, & \forall r \in \{\tau+1, \tau+2, \tau+3 \ldots \infty\} \end{cases} \tag{3.6}$$

[KON13] sets the threshold for the existence of chattering alarms at a chatter-index of ≥ 0.05.
Figure 3.10 shows the calculated chatter-indices of the aforementioned PVs. ***XMEAS 10*** and ***XMEAS 49*** are showing chatter index values ≥ 0.05 (for both HI- and LO-Alarms). Therefore, they can be considered as chattering alarms. ***XMEAS 32*** and ***XMEAS 39*** are not showing chattering behavior, hence, activated alarms can be classified as fleeting alarms. A second revision of the alarm thresholds has to be conducted in order to reduce these nuisance alarms.

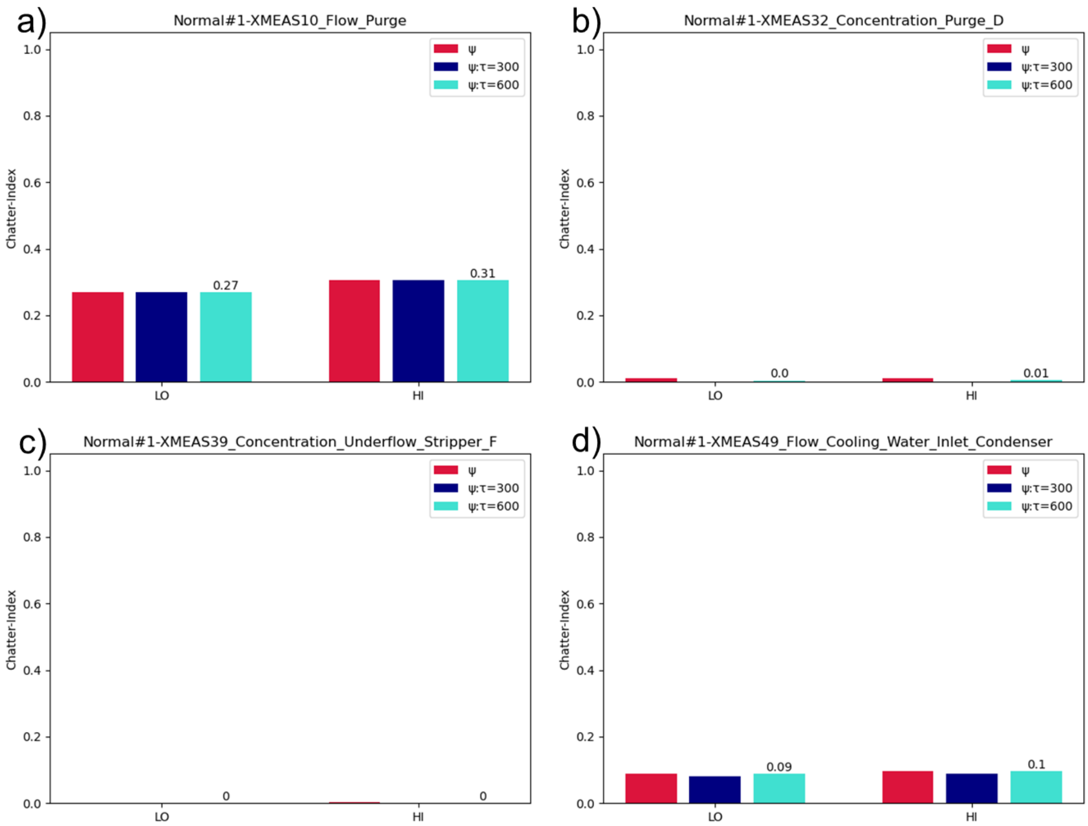

Figure 3.10: Chatter-indices of assorted XMEAS for normal operating mode using alarm thresholds from 1st revision: a) XMEAS 10, b) XMEAS 32, c) XMEAS 39, d) XMEAS 49

3.3 Alarm Design – 2nd Revision

Selection of suitable alarm management techniques can be necessary, in order to reduce different kinds of nuisance alarms [HoHa10]. ON- and OFF-Delay-Timer are typical techniques, which can be easily implemented. OFF-Delay-Timer can be used to reduce chattering alarms, but they are not able to reduce fleeting alarms during normal operation. ON-Delay-Timer can be used for this purpose, but [EEMUA 191, 2013#] recommends to only use ON-Delay-Timer if no other techniques had the desired effect, due to potential high delay of important alarms during major plant upsets. [EEMUA 191, 2013#] and [NAMUR NA 102, 2008#] are describing process signal filters as techniques to reduce both chattering and fleeting alarms. [ISS+09a], [ISS+09b] and [Adn13] examine the application of process signal filters on alarm system performance. Two filter types are shown in Figure 3.11: Moving-Average-Filter (a) and Moving-Variance-Filter (b). The specific type can be manually chosen depending on the respective process signal behavior.

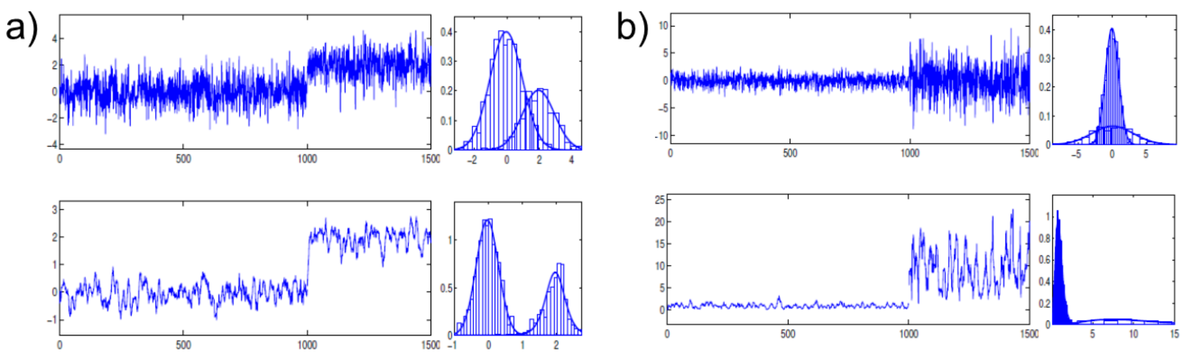

Figure 3.11: Two types of process signal filters: a) moving-average-filter, b) moving-variance-filter [ISS+09b]

At this point it shall be noted, that regarding the herein analyzed TEP simulation model, only Moving-Average-Filters are chosen, since abnormal situations (s. Section 3.5) can be solely distinguished from normal behavior by a shift of the arithmetic mean.

[ISS+09A] and [ISS+09B] analyze the trade-off between accuracy and latency using filter techniques in alarm management. A more accurate alarm system and management (lower probability of false and missed alarms) comes "[…] *at the cost of detecting the abnormal situation later. That is because a moving average filter of size 10 averages 10 consecutive samples and it takes more time for this average to reflect the change in the value. So a moving average filter of size 10 introduces a delay between 2 to 10 samples in detecting the abnormality, depending on how far apart the normal and abnormal data sets are* [ISS+09B]." Therefore, [ISS+09A] examines the application of EWMA-Filters (Exponential Weighted Moving Average). The time delay in detecting an abnormal situation can be significantly reduced compared to other filter techniques, due to exponentially higher weighting of timely newer data points. The EWMA-Filter can be calculated using the following formula:

$$\mathrm{EWMA}(i) = \begin{cases} x(1), & i = 1 \\ \alpha * x(i) + (1-\alpha) * EWMA(i-1), & i > 1 \end{cases} \tag{3.7}$$

With $x(i)$ representing the original process data, $y(i)$ representing the filtered process data and α being the filter parameter. For implementation in alarm systems [ISS+09A] recommends a filter parameter of α = 0.1, but points out, that this parameter can be also set at a lower value if the filtered process signal shows a high amount of noise. Though, this parameter tuning comes along with an extended detection delay.

According to [DoVo93] a normal distributed noise signal is simulated for each PV, wherein the standard deviation depends on the specific PV type. The following PV types are showing an increased standard deviation in the used TEP model: Level, flow and chemical composition. These three PV types are set with a filter parameter of α = 0.05. All other PV types are set with a filter parameter of α = 0.1.

Due to the implemented filter techniques, alarm thresholds for valve position variables and those representing emergency shutdown limits (as HIHI- and LOLO-Alarms) cannot be reached anymore, as they are describing maximum values. Using an EWMA-Filter only allows to asymptotically converge on the aforementioned thresholds, even if the original process data already reached the corresponding value. Subsequently, it is required to adjust the following alarm thresholds (s. Table 3.4 and Table 3.5):

- ***Valve Position*** MVs HI-Alarm (LO-Alarm): +1% (-1%)
- PVs with ***α = 0.1*** and emergency shutdown limits implemented as HIHI-Alarm (LOLO-Alarm): +1% (-1%) of steady-state value. Applies to ***XMEAS 7*** and ***9***.
- PVs with ***α = 0.05*** and emergency shutdown limits implemented as HIHI-Alarm (LOLO-Alarm): +2% (-2%) of steady-state value. Applies to ***XMEAS 8, 12*** and ***15***.

Table 3.4: Alarm thresholds 2nd revision (only revised alarm tags are shown)

ID	Type	Tag [Arr17]	Description	HI-Alarm	Normal	LO-Alarm	Unit
XMV 1	V	161	Valve Position Feed D	99.00	62.89	1.00	%
XMV 2	V	162	Valve Position Feed E	99.00	53.17	1.00	%
XMV 3	V	160	Valve Position Feed A	99.00	26.24	1.00	%
XMV 4	V	163	Valve Position Feed C	99.00	60.57	1.00	%
XMV 6	V	167	Valve Position Purge	99.00	25.94	1.00	%
XMV 7	V	168	Valve Position Underflow Separator	99.00	37.22	1.00	%
XMV 8	V	170	Valve Position Underflow Stripper	99.00	46.43	1.00	%
XMV 10	V	164	Valve Position Cooling Water Outlet Reactor	99.00	35.95	1.00	%
XMV 11	V	165	Valve Position Cooling Water Outlet Condenser	99.00	12.34	1.00	%

Table 3.5: HIHI- and LOLO-alarm thresholds 2nd revision

ID	Type	Tag [ARR17]	Description	HIHI-Alarm	HI-Alarm	Normal	LO-Alarm	LOLO-Alarm	Unit
XMEAS 7	PIR	108	Pressure Reactor	**2972.00**	2895.00	2800.00	0.00	-	kPa gauge
XMEAS 8	LIR	106	Level Reactor	**110.70**	100.00	65.00	50.00	**11.30**	%
XMEAS 9	TIR	105	Temperature Reactor	**173.77**	150.00	122.90	0.00	-	°C
XMEAS 12	LIR	117	Level Separator	**129.00**	100.00	50.00	30.00	**11.00**	%
XMEAS 15	LIR	110	Level Stripper	**119.00**	100.00	50.00	30.00	**16.00**	%

Figure 3.12 shows the resulting alarm-burst-diagram using an EWMA-Filter as well as the revised alarm thresholds. The effect of applying the EWMA-Filter as an alarm management technique can be seen by means of nearly 80% reduced average and maximum alarm activation rate per 10 minutes. Furthermore, total alarm count was reduced by approximately 80% and overall time in alarm condition by approximately 17%. Figure 3.13 shows that ***XMEAS 10, 32, 39*** and ***69*** account for 100% of the total alarm count. As there are remaining nuisance alarms during normal operating mode, a third revision of the alarm thresholds and implemented alarm management techniques has to be conducted.

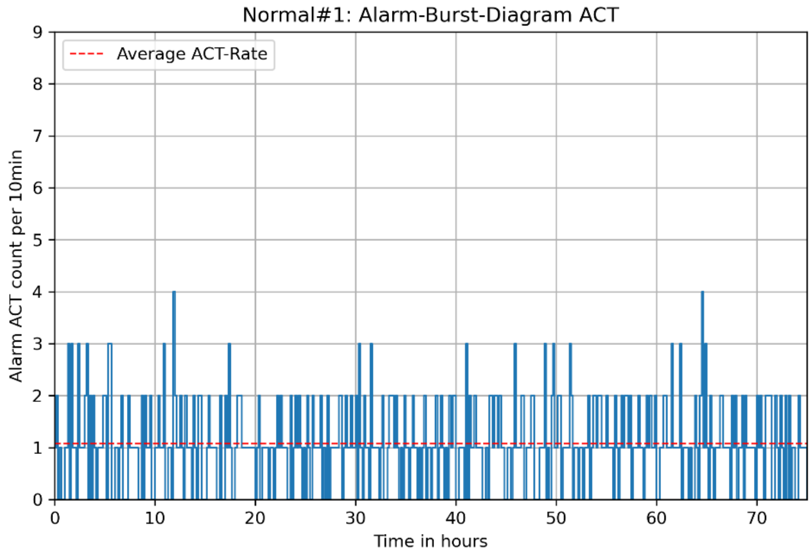

Figure 3.12: Alarm-burst-diagram for normal operating mode using alarm thresholds from 2nd revision

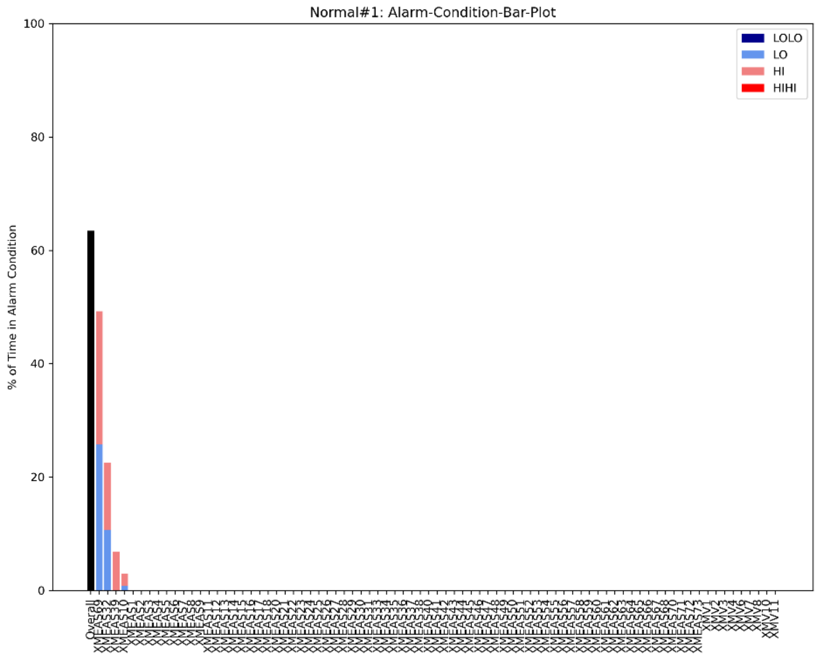

Figure 3.13: Alarm-condition-bar-plot for normal operating mode using alarm thresholds from 2nd revision

3.4 Alarm Design – 3rd Revision

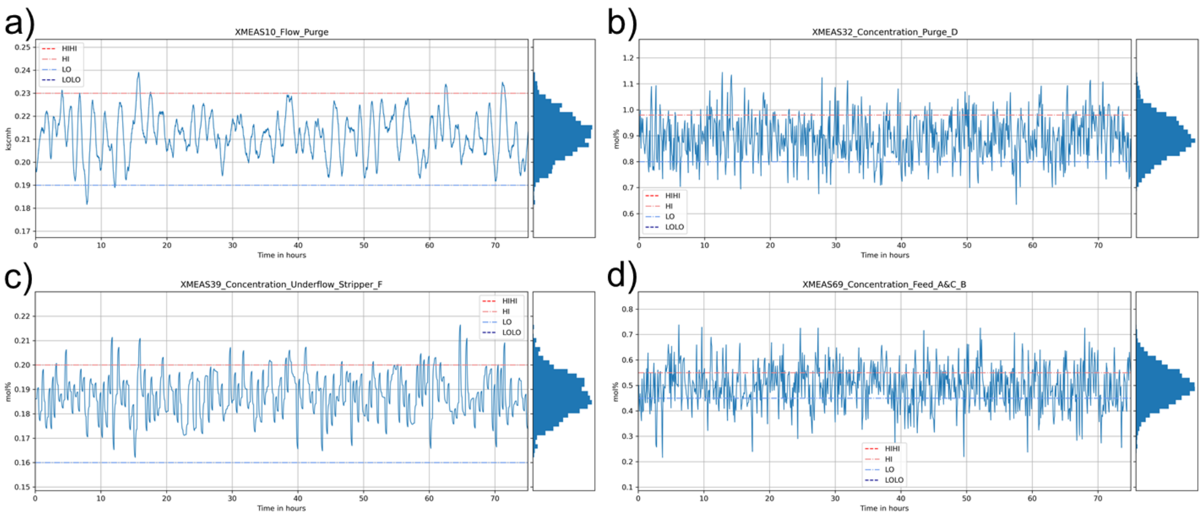

Figure 3.14: Time-trend plots of assorted XMEAS for normal operating mode using alarm thresholds from 2nd revision: a) XMEAS 10, b) XMEAS 32, c) XMEAS 39, d) XMEAS 69

Analyzing Figure 3.14 it can be seen that for the four PVs, which are still showing alarm activations during normal operation, too narrow alarm thresholds are configured. Consequently, HI- and LO-chattering as well as fleeting alarms are activated. In order to overcome these nuisance alarms, corresponding thresholds are manually adjusted (s. Table 3.6).

Table 3.6: Alarm thresholds 3rd revision (only revised alarm tags are shown)

ID	Type	Tag [ARR17]	Description	HI-Alarm	Normal	LO-Alarm	Unit
XMEAS 10	FIR	115	Flow Purge	0.25	0.21	0.17	kscmh
XMEAS 32	AIR	003	Concentration Purge (Material D)	1.25	0.89	0.53	mol%
XMEAS 39	AIR	002	Concentration Underflow Stripper (Material F)	0.23	0.18	0.13	mol%
XMEAS 69	AIR	103	Concentration Feed C (Material B)	0.85	0.50	0.15	mol%

Figure 3.15 shows the resulting alarm-burst-diagram using the revised alarm thresholds. It can be seen that no alarm activations occur during normal operation of the analyzed TEP simulation model (represented by an average alarm activation rate of zero).

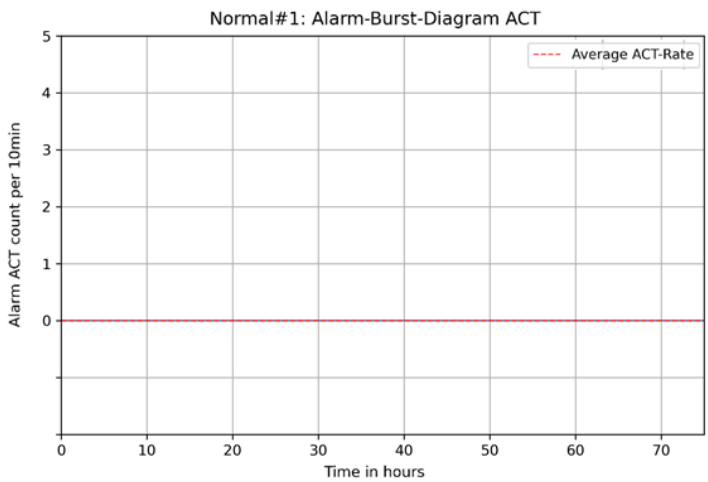

Figure 3.15: Alarm-burst-diagram for normal operating mode using alarm thresholds from 3rd revision

In a next step, the revised alarm thresholds and implemented filter technique are applied to simulation data with initiated abnormal situations, in order to further analyze the behavior of relevant variables and corresponding alarm activations.

3.5 Alarm Design – 4th Revision

[DoVo93] describes 20 different root cause disturbances (***IDV1*** to ***IDV20***), each caused by manipulating one or more process variables, leading to local or plantwide abnormal situations. The herein used TEP simulation model allows for a scaling of these root cause disturbances between 0% and 100% using a disturbance activation flag (in terms of scaling the disturbance of the initially manipulated variables) [BRJ15]. In order to further rationalize the implemented alarm thresholds and alarm management techniques three root cause disturbances have been selected, which are according to [Arr17] suitable for industrial alarm analysis purposes, due to their plantwide propagation (s. Table 3.7). A detailed description of the root cause disturbances for this TEP dataset can be found in section 4.

Table 3.7: Used root cause disturbances

IDV	Manipulated Variable	Description of the manipulated Variable
1	XMEAS 68, 70	Concentration Feed C (Materials A and C)
2	XMEAS 69	Concentration Feed C (Material B)
6	XMEAS 1	Flow Feed A

Table 3.8 gives an overview of the conducted simulation tests. Each root cause disturbance is initiated after one hour of normal operation and is terminated after a specific amount of time has elapsed (s. column *"Duration"* in Table 3.8). For ***IDV6*** with a scaling of 100% emergency shutdown limits were reached after an ARC phase of approximately seven hours.

Table 3.8: Scaling and duration of used root cause disturbances

IDV	Scaling	Duration
1	100%	5h, 10h
1	80%	5h, 10h
2	100%	5h, 10h
2	80%	5h, 10h
6	100%	5h, approx. 7h (Emergency shutdown)
6	80%	5h, 10h

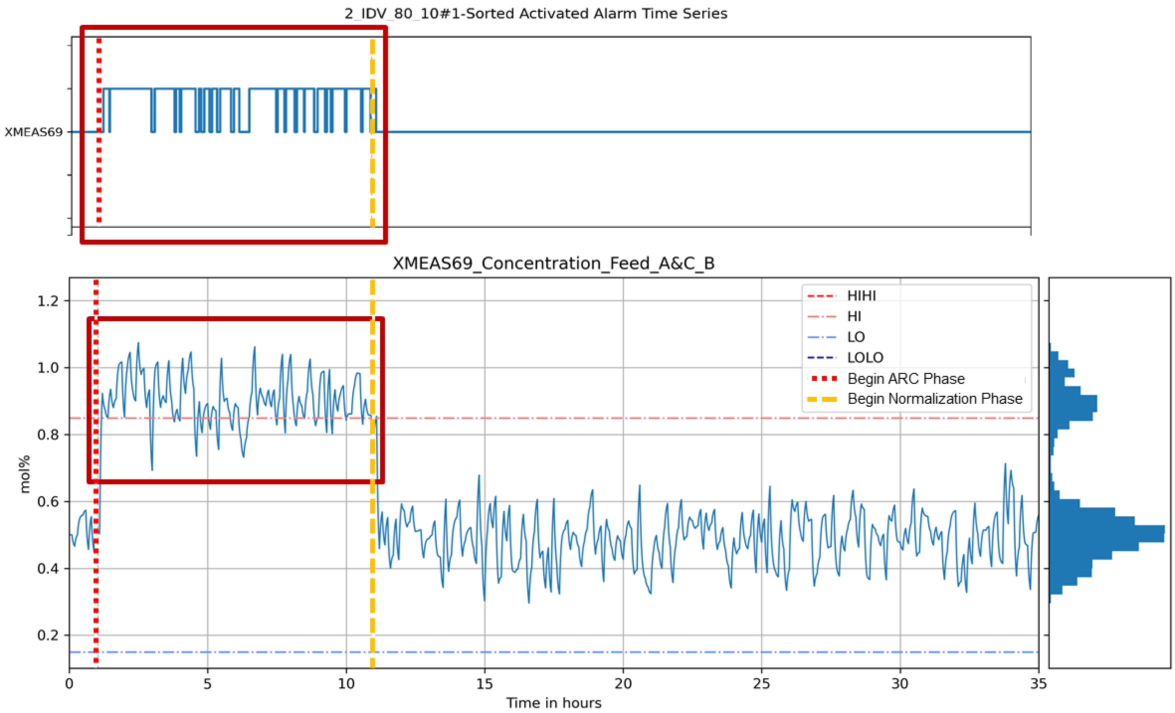

Figure 3.16: Time-trend plots for alarm and process data of XMEAS 69 (IDV2 80% 10h) using alarm thresholds from 3rd revision

Figure 3.16 shows time-trend plots for alarm as well as process data of ***XMEAS 69*** by using alarm thresholds from third revision. In this test the disturbance ***IDV2*** is initiated with a scaling of 80% and a duration of 10h. ***XMEAS 69*** is the initially disturbed variable and therefore root cause of the plant wide situation. The specific abnormal behavior of ***XMEAS 69*** appears as a step shift from a normal to an abnormal steady-state level. These two levels can be easily distinguished using the human's capability of pattern detection, whereas, due to the signal's wide range, defining a distinct division between the normal and abnormal state using only a single alarm threshold seems difficult. As a result, ***XMEAS 69*** shows chattering alarms during the ARC phase (marked with red squares). As a suitable alarm management technique, which is able to reduce chattering and fleeting alarms during abnormal situations while keeping the false alarm rate low during normal operation, [HOHA10], [EEMUA 191, 2013#] as well as [IEC 62682, 2014#] recommend to define alarm deadbands. Instead, reducing the corresponding HI-Alarm threshold, as an obvious solution to these nuisance alarms, can lead to false alarms during normal operation.

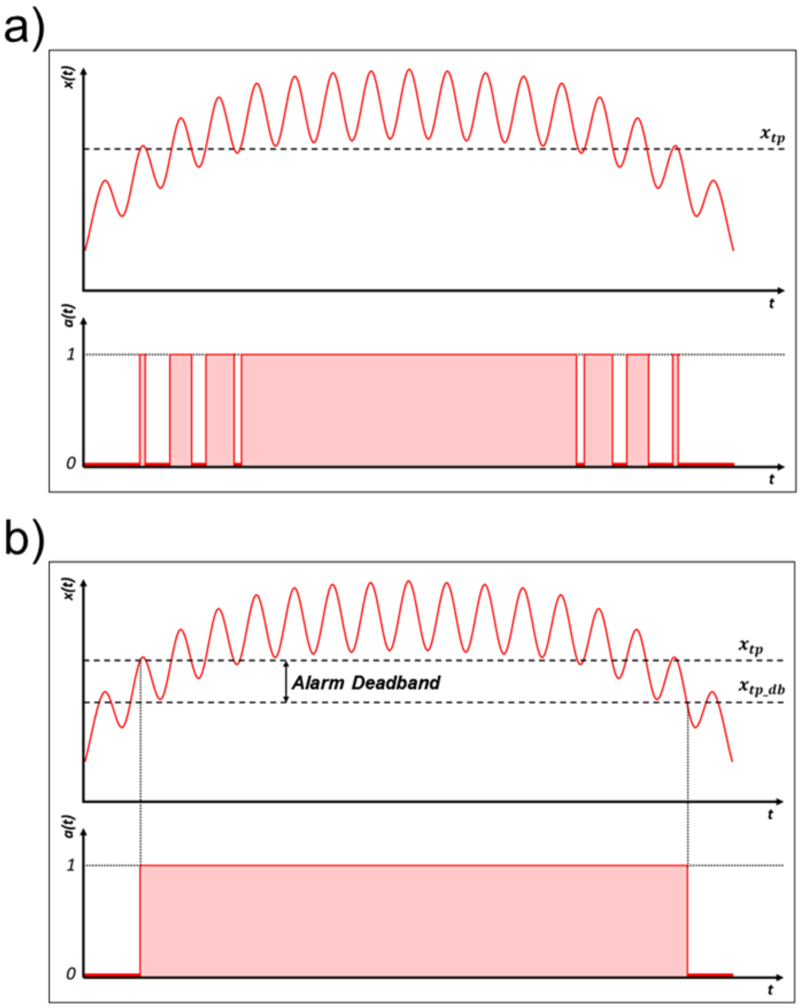

Figure 3.17: Time-trend plot for process and alarm data [HOHA10]: a) without alarm deadband, b) with alarm deadband

By using alarm deadbands it is possible to define different alarm thresholds for activation and deactivation of a specific alarm variable [IEC 62682, 2014#]. Typically, alarm deadbands are described using the percentage of the steady-state value by which a HI-Alarm threshold is decreased or a LO-Alarm threshold is increased [EEMUA 191, 2013#]. In the herein considered TEP simulation model a high number of measured PVs have a steady-state value close to zero, hence a different approach has been chosen: alarm deactivation thresholds are calculated using the alarm activation threshold as a relative base value. On the contrary, this method results in low absolute deadbands for valve position LO-Alarms, as they have thresholds set at 1%. This trade-off will be accepted, due to their low measurement noise showing hardly any nuisance alarms. Figure 3.17 shows the functionality of an alarm deadband.

Table 3.9: Recommended alarm-deadband configuration [EEMUA 191, 2013#]

PV Type	Alarm-Deadband
Flow	5%
Level	5%
Pressure	2%
Temperature	1%

[EEMUA 191, 2013#] recommends different alarm deadband configurations depending on the corresponding PV type. This recommendation will be implemented. In addition, all other PV types will be initially configured using a 5%-deadband.

3.6 Alarm Design – 5th Revision

Figure 3.18 shows time-trend plots for alarm as well as process data of ***XMEAS 69*** by using alarm thresholds and deadbands from the fourth revision. In this test the disturbance ***IDV2*** is initiated with a scaling of 80% and a duration of 10h. Compared to Figure 3.16, using alarm thresholds from third revision and no alarm deadbands at all, alarm count of ***XMEAS 69*** during abnormal situation can be reduced by 52%. Figure 3.19 illustrates the remaining chattering behavior of the aforementioned PV with a chatter-index of $\psi_{t=600} = 0.06$. Hence, HI-Alarm threshold and deadband are manually adjusted in a fifth alarm design revision. Table 3.10 displays the implemented configurations of ***XMEAS 69***, which result in activation of only one alarm and a chatter-index of zero. With a deadband of 40%, the threshold for return to normal is set at 0.48mol%.

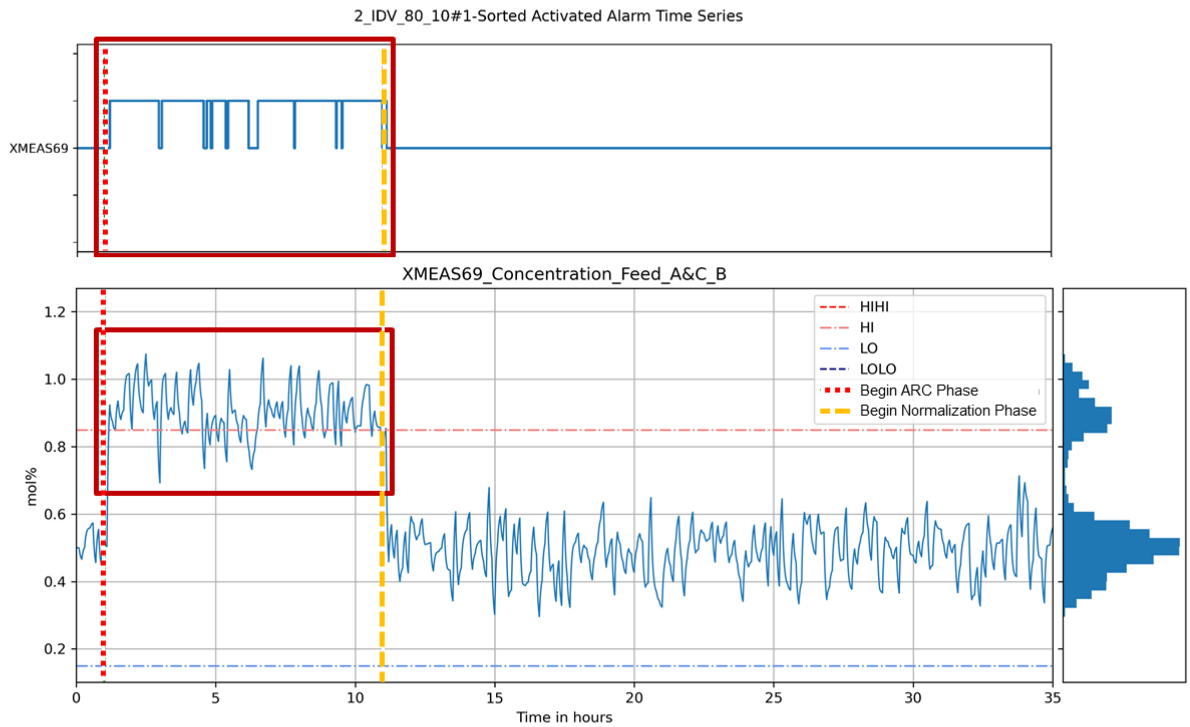

Figure 3.18: Time-trend plots for alarm and process data of XMEAS 69 (IDV2 80% 10h) using alarm thresholds and deadbands from 4th revision

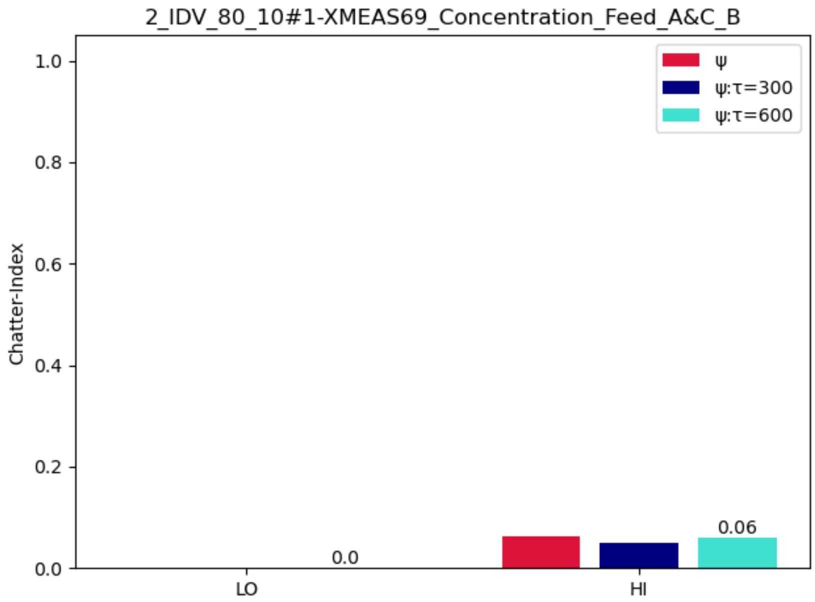

Figure 3.19: Chatter-indices of XMEAS 69 (IDV2 80% 10h) using alarm thresholds and deadbands from 4th revision

In addition to the nuisance alarm behavior of ***XMEAS 69***, PVs ***XMEAS 32*** and ***39*** are showing fleeting alarms. Figure 3.20 shows time-trend plots for alarm as well as process data of ***XMEAS 39*** by using alarm thresholds and deadbands from fourth revision. In this test the disturbance ***IDV2*** is initiated with a scaling of 100% and a duration of 10h. Two relatively short LO-Alarm instances are interrupted by a period of alarm inactivation, although ***XMEAS 39*** is still showing abnormal behavior. In order to adequately alarm the operator during abnormal situations and to prevent false alarming during normal operation, the LO-Alarm threshold is manually adjusted to 0.15mol% and deadband is set to 10%, representing a return to normal threshold of ≈0.17mol% (s. Table 3.10). Implementing these adapted settings results in only one alarm activation of ***XMEAS 39*** in the same abnormal situation as in Figure 3.20.

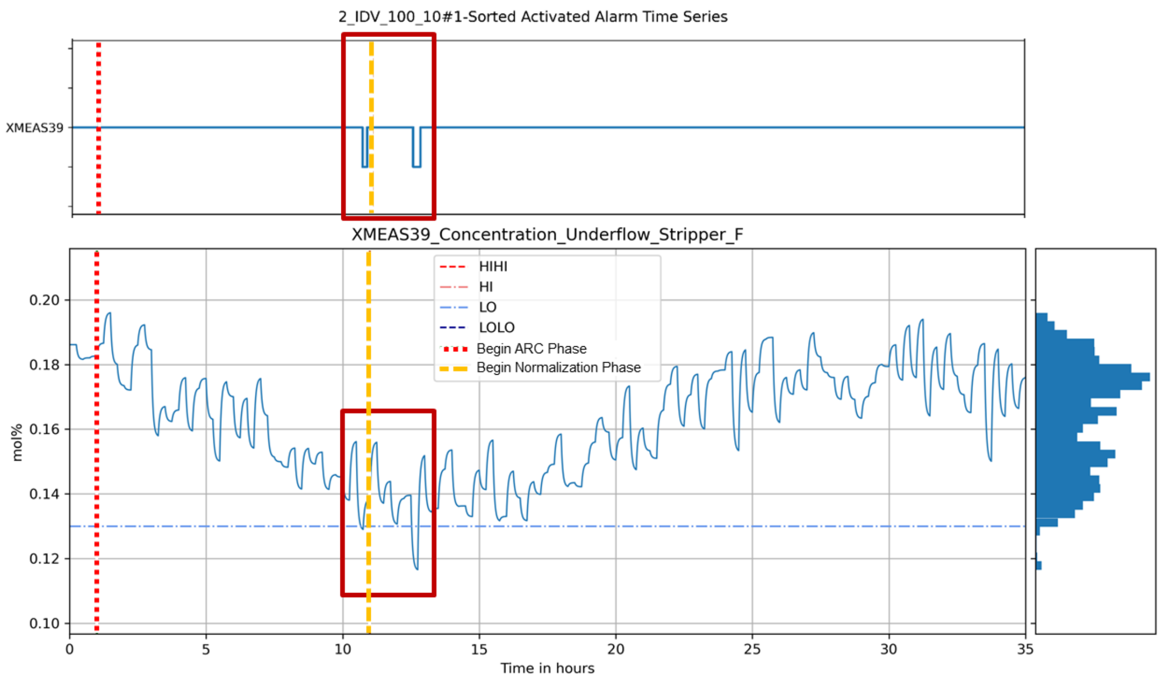

Figure 3.20: Time-trend plots for alarm and process data of XMEAS 39 (IDV2 100% 10h) using alarm thresholds and deadbands from 4th revision

Figure 3.21 shows time-trend plots for alarm as well as process data of ***XMEAS 32*** by using alarm thresholds and deadbands from fourth revision. In this test the disturbance ***IDV6*** is initiated with a scaling of 80% and a duration of 10h. ***XMEAS 32*** shows several fleeting HI- (during the ARC phase) and LO-Alarms (during the normalization phase). In order to reduce these nuisance alarms, the respective alarm design has to be adapted. Table 3.10 shows the manually implemented adjustments: the LO-Alarm threshold is reduced to 0.45mol% and deadband is increased to 28%, which corresponds to a return to normal threshold for HI-Alarms of 0.9mol%. These adjustments result in one single HI-Alarm activation during the depicted ARC phase and no LO-Alarms during the normalization phase.

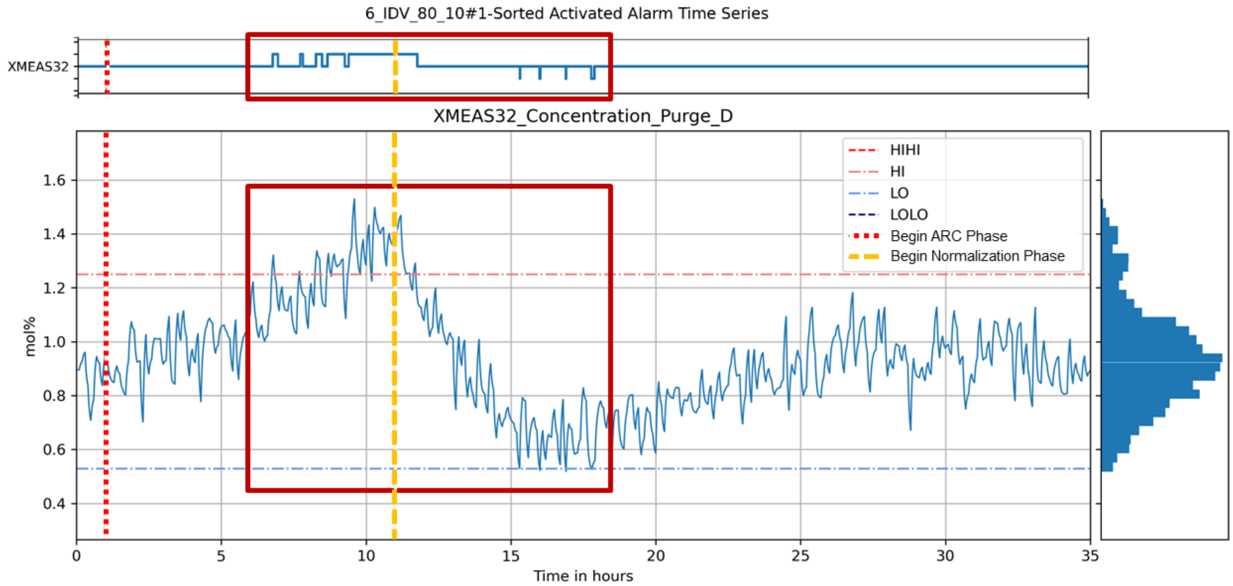

Figure 3.21: Time-trend plots for alarm and process data of XMEAS 32 (IDV6 80% 10h) using alarm thresholds and deadbands from 4th revision

Table 3.10: Alarm thresholds and deadbands 5th revision of XMEAS 32, 39 and 69

ID	Type	Tag [ARR17]	Description	HI-Alarm	Normal	LO-Alarm	Unit	Deadband
XMEAS 32	AIR	003	Concentration Purge (Material D)	1.25	0.89	**0.45**	mol%	28%
XMEAS 39	AIR	002	Concentration Underflow Stripper (Material F)	0.23	0.18	**0.15**	mol%	10%
XMEAS 69	AIR	103	Concentration Feed C (Material B)	**0.80**	0.50	0.15	mol%	40%

Figure 3.22 shows time-trend plots for alarm data of ***XMEAS 1*** and ***10*** by using alarm thresholds and deadbands from fourth revision. In this test the disturbance ***IDV6*** is initiated with a scaling of 100% and a duration of 5h. Both depicted PVs tend to toggle between the active and inactive alarm state with varying time intervals, which results in a normalization phase duration of at least 24 hours. A similar behavior can be observed during ***IDV8***. This phenomenon will be further investigated, as it primarily applies to these particular PVs. Other variables also show a behavior, where the normalization phase takes longer than the ARC phase, since the normalization propagates slower through the process. In comparison, ***XMEAS 1*** and ***10*** oscillate for a significantly longer time period than other PVs between the HI-Alarm and LO-Alarm state, as well as the inactive alarm condition. There are two reasons for that:

1. ***XMEAS 1*** and ***10*** have relatively low steady state values during normal operation. Therefore, small deviations can lead to alarm activations.
2. ***XMEAS 1*** and ***10*** both are controlled and are part of several control loops, where they are used to control other variables, e.g., composition of feed A or reactor pressure.

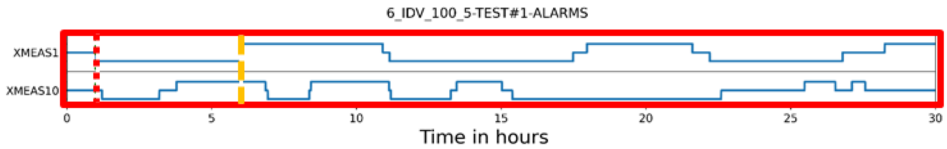

Figure 3.22: Time-trend plots for alarm data of XMEAS 1 and 10 (IDV6 100% 5h) using alarm thresholds and deadbands from 4th revision

Time-trend plots of ***IDV6*** in Figure 3.23 and Figure 3.24 facilitate comparisons of ***XMEAS 1*** and ***XMEAS 10*** (a) with their corresponding valve position variables ***XMV 3*** and ***XMV 6*** (b), respectively. Due to the effective causal dependency between a valve opening and the respective inlet or outlet flow, ***XMEAS 1*** and ***XMV 3,*** as well as ***XMEAS 10*** and ***XMV 6*** demonstrate a similar behavior regarding their process signals. The corresponding alarm variables show a disproportional and undesired deviation. After the termination of ***IDV6*** (disturbance of ***XMEAS 1***), ***XMV 3*** switches between the HI- and LO-Alarm state, in order to control the inlet flow of feed A. At around nine hours into the normalization phase (15 hours total), ***XMV 3*** starts to oscillate around the initial steady-state value with a relatively small range. This leads to no alarm activations for the remaining time of this test, whereas ***XMEAS 1*** keeps toggling between both implemented alarm states. This applies analogously to ***XMEAS 10*** and ***XMV 6***. From this discrepancy one can conclude that alarm thresholds for ***XMEAS 1*** (***XMEAS 10***) have to be adapted to those of ***XMV 3*** (***XMV 6***), so that in case of an abnormal situation both variables are simultaneously in an active alarm condition. If one of these variables is externally disturbed and therefore the root cause of an abnormal situation, it will be possible to distinguish this case as both variables should show contrarious alarm states (HI and LO or LO and HI). Table 3.11 summarizes the adjusted alarm thresholds.

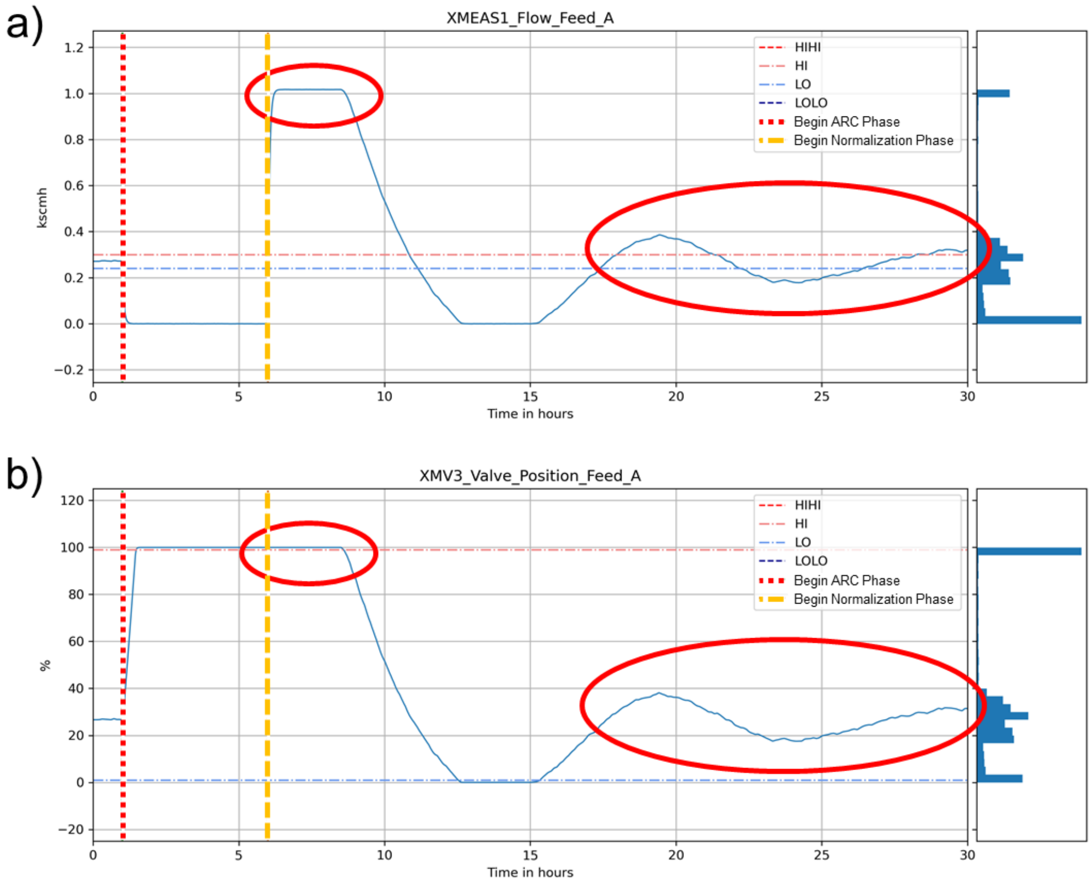

Figure 3.23: Time-trend plots for process data (IDV6 100% 5h) using alarm thresholds and deadbands from 4th revision: a) XMEAS 1, b) XMV 3

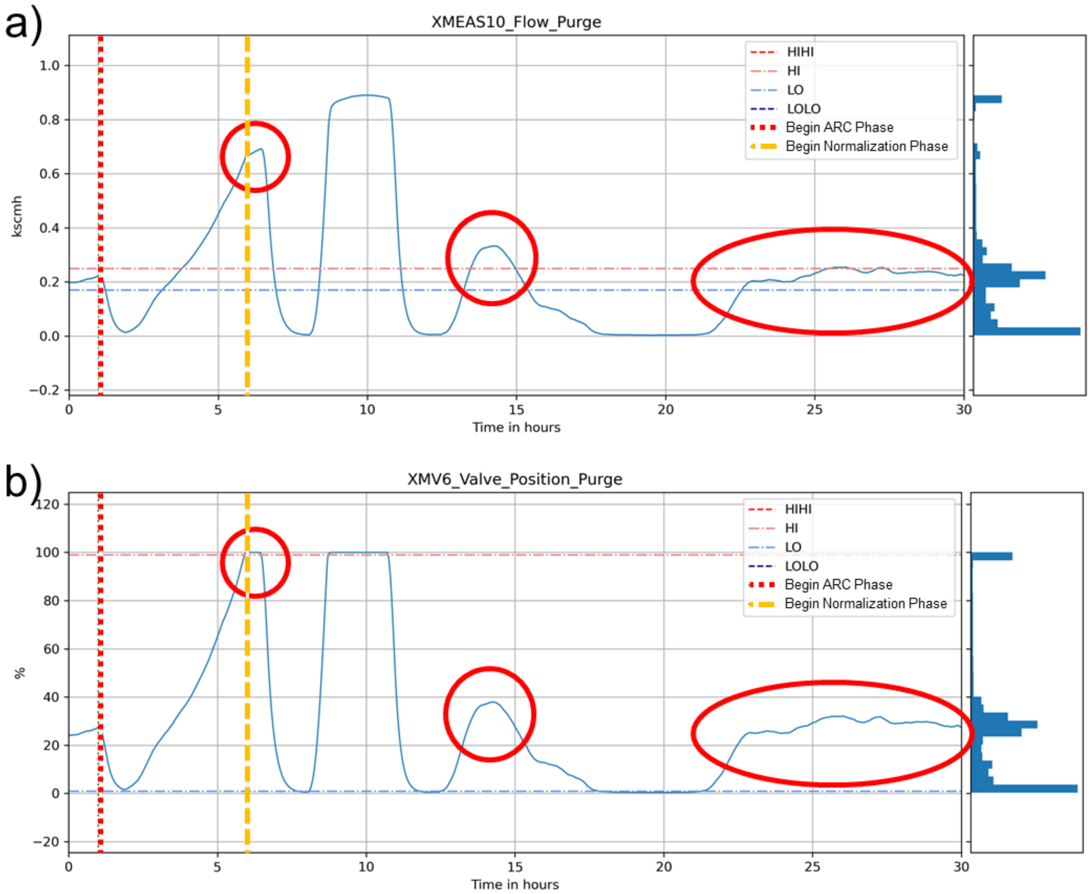

Figure 3.24: Time-trend plots for process data (IDV6 100% 5h) using alarm thresholds and deadbands from 4th revision: a) XMEAS 10, b) XMV 6

Table 3.11: Alarm thresholds 5th revision for XMEAS 1 and 10

ID	Type	Tag [ARR17]	Description	HI-Alarm	Normal	LO-Alarm	Unit
XMEAS 1	FIR	100	Flow Feed A	0.95	0.27	0.05	kscmh
XMEAS 10	FIR	115	Flow Purge	0.65	0.21	0.05	kscmh

In addition to the adaption of ***XMEAS 32***, all other PVs, which represent chemical composition of the purge outlet, will be adjusted as well, as they tend to trigger alarms during normal regulatory oscillations of ***XMEAS 10*** (purge outlet flow). Therefore, HI- and LO-Alarm thresholds are increased to values ±15% of the respective steady-state value. The resulting alarm thresholds for ***XMEAS 29*** to ***31*** and ***XMEAS 33*** to ***36*** are shown in Table 3.12.

Table 3.12: Alarm thresholds 5th revision for XMEAS 29 to 31 and XMEAS 33 to 36

ID	Type	Tag [ARR17]	Description	HI-Alarm	Normal	LO-Alarm	Unit
XMEAS 29	AIR	003	Concentration Purge (Material A)	37.61	32.70	27.80	mol%
XMEAS 30	AIR	003	Concentration Purge (Material B)	24.98	21.72	18.46	mol%
XMEAS 31	AIR	003	Concentration Purge (Material C)	15.20	13.22	11.24	mol%
XMEAS 33	AIR	003	Concentration Purge (Material E)	18.53	16.11	13.69	mol%
XMEAS 34	AIR	003	Concentration Purge (Material F)	6.21	5.40	4.59	mol%
XMEAS 35	AIR	003	Concentration Purge (Material G)	7.68	6.68	5.68	mol%
XMEAS 36	AIR	003	Concentration Purge (Material H)	3.75	3.26	2.77	mol%

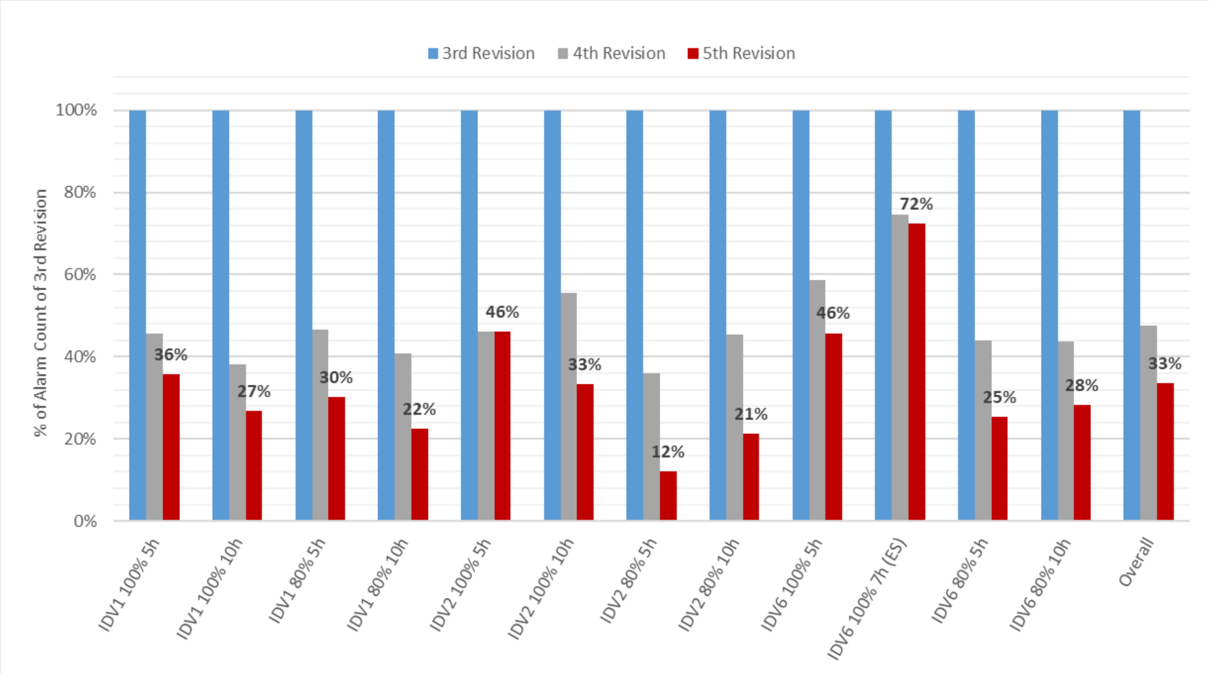

Figure 3.25: Bar-plot showing percentage of alarm count for abnormal situations using alarm design from 3rd, 4th and 5th revision and alarm count of 3rd revision as a base value

In order to evaluate the adjusted alarm thresholds and alarm management techniques, Figure 3.25 illustrates reduction of alarm count over all examined abnormal situations using the alarm design from third, fourth and fifth revision. The shown bar-plots represent the remaining percentage of initial alarm count using the alarm design from the third revision as a base-value (e.g., a value of 36% for fifth revision in *"**IDV1** 100% 5h"* implies a reduction of 64% compared to third revision). The displayed numerical value refers to fifth revision. The overall effectiveness of implemented measures can be seen on the rightmost bar-plots. Implementing alarm deadbands in the fourth revision accounts for an alarm count reduction of more than 50%. An additional reduction of 15% can be achieved by implementing the adjustments from the fifth revision, which activate only one third of the initial alarm count. Furthermore, no chattering or fleeting alarms arise using alarm thresholds and alarm management techniques from the fifth revision.

A comprehensive list of all alarm thresholds deriving from this fifth and final revision can be found in Appendix C.

4 Tests

4.1 Root Cause Disturbances

[DoVo93][DoVo93] describes 20 different root cause disturbances (***IDV1*** to ***IDV20***), each caused by manipulating one or more process variables, which leads to local or plantwide abnormal situations. In addition, another eight root cause disturbances were presented in [BRJ15] The herein used TEP simulation model allows for a scaling of these root cause disturbances between 0% and 100% using a disturbance activation flag (in terms of scaling the disturbance of the initially manipulated variables) [BRJ15][BRJ15]. [Arr17] describes ten additional disturbances initiated by full closure of a single control valve. Here, a 100% scaling represents full closure, whereas the corresponding setpoint is 0%.

Root cause disturbances can either arise in a single abnormal situation or they can emerge temporally overlapping, simultaneously or sequentially. Due to high interconnection and causal dependencies in this TEP simulation model, it is impossible or at least unlikely to observe two simultaneously occurring abnormal situations, which can be classified as causal independent in their respective effect on the process. Instead, if more than one root cause disturbance is active, they are

part of one abnormal situation. Abnormal situations, which consist of more than one root cause disturbance are part of the additional tests, which are presented in Section 5.
The following root cause disturbance types are described in [DoVo93] and [BRJ15]:

1. ***Step:*** Sudden variation of a single PV or a combination of PVs in terms of shifting the respective steady-state value.
2. ***Random variation:*** Continuous random variation of a single PV in terms of shifting the respective variance of the signal.
3. ***Slow drift:*** Random and slow-growing variation of reaction kinetics.
4. ***Sticking:*** Randomly occurring stick-slip phenomenon in one of the controlled valves.
5. ***Unknown:*** Originally specified as ***unknown*** by [DoVo93], [BRJ15] describes them as random deviation in heat transfer in stripper, condenser and reactor.

This case study will be limited to root cause disturbances of type ***step***, as all others do not generate similar alarm sequences, due to their random behavior. An overview of all selected root cause disturbances can be found in Table 4.1 (IDV) and Table 4.2 (XMV).

Table 4.1: Selection of IDV-root cause disturbances from [DoVo93] and [BRJ15]

IDV	Type	Manipulated Variable	Description of the Manipulated Variable
1	Step	XMEAS 68, 70	Concentration Feed C (Materials A und C)
2	Step	XMEAS 69	Concentration Feed C (Material B)
3	Step	XMEAS 43	Temperature Feed D
4	Step	XMEAS 46	Temperature Cooling Water Inlet Reactor
5	Step	XMEAS 48	Temperature Cooling Water Inlet Condenser
6	Step	XMEAS 1	Flow Feed A
7	Step	-	Pressure Feed C

Table 4.2: Selection of XMV-root cause disturbances from [Arr17]

XMV	Type	Description of the Manipulated Variable
1	Step	Valve Position Feed D
2	Step	Valve Position Feed E
3	Step	Valve Position Feed A
4	Step	Valve Position Feed C
5	Step	Valve Position Compressor Re-Cycle
6	Step	Valve Position Purge
7	Step	Valve Position Underflow Separator
8	Step	Valve Position Underflow Stripper
9	Step	Valve Position Stripper Steam
10	Step	Valve Position Cooling Water Outlet Reactor
11	Step	Valve Position Cooling Water Outlet Condenser

[DoVo93] recommends a simulation time of 24 to 48 hours regarding ***IDVs 1*** to ***7***. Other relevant publications, e.g. [BRJ15], [Arr17] or [MaLi17], do not provide any suggestions regarding simulation times. [Kir19] states using a disturbance duration of 7.5 hours.

Table 4.3: Analysis of IDV-root cause disturbances IDVs 1 to 7

IDV	Manipulated Variable	Description of the Manipulated Variable	Emergency Shutdown (ESD) or Normalization (RTN)	Count of PVs/MVs in Alarm Condition
1	XMEAS 68, 70	Concentration Feed C (Materials A und C)	**RTN** after **14h 45min**	15
2	XMEAS 69	Concentration Feed C (Material B)	-	5
3	XMEAS 43	Temperature Feed D	-	1
4	XMEAS 46	Temperature Cooling Water Inlet Reactor	-	1
5	XMEAS 48	Temperature Cooling Water Inlet Condenser	-	2
6	XMEAS 1	Flow Feed A	**ESD** after **7h**	32
7	-	Pressure Feed C	-	0

Table 4.3 gives an overview of the analysis results of ***IDVs 1*** to ***7*** with a targeted simulation time of 48 hours. ***IDV1*** shows a permanent return to normal for all initially activated alarms after 14 hours and

45 minutes, while the root cause disturbance is still active. Hence, only those ***IDV1*** situations with a maximum duration of ten hours will be considered. ***IDV6*** results in an emergency shutdown after simulating for seven hours, which is true for a scaling of 100%. Reducing the root cause disturbance of ***XMEAS 1*** is followed by an altered abnormal behavior. A scaling of 90% results in an emergency shutdown after approximately 12 hours and 15 minutes, whereas a scaling of 80% causes no shutdown during 48 hours of simulation. However, the latter leads to an emergency shutdown during the normalization phase, if the disturbance is terminated after more than 15 hours. Thus, a scaling of 100%, 90%, and 80% will be considered in this TEP dataset. Furthermore, only ***IDVs 1, 2, 5,*** and ***6*** are show a suitable number of PVs and MVs in alarm condition (>1), which can be used for advanced alarm management methods, e.g., like alarm grouping or prediction of alarms. Therefore, Table 4.4 lists a selection of IDVs further considered for the test design.

Table 4.4: Selection of IDV-root cause disturbances for test design

IDV	Manipulated Variable	Description of the Manipulated Variable
1	XMEAS 68, 70	Concentration Feed C (Materials A und C)
2	XMEAS 69	Concentration Feed C (Material B)
5	XMEAS 48	Temperature Cooling Water Inlet Condenser
6	XMEAS 1	Flow Feed A

Table 4.5 gives an overview of the analysis results of all considered XMV-root cause disturbances. Manipulation of ***XMVs 5*** and ***9*** have no effect on alarm activations, because full closure is the defined setpoint of these values as described in [RIC96]. Disturbances, which arise from ***XMVs 1, 7, 8, 10*** and ***11*** result in an emergency shutdown after only a few minutes. Hence, they are not suitable for methods such as alarm prediction and will not be considered in this dataset. ***XMVs 2, 3, 4*** and ***6*** show suitable durations, furthermore Table 4.6 shows that for these XMV-root cause disturbances the individual number of PVs and MVs in alarm condition is in all cases >1. Therefore, these four root cause disturbances are selected for further test design.

Table 4.5: Analysis of XMV-root cause disturbances XMVs 1 to 11

XMV	Description of the Manipulated Variable	Emergency Shutdown (ESD)
1	Valve Position Feed D	**11** min
2	Valve Position Feed E	**33** min
3	Valve Position Feed A	**7** h **0** min
4	Valve Position Feed C	**33** min
5	Valve Position Compressor Re-Cycle	no ESD, as 0% is the Setpoint
6	Valve Position Purge	**5** h **36** min
7	Valve Position Underflow Separator	**10** min
8	Valve Position Underflow Stripper	**8** min
9	Valve Position Stripper Steam	no ESD, as 0% is the Setpoint
10	Valve Position Cooling Water Outlet Reactor	**7** min
11	Valve Position Cooling Water Outlet Condenser	**14** min

Table 4.6: Analysis and selection of XMV-root cause disturbances for test design

XMV	Description of the Manipulated Variable	Count of PVs/MVs in Alarm Condition
2	Valve Position Feed E	20
3	Valve Position Feed A	32
4	Valve Position Feed C	30
6	Valve Position Purge	9

4.2 Test Design

To the best of the authors knowledge, no publication on the TEP took normalization phases, which are successors to an effectual operator intervention or a random termination of the root cause disturbance, into account. Due to complex interconnections and causal dependencies, it is possible for a normalization phase to take longer and arise more alarms than the corresponding ARC phase, which can confuse the operator albeit his reasonable primary intervention and lead to misguided follow-up actions. Therefore, it is of utter importance to take normalization phases into consideration.

In order to allow for alarm subsequence detection methods to be tested upon this dataset, tests will be designed, which consist of consecutive non-overlapping abnormal situations. From this it follows that all abnormal situations, except the last one, are obliged to have a normalization phase, which needs to return to a state of no active alarms (normal operation) before the next disturbance can be initiated.

The exact moment in time a normalization phase starts depends on non-causal external interventions (or at least unobserved causalities), e.g., operator actions, which cannot be easily predicted. It is necessary to distinguish between an ARC phase and the correspondent normalization phase, otherwise one could falsely predict the normalization of the process as well as accompanied alarm activations and deactivations, because this return to normal has been observed as a consecutive event to the initial ARC phase. Furthermore, the following test design aims to provide a suitable amount of normalization sets, starting at different points in time, in order to analyze whether it is possible to find similarities in them and to identify them during operation, hence being able to predict future trends.

Table 4.7 gives an overview of the maximum duration of all four selected IDV-root cause disturbances and the respective variation in time for the beginning of the normalization phase (or termination of the root cause disturbance). The resultant test structure for ***IDV1*** can be found in Table 4.8 with a total of ten different tests, each defined by a specific start time of the normalization phase, which corresponds to the duration of the initial root cause disturbance. For example, test No. 1 is composed of a root cause disturbance, which lasts for ten hours, followed by a normalization phase. Whereas in test No. 10 the normalization phase starts after seven hours and 45 minutes. Each of the tests will be conducted three times. This approach applies analogously to ***IDVs 2, 5*** and ***6 (80%)***.

Table 4.7: Duration of longest ARC phases and variation in time for the begin of the normalization phase for the selection of IDV-root cause disturbances

IDV	Manipulated Variable	Description of the Manipulated Variable	Duration of Longest ARC Phase	Variation for Begin of Normalization Phase
1	XMEAS 68, 70	Concentration Feed C (Materials A und C)	10h	15min
2	XMEAS 69	Concentration Feed C (Material B)	48h	30min
5	XMEAS 48	Temperature Cooling Water Inlet Condenser	48h	30min
6 (80%)	XMEAS 1	Flow Feed A	15h	15min

Table 4.8: Test-structure and begin of the normalization phase for IDV 1

IDV	Test No.	Begin of Normalization
1	1	10h 00min
	2	9h 45min
	3	9h 30min
	4	9h 15min
	5	9h 00min
	6	8h 45min
	7	8h 30min
	8	8h 15min
	9	8h 00min
	10	7h 45min

Each of the four XMV-root cause disturbances, as well as ***IDVs 6 (90%)*** and ***6 (100%)*** will be conducted ten times, since they are causing an emergency shutdown with no need for variation of the normalization (the root cause disturbance is not terminated). Altogether this adds up to a total number of 180 abnormal situation tests including 60 tests, which cause an emergency shutdown. As the latter can only be placed at the end of a test, 60 test will be conducted, each consisting of three single abnormal situations (see Table 4.9 and Table 4.10).

Table 4.9: Tests no. 1 to 30

Test	1. Abnormal Situation	2. Abnormal Situation	3. Abnormal Situation
1	IDV 1 (10h 00min)	IDV 2 (47h 00min)	XMV 2
2	IDV 5 (47h 00min)	IDV 1 (9h 30min)	XMV 2
3	IDV 1 (9h 00min)	IDV 6 (80%) (13h 00min)	XMV 2
4	IDV 2 (44h 30min)	IDV 1 (8h 30min)	XMV 2
5	IDV 1 (8h 00min)	IDV 5 (46h 30min)	XMV 2
6	IDV 2 (46h 30min)	IDV 6 (80%) (13h 15min)	XMV 2
7	IDV 5 (44h 00min)	IDV 2 (44h 00min)	XMV 2
8	IDV 2 (47h 30min)	IDV 6 (80%) (13h 30min)	XMV 2
9	IDV 5 (45h 00min)	IDV 6 (80%) (14h 00min)	XMV 2
10	IDV 6 (80%) (14h 15min)	IDV 5 (47h 30min)	XMV 2
11	IDV 1 (9h 30min)	IDV 6 (80%) (12h 45min)	XMV 3
12	IDV 5 (46h 00min)	IDV 1 (10h 00min)	XMV 3
13	IDV 1 (8h 30min)	IDV 2 (45h 00min)	XMV 3
14	IDV 6 (80%) (13h 15min)	IDV 1 (9h 00min)	XMV 3
15	IDV 1 (7h 45min)	IDV 6 (80%) (15h 00min)	XMV 3
16	IDV 2 (48h 00min)	IDV 5 (48h 00min)	XMV 3
17	IDV 5 (43h 30min)	IDV 2 (45h 30min)	XMV 3
18	IDV 2 (44h 00min)	IDV 6 (80%) (14h 45min)	XMV 3
19	IDV 6 (80%) (14h 00min)	IDV 5 (47h 00min)	XMV 3
20	IDV 5 (44h 30min)	IDV 6 (80%) (13h 00min)	XMV 3
21	IDV 1 (10h 00min)	IDV 5 (45h 30min)	XMV 4
22	IDV 2 (47h 00min)	IDV 1 (9h 30min)	XMV 4
23	IDV 1 (9h 00min)	IDV 6 (80%) (13h 30min)	XMV 4
24	IDV 6 (80%) (14h 30min)	IDV 1 (8h 30min)	XMV 4
25	IDV 1 (8h 00min)	IDV 2 (46h 00min)	XMV 4
26	IDV 2 (44h 30min)	IDV 5 (43h 30min)	XMV 4
27	IDV 5 (46h 30min)	IDV 2 (47h 30min)	XMV 4
28	IDV 2 (43h 30min)	IDV 6 (80%) (14h 30min)	XMV 4
29	IDV 5 (48h 00min)	IDV 6 (80%) (12h 45min)	XMV 4
30	IDV 6 (80%) (15h 00min)	IDV 5 (44h 00min)	XMV 4

For each test it has to be determined at which point in time the contained root cause disturbances are ought to be initiated and terminated, respectively. Therefore, the rounded up maximum normalization phase duration of all considered root cause disturbance types was measured by simulating all single tests:

- ***IDV1:*** 15h
- ***IDV2:*** 23h
- ***IDV5:*** 1h
- ***IDV6 (80%):*** 46h

The end of a normalization phase is defined as the first point in time with no active alarms, resulting in a stable normal operation of the process. In a next step, the start and end times for all ARC phases and their respective normalization phases have to be calculated. Each test starts with a normal operation period of one hour, followed by a first abnormal situation. For the time distance between termination of one and start of the next root cause disturbance, , the respective maximum normalization phase duration added by a random period between one and ten hours is used. This assures statistical variation in temporal distance between abnormal situations. Appendix D gives a comprehensive overview of the conducted tests no. 1 to no. 60.

Table 4.10: Tests no. 31 to 60

Test	1. Abnormal Situation	2. Abnormal Situation	3. Abnormal Situation
31	IDV 1 (9h 45min)	IDV 6 (80%) (14h 15min)	XMV 6
32	IDV 6 (80%) (14h 45min)	IDV 1 (9h 15min)	XMV 6
33	IDV 1 (8h 45min)	IDV 2 (48h 00min)	XMV 6
34	IDV 5 (48h 00min)	IDV 1 (8h 15min)	XMV 6
35	IDV 2 (45h 30min)	IDV 1 (7h 45min)	XMV 6
36	IDV 2 (46h 00min)	IDV 5 (45h 00min)	XMV 6
37	IDV 5 (44h 30min)	IDV 2 (47h 00min)	XMV 6
38	IDV 2 (43h 30min)	IDV 6 (80%) (13h 45min)	XMV 6
39	IDV 6 (80%) (13h 30min)	IDV 5 (46h 00min)	XMV 6
40	IDV 5 (46h 30min)	IDV 6 (80%) (13h 15min)	XMV 6
41	IDV 1 (9h 15min)	IDV 5 (45h 00min)	IDV 6 (100%)
42	IDV 2 (46h 30min)	IDV 1 (9h 45min)	IDV 6 (100%)
43	IDV 1 (8h 15min)	IDV 6 (80%) (13h 45min)	IDV 6 (100%)
44	IDV 5 (47h 30min)	IDV 1 (8h 45min)	IDV 6 (100%)
45	IDV 6 (80%) (12h 45min)	IDV 1 (8h 00min)	IDV 6 (100%)
46	IDV 2 (45h 30min)	IDV 6 (80%) (14h 15min)	IDV 6 (100%)
47	IDV 5 (43h 30min)	IDV 2 (44h 30min)	IDV 6 (100%)
48	IDV 6 (80%) (15h 00min)	IDV 2 (47h 30min)	IDV 6 (100%)
49	IDV 2 (45h 00min)	IDV 5 (47h 00min)	IDV 6 (100%)
50	IDV 5 (45h 30min)	IDV 6 (80%) (13h 45min)	IDV 6 (100%)
51	IDV 1 (9h 45min)	IDV 2 (45h 00min)	IDV 6 (90%)
52	IDV 5 (44h 30min)	IDV 1 (9h 15min)	IDV 6 (90%)
53	IDV 1 (8h 45min)	IDV 6 (80%) (14h 00min)	IDV 6 (90%)
54	IDV 2 (43h 30min)	IDV 1 (8h 15min)	IDV 6 (90%)
55	IDV 6 (80%) (13h 00min)	IDV 1 (7h 45min)	IDV 6 (90%)
56	IDV 2 (46h 00min)	IDV 5 (46h 00min)	IDV 6 (90%)
57	IDV 6 (80%) (14h 30min)	IDV 2 (44h 00min)	IDV 6 (90%)
58	IDV 5 (45h 30min)	IDV 2 (46h 30min)	IDV 6 (90%)
59	IDV 2 (48h 00min)	IDV 5 (47h 30min)	IDV 6 (90%)
60	IDV 5 (44h 00min)	IDV 6 (80%) (14h 45min)	IDV 6 (90%)

5 Additional Tests

5.1 Root Cause Disturbances

The herein presented additional tests include abnormal situations, which consist of one and more root cause disturbances.

Based on the in-depth analysis and root cause disturbance selection carried out in Section 4, this Section considers root cause disturbances described in Table 4.4 (IDV) and Table 4.6 (XMV). Furthermore, in order to extend the previously designed tests, these root cause disturbances are used with the following settings:

1. IDV-root cause disturbances with a scaling below 100%.
2. XMV-root cause disturbances with a scaling below 100% (valve opening greater than 0%).
3. IDV- and XMV-root cause disturbances with a short activation time.
4. Combined IDV-root cause disturbances comprised of more than one concurrent root cause disturbance.

Regarding ***1.:***
In Section 4, root cause disturbances IDVs 1, 2, and 5 were initiated with a scaling of 100%, as well as IDV 6 with scaling of 100%, 90% and 80%. The herein presented additional tests extend these scaling settings by utilizing a scaling of 95% for IDVs 1, 2, and 5, and a scaling of 75% for IDV 6, thus enabling similarity analysis between alarm sequences of identical IDVs with different disturbance scaling. Alike Section 4, the following activation durations for the underlying root cause disturbances are used: 10 hours for IDV 1, 48 hours for IDVs 2 and 5, as well as 15 hours for IDV 6.

Regarding ***2.:***
In addition to a suggested XMV scaling of 100% [ARR17], further values of 97.5% and 95% are considered for all XMV-root cause disturbances. As shown in Section 4, the TEP simulation model is

sensitive to this kind of root cause disturbances, thus all three values result in an emergency shutdown after a certain time has elapsed. The average time for each XMV-root cause disturbance over 10 tests can be seen in Table 5.1.

Table 5.1: Average time calculated over ten tests until an emergency shutdown (ESD) occurs using different XMV-root cause disturbances and three disturbance scaling

XMV	Description of the Disturbed Variable	Average Time until ESD for 100% Scaling	Average Time until ESD for 97.5% Scaling	Average Time until ESD for 95% Scaling
2	Valve Position Feed E	0.543 h	0.567 h	0.590 h
3	Valve Position Feed A	7.156 h	7.780 h	8.881 h
4	Valve Position Feed C	0.545 h	0.507 h	0.509 h
6	Valve Position Purge	5.763 h	6.434 h	7.216 h

ä

Regarding ***3.:***
Following the recommendations given in [DoVo93], Section 4 focusses on situations that are characterized by relatively long ARC phases. Hence, this addition considers the following root cause disturbances with comparatively short ARC phases of one hour each:

- IDV 1 with a disturbance scaling of 95%
- IDV 5 with a disturbance scaling of 100%
- XMV 3 with a disturbance scaling of 97.5%
- XMV 6 with a disturbance scaling of 95%

Regarding ***4.:***
[Arr17] describes different abnormal situations, each composed of two or three concurrent root cause disturbances. Three of these combined IDV-root cause disturbances, more precisely those which are showing a sufficient number of triggered alarms and are not resulting in a promptly ESD, are selected for test design. In [Arr17], two different types are used regarding initiation of the corresponding root cause disturbances. They are either initiated simultaneously or with a time gap of 15 minutes. As this dataset also considers normalization phases, two alike types are used regarding termination of the considered root cause disturbances. Table 5.2 shows all herein conducted IDV combinations and their corresponding types. Two common parameter settings are a combined ARC phase that lasts for ten hours and a disturbance scaling of 100%.

Table 5.2: Used combined IDV-root cause disturbances composed of more than one concurrent root cause disturbance and their corresponding settings regarding the initiation and termination of the root cause disturbances

IDVs	Disturbed Variables	Description of the Disturbed Variable	Type	Initiation of Disturbance	Termination of Disturbance
1, 2	XMEAS 68, 69, 70	Concentration Feed C (Materials A, B and C)	T1	Simultaneous	Simultaneous
			T2	15min gap (IDV1 than IDV2)	Simultaneous
			T3	15min gap (IDV2 than IDV1)	Simultaneous
			T4	Simultaneous	15min gap (IDV1 than IDV2)
			T5	Simultaneous	15min gap (IDV2 than IDV1)
1, 5	XMEAS 48, 68, 70	Concentration Feed C (Materials A and C), Temperature Cooling Water Inlet Condenser	T1	Simultaneous	Simultaneous
			T2	15min gap (IDV1 than IDV5)	Simultaneous
			T3	15min gap (IDV5 than IDV1)	Simultaneous
			T4	Simultaneous	15min gap (IDV1 than IDV5)
			T5	Simultaneous	15min gap (IDV5 than IDV1)
1, 2, 5	XMEAS 48, 68, 69, 70	Concentration Feed C (Materials A, B and C), Temperature Cooling Water Inlet Condenser	-	Simultaneous	Simultaneous

5.2 Test Design

In order to allow for alarm subsequence detection methods to be tested upon this dataset, tests are designed, which consist of consecutive non-overlapping abnormal situations. From this it follows that all abnormal situations, except the last one, are obliged to have a normalization phase, which needs to return to a state of entirely inactive alarms (normal operation) before the next root cause disturbance can be initiated.

Table 5.3: Overview over all abnormal situations and their respective durations as well as number of conducted tests

Root Cause Disturbance	Description of the Disturbed Variable	Scaling	Duration of ARC Phase	Maximum Duration of Normalisation Phase	Number of Conducted Tests
IDV 1	Concentration Feed C (Materials A and C)	95%	10.0h	15.0h	5
IDV 1	Concentration Feed C (Materials A and C)	95%	1.0h	6.5h	5
IDV 2	Concentration Feed C (Material B)	95%	48.0h	23.0h	5
IDV 5	Temperature Cooling Water Inlet Condenser	95%	48.0h	0.1h	5
IDV 5	Temperature Cooling Water Inlet Condenser	100%	1.0h	0.1h	5
IDV 6	Flow Feed A	75%	15.0h	46.0h	5
IDVs 1, 2	Concentration Feed C (Materials A, B and C)	100%	10.0h	25.0h	15 (3 per setting)
IDVs 1, 5	Concentration Feed C (Materials A and C), Temperature Cooling Water Inlet Condenser	100%	10.0h	15.0h	15 (3 per setting)
IDVs 1, 2, 5	Concentration Feed C (Materials A, B and C), Temperature Cooling Water Inlet Condenser	100%	10.0h	25.0h	10
XMV 2	Valve Position Feed E	97.5%	until ESD	-	5
XMV 2	Valve Position Feed E	95%	until ESD	-	5
XMV 3	Valve Position Feed A	97.5%	until ESD	-	5
XMV 3	Valve Position Feed A	95%	until ESD	-	5
XMV 3	Valve Position Feed A	97.5%	1.0h	2.0h	5
XMV 4	Valve Position Feed C	97.5%	until ESD	-	5
XMV 4	Valve Position Feed C	95%	until ESD	-	5
XMV 6	Valve Position Purge	97.5%	until ESD	-	5
XMV 6	Valve Position Purge	95%	until ESD	-	5
XMV 6	Valve Position Purge	95%	1.0h	1.5h	5

Table 5.3 gives an overview of the herein utilized abnormal situations with their respective ARC phase and maximum normalization phase duration. The latter was measured over the given number of tests. Altogether this adds up to a total number of 120 abnormal situations, including 40 tests that are causing an emergency shutdown. As the latter can only be placed at the end of a scenario, 40 test are conducted, each consisting of three abnormal situations. Each test starts with a normal operation period of 30 minutes, followed by a first abnormal situation. For the time distance between termination of one and start of the next root cause disturbance, the respective maximum normalization duration amended by a random period between one and five hours will be used. This assures statistical variation in temporal distance between abnormal situations Appendix D gives a comprehensive overview of the tests no. 1 to no. 100.

6 Dataset Layout

6.1 Overview

Figure 6.1 shows the global layout for this TEP dataset. Two folders were generated, which contain the aforementioned tests and the corresponding extracted abnormal situations.

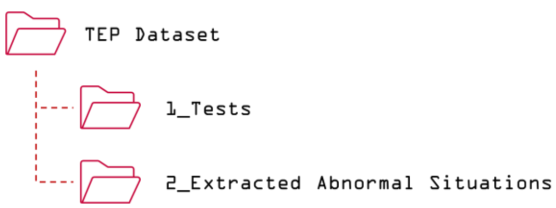

Figure 6.1: Dataset layout

6.2 Tests

Figure 6.2 summarizes the data collected from the tests no. 1 to no. 100. Each test is saved in a separate folder labelled with the respective test number (1 to 100). The subsidiary structure is divided into three folders, one for the original data without implementation of any alarm management techniques, one for the filtered data and one that contains data with implemented filters and alarm deadbands. Each of these folders includes four Excel-Files, which are explained in detail in Section 2. The order of columns in these files follows directly descending order in the corresponding tables:

- ***ALARMS***.xlsx: Alarm threshold table in Appendix C
- ***SIMOUT***.xlsx: Process variables in Table 2.2
- ***XMV***.xlsx: Manipulated variables in Table 2.3

It has to be noted that for all three folders, *"1_Original"*, *"2_Filter"* and *"3_Deadband"*, the exact same alarm thresholds have been used, which can be found in Appendix C. Furthermore, a text file is included, which contains the specific random number generator seed, which can be used to reproduce the generated simulation data.

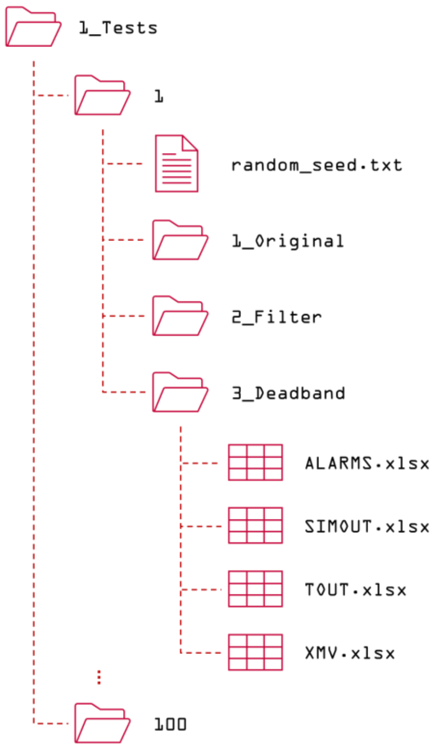

Figure 6.2: Dataset layout: Tests

6.3 Extracted Abnormal Situations

In order to provide pre-processed data for analysis and investigation of the aforementioned complex test, a sub-dataset of extracted abnormal situations is included in this dataset. For this purpose, only data from folder *"3_Deadband"* are considered. Figure 6.3 shows the corresponding layout. The following folders are part of this sub-dataset:

- ***"1_ARC Phases":*** Starting with one hour of normal operation and ending when either normalization starts (termination of the root cause disturbance), or an emergency shutdown occurs.
- ***"2_Normalization Phases":*** Starting directly with the termination of the corresponding root cause disturbance and lasting just as long as the maximum normalization phase duration of this specific type amended. Disturbances resulting in an emergency shutdown are not included.
- ***"3_ARC Phases and Normalization Phases":*** Combination of the previous two sub-sets.

Each single abnormal situation is stored in an individual folder tagged with the test number from which it was extracted. The ending ***"-1h"*** refers to abnormal situations with an ARC phase of one hour.

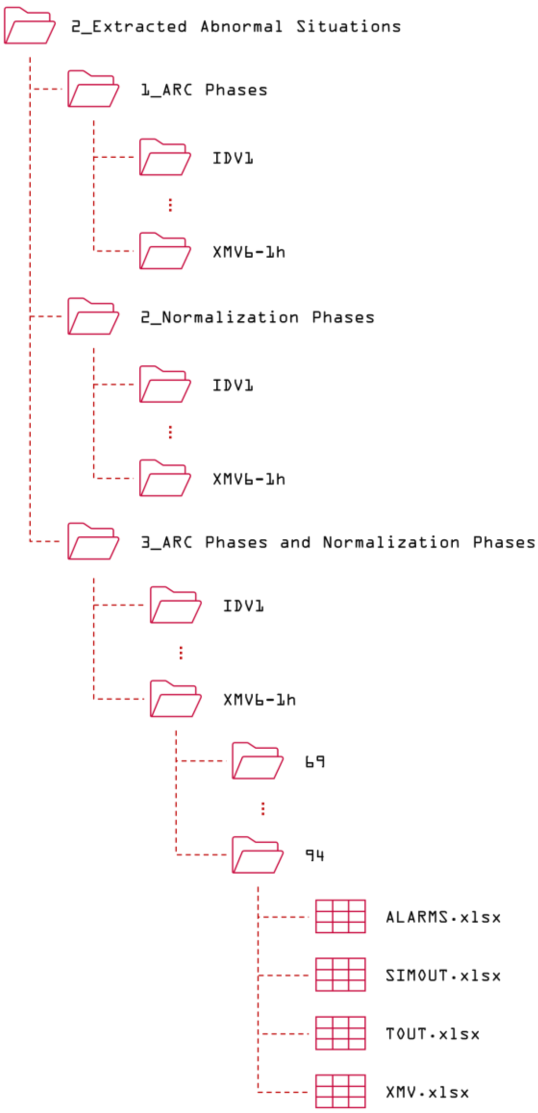

Figure 6.3: Dataset layout: Extracted abnormal situations

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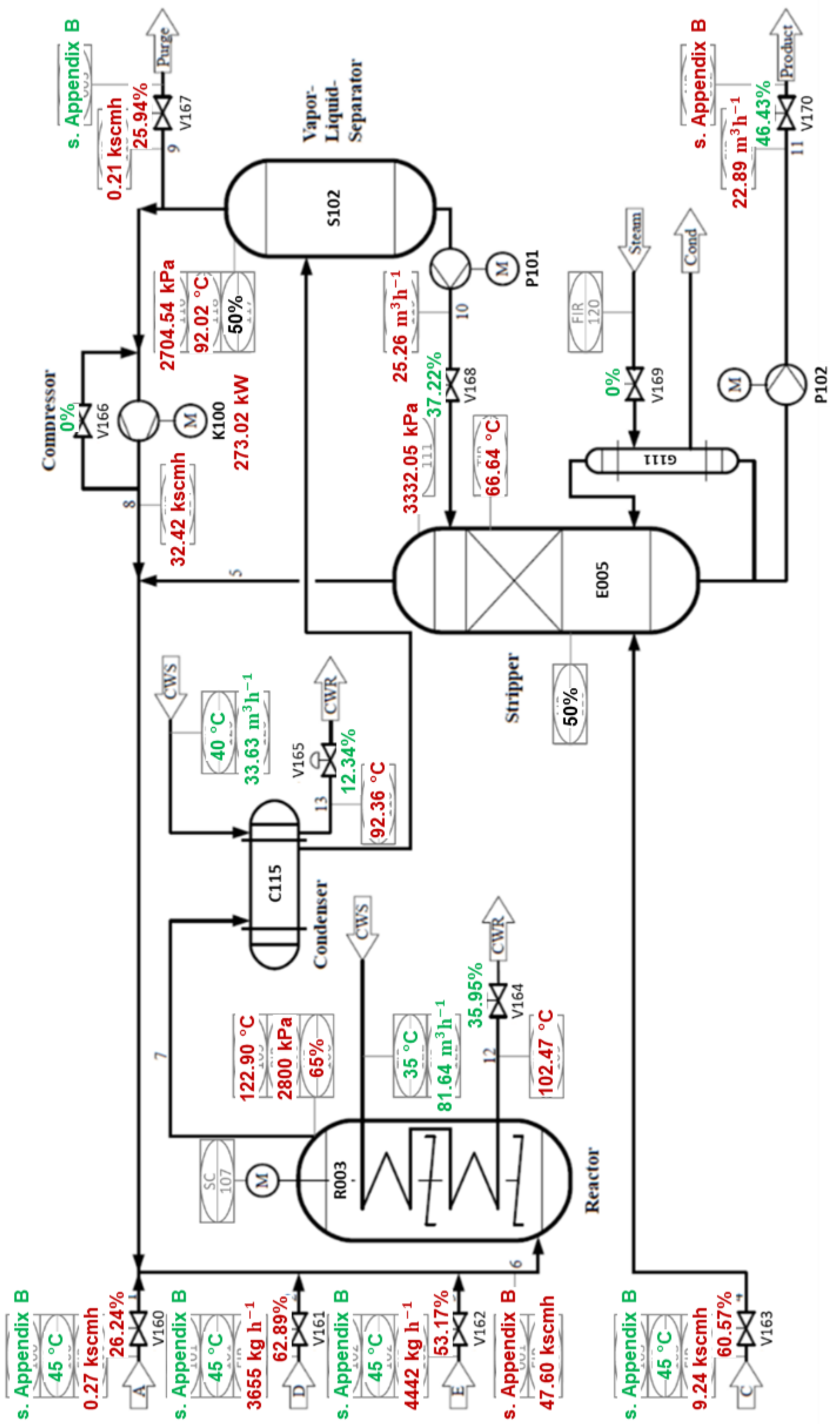
Appendix

A: Comparison of TEP Operating Modes

Adjusted normal operating mode using the control structure from [RIC96] and additional process variables from [BRJ15] compared to normal operating mode 1 ("Base Case") of the TEP according to [DOVO93], [MALI17] and [KIR19].

Steady-State Values: Additional process variables are marked “***green***”, altered values are marked “***red***” and unaltered values are marked “***black***”. Values derive from simulated normal operating mode and additional descriptions in [RIC96].



B: Alarm Thresholds 1st Revision

ID	Type	Tag [ARR17]	Description	HI-Alarm	Normal	LO-Alarm	Unit
XMEAS 1	FIR	100	Flow Feed A	0.30	0.27	0.24	kscmh
XMEAS 2	FIR	101	Flow Feed D	4020.50	3655.00	3289.50	kg h^{-1}
XMEAS 3	FIR	102	Flow Feed E	4886.20	4442.00	3997.80	kg h^{-1}
XMEAS 4	FIR	103	Flow Feed C	10.16	9.24	8.32	kscmh
XMEAS 5	FIR	114	Flow Compressor Re-Cycle	35.66	32.42	29.18	kscmh
XMEAS 6	FIR	104	Flow Reactor Feed	52.36	47.60	42.84	kscmh
XMEAS 7	PIR	108	Pressure Reactor	2895.00	2800.00	0.00	kPa gauge
XMEAS 8	LIR	106	Level Reactor	100.00	65.00	50.00	%
XMEAS 9	TIR	105	Temperature Reactor	150.00	122.90	0.00	°C
XMEAS 10	FIR	115	Flow Purge	0.23	0.21	0.19	kscmh
XMEAS 11	TIR	118	Temperature Separator	101.22	92.02	82.82	°C
XMEAS 12	LIR	117	Level Separator	100.00	50.00	30.00	%
XMEAS 13	PIR	116	Pressure Separator	2974.99	2704.54	2434.09	kPa gauge
XMEAS 14	FIR	119	Underflow Separator	27.79	25.26	22.73	m^3 h^{-1}
XMEAS 15	LIR	110	Level Stripper	100.00	50.00	30.00	%
XMEAS 16	PIR	111	Pressure Stripper	3665.255	3332.05	2998.85	kPa gauge
XMEAS 17	FIR	121	Underflow Stripper	25.18	22.89	20.60	m^3 h^{-1}
XMEAS 18	TIR	111	Temperature Stripper	73.30	66.64	59.98	°C
XMEAS 20	K	100	Compressor Work	300.32	273.02	245.72	kW
XMEAS 21	TIR	109	Temperature Cooling Water Outlet Reactor	112.72	102.47	92.22	°C
XMEAS 22	TIR	113	Temperature Cooling Water Outlet Condenser	101.60	92.36	83.12	°C
XMEAS 23	AIR	001	Concentration Reactor Feed (Material A)	35.42	32.20	28.98	mol%
XMEAS 24	AIR	001	Concentration Reactor Feed (Material B)	16.38	14.89	13.40	mol%
XMEAS 25	AIR	001	Concentration Reactor Feed (Material C)	20.68	18.80	16.92	mol%
XMEAS 26	AIR	001	Concentration Reactor Feed (Material D)	6.59	5.99	5.39	mol%
XMEAS 27	AIR	001	Concentration Reactor Feed (Material E)	18.30	16.64	14.98	mol%
XMEAS 28	AIR	001	Concentration Reactor Feed (Material F)	4.46	4.05	3.65	mol%
XMEAS 29	AIR	003	Concentration Purge (Material A)	35.97	32.70	29.43	mol%
XMEAS 30	AIR	003	Concentration Purge (Material B)	23.89	21.72	19.55	mol%
XMEAS 31	AIR	003	Concentration Purge (Material C)	14.54	13.22	11.90	mol%
XMEAS 32	AIR	003	Concentration Purge (Material D)	0.98	0.89	0.80	mol%
XMEAS 33	AIR	003	Concentration Purge (Material E)	17.72	16.11	14.50	mol%
XMEAS 34	AIR	003	Concentration Purge (Material F)	5.94	5.40	4.86	mol%
XMEAS 35	AIR	003	Concentration Purge (Material G)	7.35	6.68	6.01	mol%
XMEAS 36	AIR	003	Concentration Purge (Material H)	3.59	3.26	2.93	mol%
XMEAS 37	AIR	002	Concentration Underflow Stripper (Material D)	1.00	0.01	-1.00	mol%
XMEAS 38	AIR	002	Concentration Underflow Stripper (Material E)	0.63	0.57	0.51	mol%
XMEAS 39	AIR	002	Concentration Underflow Stripper (Material F)	0.20	0.18	0.16	mol%
XMEAS 40	AIR	002	Concentration Underflow Stripper (Material G)	59.18	53.80	48.42	mol%
XMEAS 41	AIR	002	Concentration Underflow Stripper (Material H)	48.35	43.95	39.56	mol%
XMEAS 42	TIR	100	Temperature Feed A	49.5	45.00	40.50	°C
XMEAS 43	TIR	101	Temperature Feed D	49.5	45.00	40.50	°C
XMEAS 44	TIR	102	Temperature Feed E	49.5	45.00	40.50	°C
XMEAS 45	TIR	103	Temperature Feed C	49.5	45.00	40.50	°C
XMEAS 46	TIR	122	Temperature Cooling Water Inlet Reactor	38.5	35.00	31.50	°C
XMEAS 47	FIR	122	Flow Cooling Water Inlet Reactor	89.804	81.64	73.48	m^3 h^{-1}
XMEAS 48	TIR	123	Temperature Cooling Water Inlet Condenser	44.00	40.00	36.00	°C
XMEAS 49	FIR	123	Flow Cooling Water Inlet Condenser	36.993	33.63	30.27	m^3 h^{-1}
XMEAS 50	AIR	100	Concentration Feed A (Material A)	109.99	99.99	89.99	mol%
XMEAS 51	AIR	100	Concentration Feed A (Material B)	1.00	0.01	-1.00	mol%
XMEAS 52	AIR	100	Concentration Feed A (Material C)	1.00	0.00	-1.00	mol%
XMEAS 53	AIR	100	Concentration Feed A (Material D)	1.00	0.00	-1.00	mol%
XMEAS 54	AIR	100	Concentration Feed A (Material E)	1.00	0.00	-1.00	mol%
XMEAS 55	AIR	100	Concentration Feed A (Material F)	1.00	0.00	-1.00	mol%

ID	Type	Tag [Arr17]	Description	HI-Alarm	Normal	LO-Alarm	Unit
XMEAS 56	AIR	101	Concentration Feed D (Material A)	1.00	0.00	-1.00	mol%
XMEAS 57	AIR	101	Concentration Feed D (Material B)	1.00	0.01	-1.00	mol%
XMEAS 58	AIR	101	Concentration Feed D (Material C)	1.00	0.00	-1.00	mol%
XMEAS 59	AIR	101	Concentration Feed D (Material D)	109.99	99.99	89.99	mol%
XMEAS 60	AIR	101	Concentration Feed D (Material E)	1.00	0.00	-1.00	mol%
XMEAS 61	AIR	101	Concentration Feed D (Material F)	1.00	0.00	-1.00	mol%
XMEAS 62	AIR	102	Concentration Feed E (Material A)	1.00	0.00	-1.00	mol%
XMEAS 63	AIR	102	Concentration Feed E (Material B)	1.00	0.00	-1.00	mol%
XMEAS 64	AIR	102	Concentration Feed E (Material C)	1.00	0.00	-1.00	mol%
XMEAS 65	AIR	102	Concentration Feed E (Material D)	1.00	0.00	-1.00	mol%
XMEAS 66	AIR	102	Concentration Feed E (Material E)	109.99	99.99	89.99	mol%
XMEAS 67	AIR	102	Concentration Feed E (Material F)	1.00	0.01	-1.00	mol%
XMEAS 68	AIR	103	Concentration Feed C (Material A)	53.35	48.50	43.65	mol%
XMEAS 69	AIR	103	Concentration Feed C (Material B)	0.55	0.50	0.45	mol%
XMEAS 70	AIR	103	Concentration Feed C (Material C)	56.10	51.00	45.90	mol%
XMEAS 71	AIR	103	Concentration Feed C (Material D)	1.00	0.00	-1.00	mol%
XMEAS 72	AIR	103	Concentration Feed C (Material E)	1.00	0.00	-1.00	mol%
XMEAS 73	AIR	103	Concentration Feed C (Material F)	1.00	0.00	-1.00	mol%
XMV 1	V	161	Valve Position Feed D	100.00	62.89	0.00	%
XMV 2	V	162	Valve Position Feed E	100.00	53.17	0.00	%
XMV 3	V	160	Valve Position Feed A	100.00	26.24	0.00	%
XMV 4	V	163	Valve Position Feed C	100.00	60.57	0.00	%
XMV 6	V	167	Valve Position Purge	100.00	25.94	0.00	%
XMV 7	V	168	Valve Position Underflow Separator	100.00	37.22	0.00	%
XMV 8	V	170	Valve Position Underflow Stripper	100.00	46.43	0.00	%
XMV 10	V	164	Valve Position Cooling Water Outlet Reactor	100.00	35.95	0.00	%
XMV 11	V	165	Valve Position Cooling Water Outlet Condenser	100.00	12.34	0.00	%

C: Alarm Thresholds 5th Revision

ID	Type	Tag [ARR17]	Description	HI-Alarm	Normal	LO-Alarm	Unit
XMEAS 1	FIR	100	Flow Feed A	0.95	0.27	0.05	kscmh
XMEAS 2	FIR	101	Flow Feed D	4020.50	3655.00	3289.50	kg h^{-1}
XMEAS 3	FIR	102	Flow Feed E	4886.20	4442.00	3997.80	kg h^{-1}
XMEAS 4	FIR	103	Flow Feed C	10.16	9.24	8.32	kscmh
XMEAS 5	FIR	114	Flow Compressor Re-Cycle	35.66	32.42	29.18	kscmh
XMEAS 6	FIR	104	Flow Reactor Feed	52.36	47.60	42.84	kscmh
XMEAS 7	PIR	108	Pressure Reactor	2895.00	2800.00	0.00	kPa gauge
XMEAS 8	LIR	106	Level Reactor	100.00	65.00	50.00	%
XMEAS 9	TIR	105	Temperature Reactor	150.00	122.90	0.00	°C
XMEAS 10	FIR	115	Flow Purge	0.65	0.21	0.05	kscmh
XMEAS 11	TIR	118	Temperature Separator	101.22	92.02	82.82	°C
XMEAS 12	LIR	117	Level Separator	100.00	50.00	30.00	%
XMEAS 13	PIR	116	Pressure Separator	2974.99	2704.54	2434.09	kPa gauge
XMEAS 14	FIR	119	Underflow Separator	27.79	25.26	22.73	m^3 h^{-1}
XMEAS 15	LIR	110	Level Stripper	100.00	50.00	30.00	%
XMEAS 16	PIR	111	Pressure Stripper	3665.255	3332.05	2998.85	kPa gauge
XMEAS 17	FIR	121	Underflow Stripper	25.18	22.89	20.60	m^3 h^{-1}
XMEAS 18	TIR	111	Temperature Stripper	73.30	66.64	59.98	°C
XMEAS 20	K	100	Compressor Work	300.32	273.02	245.72	kW
XMEAS 21	TIR	109	Temperature Cooling Water Outlet Reactor	112.72	102.47	92.22	°C
XMEAS 22	TIR	113	Temperature Cooling Water Outlet Condenser	101.60	92.36	83.12	°C
XMEAS 23	AIR	001	Concentration Reactor Feed (Material A)	35.42	32.20	28.98	mol%
XMEAS 24	AIR	001	Concentration Reactor Feed (Material B)	16.38	14.89	13.40	mol%
XMEAS 25	AIR	001	Concentration Reactor Feed (Material C)	20.68	18.80	16.92	mol%
XMEAS 26	AIR	001	Concentration Reactor Feed (Material D)	6.59	5.99	5.39	mol%
XMEAS 27	AIR	001	Concentration Reactor Feed (Material E)	18.30	16.64	14.98	mol%
XMEAS 28	AIR	001	Concentration Reactor Feed (Material F)	4.46	4.05	3.65	mol%
XMEAS 29	AIR	003	Concentration Purge (Material A)	37.61	32.70	27.80	mol%
XMEAS 30	AIR	003	Concentration Purge (Material B)	24.98	21.72	18.46	mol%
XMEAS 31	AIR	003	Concentration Purge (Material C)	15.20	13.22	11.24	mol%
XMEAS 32	AIR	003	Concentration Purge (Material D)	1.25	0.89	0.45	mol%
XMEAS 33	AIR	003	Concentration Purge (Material E)	18.53	16.11	13.69	mol%
XMEAS 34	AIR	003	Concentration Purge (Material F)	6.21	5.40	4.59	mol%
XMEAS 35	AIR	003	Concentration Purge (Material G)	7.68	6.68	5.68	mol%
XMEAS 36	AIR	003	Concentration Purge (Material H)	3.59	3.26	2.93	mol%
XMEAS 37	AIR	002	Concentration Underflow Stripper (Material D)	1.00	0.01	-1.00	mol%
XMEAS 38	AIR	002	Concentration Underflow Stripper (Material E)	0.63	0.57	0.51	mol%
XMEAS 39	AIR	002	Concentration Underflow Stripper (Material F)	0.23	0.18	0.15	mol%
XMEAS 40	AIR	002	Concentration Underflow Stripper (Material G)	59.18	53.80	48.42	mol%
XMEAS 41	AIR	002	Concentration Underflow Stripper (Material H)	48.35	43.95	39.56	mol%
XMEAS 42	TIR	100	Temperature Feed A	49.5	45.00	40.50	°C
XMEAS 43	TIR	101	Temperature Feed D	49.5	45.00	40.50	°C
XMEAS 44	TIR	102	Temperature Feed E	49.5	45.00	40.50	°C
XMEAS 45	TIR	103	Temperature Feed C	49.5	45.00	40.50	°C
XMEAS 46	TIR	122	Temperature Cooling Water Inlet Reactor	38.5	35.00	31.50	°C
XMEAS 47	FIR	122	Flow Cooling Water Inlet Reactor	89.804	81.64	73.48	m^3 h^{-1}
XMEAS 48	TIR	123	Temperature Cooling Water Inlet Condenser	44.00	40.00	36.00	°C
XMEAS 49	FIR	123	Flow Cooling Water Inlet Condenser	36.993	33.63	30.27	m^3 h^{-1}
XMEAS 50	AIR	100	Concentration Feed A (Material A)	109.99	99.99	89.99	mol%
XMEAS 51	AIR	100	Concentration Feed A (Material B)	1.00	0.01	-1.00	mol%
XMEAS 52	AIR	100	Concentration Feed A (Material C)	1.00	0.00	-1.00	mol%
XMEAS 53	AIR	100	Concentration Feed A (Material D)	1.00	0.00	-1.00	mol%
XMEAS 54	AIR	100	Concentration Feed A (Material E)	1.00	0.00	-1.00	mol%
XMEAS 55	AIR	100	Concentration Feed A (Material F)	1.00	0.00	-1.00	mol%

ID	Type	Tag [ARR17]	Description	HI-Alarm	Normal	LO-Alarm	Unit
XMEAS 56	AIR	101	Concentration Feed D (Material A)	1.00	0.00	-1.00	mol%
XMEAS 57	AIR	101	Concentration Feed D (Material B)	1.00	0.01	-1.00	mol%
XMEAS 58	AIR	101	Concentration Feed D (Material C)	1.00	0.00	-1.00	mol%
XMEAS 59	AIR	101	Concentration Feed D (Material D)	109.99	99.99	89.99	mol%
XMEAS 60	AIR	101	Concentration Feed D (Material E)	1.00	0.00	-1.00	mol%
XMEAS 61	AIR	101	Concentration Feed D (Material F)	1.00	0.00	-1.00	mol%
XMEAS 62	AIR	102	Concentration Feed E (Material A)	1.00	0.00	-1.00	mol%
XMEAS 63	AIR	102	Concentration Feed E (Material B)	1.00	0.00	-1.00	mol%
XMEAS 64	AIR	102	Concentration Feed E (Material C)	1.00	0.00	-1.00	mol%
XMEAS 65	AIR	102	Concentration Feed E (Material D)	1.00	0.00	-1.00	mol%
XMEAS 66	AIR	102	Concentration Feed E (Material E)	109.99	99.99	89.99	mol%
XMEAS 67	AIR	102	Concentration Feed E (Material F)	1.00	0.01	-1.00	mol%
XMEAS 68	AIR	103	Concentration Feed C (Material A)	53.35	48.50	43.65	mol%
XMEAS 69	AIR	103	Concentration Feed C (Material B)	0.80	0.50	0.15	mol%
XMEAS 70	AIR	103	Concentration Feed C (Material C)	56.10	51.00	45.90	mol%
XMEAS 71	AIR	103	Concentration Feed C (Material D)	1.00	0.00	-1.00	mol%
XMEAS 72	AIR	103	Concentration Feed C (Material E)	1.00	0.00	-1.00	mol%
XMEAS 73	AIR	103	Concentration Feed C (Material F)	1.00	0.00	-1.00	mol%
XMV 1	V	161	Valve Position Feed D	99.00	62.89	1.00	%
XMV 2	V	162	Valve Position Feed E	99.00	53.17	1.00	%
XMV 3	V	160	Valve Position Feed A	99.00	26.24	1.00	%
XMV 4	V	163	Valve Position Feed C	99.00	60.57	1.00	%
XMV 6	V	167	Valve Position Purge	99.00	25.94	1.00	%
XMV 7	V	168	Valve Position Underflow Separator	99.00	37.22	1.00	%
XMV 8	V	170	Valve Position Underflow Stripper	99.00	46.43	1.00	%
XMV 10	V	164	Valve Position Cooling Water Outlet Reactor	99.00	35.95	1.00	%
XMV 11	V	165	Valve Position Cooling Water Outlet Condenser	99.00	12.34	1.00	%

D: Tests No. 1 to 100

Test	1. Abnormal Situation			2. Abnormal Situation			3. Abnormal Situation	
	Description	Start of ARC Phase	End of ARC Phase	Description	Start of ARC Phase	End of ARC Phase	Description	Start of ARC Phase
1	**IDV 1** (100%, 10h)	1h	11h	**IDV 2** (100%, 47h)	29h	76h	**XMV 2** (100%)	103h
2	**IDV 5** (100%, 47h)	1h	48h	**IDV 1** (100%, 9.5h)	52h	61.5h	**XMV 2** (100%)	86.5h
3	**IDV 1** (100%, 9h)	1h	10h	**IDV 6** (80%, 13h)	29h	42h	**XMV 2** (100%)	93h
4	**IDV 2** (100%, 44.5h)	1h	45.5h	**IDV 1** (100%, 8.5h)	77.5h	86h	**XMV 2** (100%)	106h
5	**IDV 1** (100%, 8h)	1h	9h	**IDV 5** (100%, 46.5h)	31h	77.5h	**XMV 2** (100%)	88.5h
6	**IDV 2** (100%, 46.5h)	1h	47.5h	**IDV 6** (80%, 13.25h)	74.5h	87.75h	**XMV 2** (100%)	135.75h
7	**IDV 5** (100%, 44h)	1h	45h	**IDV 2** (100%, 44h)	51h	95h	**XMV 2** (100%)	126h
8	**IDV 2** (100%, 47.5h)	1h	48.5h	**IDV 6** (80%, 13.5h)	81.5h	95h	**XMV 2** (100%)	146h
9	**IDV 5** (100%, 45h)	1h	46h	**IDV 6** (80%, 14h)	51h	65h	**XMV 2** (100%)	116h
10	**IDV 6** (80%, 14.25h)	1h	15.25h	**IDV 5** (100%, 47.5h)	67.25h	114.75h	**XMV 2** (100%)	116.75h
11	**IDV 1** (100%, 9.5h)	1h	10.5h	**IDV 6** (80%, 12.75h)	26.5h	39.25h	**XMV 3** (100%)	91.25h
12	**IDV 5** (100%, 46h)	1h	47h	**IDV 1** (100%, 10h)	51h	61h	**XMV 3** (100%)	82h
13	**IDV 1** (100%, 8h.5)	1h	9.5h	**IDV 2** (100%, 45h)	34.5h	79.5h	**XMV 3** (100%)	109.5h
14	**IDV 6** (80%, 13.25h)	1h	14.25h	**IDV 1** (100%, 9h)	70.25h	79.25h	**XMV 3** (100%)	102.25h
15	**IDV 1** (100%, 7.75h)	1h	8.75h	**IDV 6** (80%, 15h)	24.75h	39.75h	**XMV 3** (100%)	91.75h
16	**IDV 2** (100%, 48h)	1h	49h	**IDV 5** (100%, 48h)	80h	128h	**XMV 3** (100%)	137h
17	**IDV 5** (100%, 43.5h)	1h	44.5h	**IDV 2** (100%, 45.5h)	52.5h	98h	**XMV 3** (100%)	128h
18	**IDV 2** (100%, 44h)	1h	45h	**IDV 6** (80%, 14.75h)	71h	85.75h	**XMV 3** (100%)	134.75h
19	**IDV 6** (80%, 14h)	1h	15h	**IDV 5** (100%, 47h)	67h	114h	**XMV 3** (100%)	124h
20	**IDV 5** (100%, 44.5h)	1h	45.5h	**IDV 6** (80%, 13h)	55.5h	68.5h	**XMV 3** (100%)	121.5h
21	**IDV 1** (100%, 10h)	1h	11h	**IDV 5** (4100%, 5.5h)	28h	73.5h	**XMV 4** (100%)	79.5h
22	**IDV 2** (100%, 47h)	1h	48h	**IDV 1** (100%, 9.5h)	72h	81.5h	**XMV 4** (100%)	105.5h
23	**IDV 1** (100%, 9h)	1h	10h	**IDV 6** (80%, 13.5h)	35h	48.5h	**XMV 4** (100%)	99.5h
24	**IDV 6** (80%, 14.5h)	1h	15.5h	**IDV 1** (100%, 8.5h)	69.5h	78h	**XMV 4** (100%)	96h
25	**IDV 1** (100%, 8h)	1h	9h	**IDV 2** (100%, 46h)	28h	74h	**XMV 4** (100%)	105h
26	**IDV 2** (100%, 44.5h)	1h	45.5h	**IDV 5** (100%, 43.5h)	76.5h	120h	**XMV 4** (100%)	124h
27	**IDV 5** (100%, 46.5h)	1h	47.5h	**IDV 2** (47.5h)	53.5h	101h	**XMV 4** (100%)	128h
28	**IDV 2** (100%, 43.5h)	1h	44.5h	**IDV 6** (80%, 14.5h)	75.5h	90h	**XMV 4** (100%)	142h
29	**IDV 5** (100%, 48h)	1h	49h	**IDV 6** (80%, 12.75h)	53h	65.75h	**XMV 4** (100%)	115.75h
30	**IDV 6** (80%, 15h)	1h	16h	**IDV 5** (100%, 44h)	65h	109h	**XMV 4** (100%)	118h
31	**IDV 1** (100%, 9.75h)	1h	10.75h	**IDV 6** (80%, 14.25h)	29.75h	44h	**XMV 6** (100%)	94h
32	**IDV 6** (80%, 14.75h)	1h	15.75h	**IDV 1** (100%, 9.25h)	69.75h	79h	**XMV 6** (100%)	98h
33	**IDV 1** (100%, 8.75h)	1h	9.75h	**IDV 2** (100%, 48h)	33.75h	81.75h	**XMV 6** (100%)	113.75h
34	**IDV 5** (100%, 48h)	1h	49h	**IDV 1** (100%, 8.25h)	51h	59.25h	**XMV 6** (100%)	80.25h
35	**IDV 2** (100%, 45.5h)	1h	46.5h	**IDV 1** (100%, 7.75h)	73.5h	81.25h	**XMV 6** (100%)	106.25h
36	**IDV 2** (100%, 46h)	1h	47h	**IDV 5** (100%, 45h)	75h	120h	**XMV 6** (100%)	125h
37	**IDV 5** (100%, 44.5h)	1h	45.5h	**IDV 2** (100%, 47h)	52.5h	99.5h	**XMV 6** (100%)	127.5h
38	**IDV 2** (100%, 43.5h)	1h	44.5h	**IDV 6** (80%, 13.75h)	76.5h	90.25h	**XMV 6** (100%)	142.25h
39	**IDV 6** (80%, 13.5h)	1h	14.5h	**IDV 5** (100%, 46h)	64.5h	110.5h	**XMV 6** (100%)	113.5h
40	**IDV 5** (100%, 46.5h)	1h	47.5h	**IDV 6** (80%, 13.25h)	57.5h	70.75h	**XMV 6** (100%)	118.75h
41	**IDV 1** (100%, 9.25h)	1h	10.25h	**IDV 5** (100%, 45h)	34.25h	79.25h	**IDV 6** (100%)	83.25h
42	**IDV 2** (100%, 46.5h)	1h	47.5h	**IDV 1** (100%, 9.75h)	75.5h	85.25h	**IDV 6** (100%)	104.25h
43	**IDV 1** (100%, 8.25h)	1h	9.25h	**IDV 6** (80%, 13.75h)	32.25h	46h	**IDV 6** (100%)	96h
44	**IDV 5** (100%, 47.5h)	1h	48.5h	**IDV 1** (100%, 8.75h)	57.5h	66.25h	**IDV 6** (100%)	87.25h
45	**IDV 6** (80%, 12.75h)	1h	13.75h	**IDV 1** (100%, 8h)	60.75h	68.75h	**IDV 6** (100%)	91.75h
46	**IDV 2** (100%, 45.5h)	1h	46.5h	**IDV 6** (80%, 14.25h)	75.5h	89.75h	**IDV 6** (100%)	141.75h
47	**IDV 5** (100%, 43.5h)	1h	44.5h	**IDV 2** (100%, 44.5h)	47.5h	92h	**IDV 6** (100%)	117h
48	**IDV 6** (80%, 15h)	1h	16h	**IDV 2** (100%, 47.5h)	70h	117.5h	**IDV 6** (100%)	144.5h
49	**IDV 2** (100%, 45h)	1h	46h	**IDV 5** (100%, 47h)	76h	123h	**IDV 6** (100%)	126h
50	**IDV 5** (100%, 45.5h)	1h	46.5h	**IDV 6** (80%, 13.75h)	49.5h	63.25h	**IDV 6** (100%)	113.25h
51	**IDV 1** (100%, 9.75h)	1h	10.75h	**IDV 2** (100%, 45h)	28.75h	73.75h	**IDV 6** (90%)	99.75h
52	**IDV 5** (100%, 44.5h)	1h	45.5h	**IDV 1** (100%, 9.25h)	50.5h	59.75h	**IDV 6** (90%)	75.75h
53	**IDV 1** (100%, 8.75h)	1h	9.75h	**IDV 6** (80%, 14h)	27.75h	41.75h	**IDV 6** (90%)	92.75h
54	**IDV 2** (100%, 43.5h)	1h	44.5h	**IDV 1** (100%, 8.25h)	76.5h	84.75h	**IDV 6** (90%)	103.75h
55	**IDV 6** (80%, 13h)	1h	14h	**IDV 1** (100%, 7.75h)	62h	69.75h	**IDV 6** (90%)	85.75h
56	**IDV 2** (100%, 46h)	1h	47h	**IDV 5** (100%, 46h)	71h	117h	**IDV 6** (90%)	121h
57	**IDV 6** (80%, 14.5h)	1h	15.5h	**IDV 2** (100%, 44h)	64.5h	108.5h	**IDV 6** (90%)	138.5h
58	**IDV 5** (100%, 45.5h)	1h	46.5h	**IDV 2** (100%, 46.5h)	52.5h	99h	**IDV 6** (90%)	125h
59	**IDV 2** (100%, 48.5h)	1h	49h	**IDV 5** (100%, 47.5h)	80h	127.5h	**IDV 6** (90%)	129.5h
60	**IDV 5** (100%, 44.5h)	1h	45h	**IDV 6** (80%, 14.75h)	56h	70.75h	**IDV 6** (90%)	124.75h

Test	1. Abnormal Situation			2. Abnormal Situation			3. Abnormal Situation	
	Description	Start of ARC Phase	End of ARC Phase	Description	Start of ARC Phase	End of ARC Phase	Description	Start of ARC Phase
61	**IDV 5** (100%, 1h)	0.5h	1.5h	**IDV 1** (95%, 1h)	3h	4h	**XMV 2** (97.5%)	13h
62	**IDV 1** (95%, 10h)	0.5h	10.5h	**IDV 1, 2, 5**	26h	36h	**XMV 2** (97.5%)	61h
63	**IDV 1, 5** - T4	0.5h	10.5h	**XMV 3** (97.5%, 1h)	28h	29h	**XMV 2** (97.5%)	33h
64	**IDV 1, 2** - T1	0.5h	10.5h	**IDV 1, 2, 5**	38h	48h	**XMV 2** (97.5%)	74h
65	**IDV 1, 5** - T1	0.5h	10.5h	**IDV 6** (75%, 15h)	28h	43h	**XMV 2** (97.5%)	90h
66	**IDV 5** (100%, 1h)	0.5h	1.5h	**IDV 1, 2** - T4	2h	12h	**XMV 2** (95%)	38h
67	**IDV 1, 2, 5**	0.5h	10.5h	**IDV 5** (95%, 48h)	38h	86h	**XMV 2** (95%)	88h
68	**IDV 2** (95%, 48h)	0.5h	48.5h	**IDV 1, 2** - T4	73	83h	**XMV 2** (95%)	110h
69	**XMV 6** (5%, 1h)	0.5h	1.5h	**IDV 1, 5** - T5	4h	14h	**XMV 2** (95%)	34h
70	**IDV 6** (75%, 15h)	0.5h	15.5h	**IDV 1** (95%, 1h)	65h	66h	**XMV 2** (95%)	77h
71	**IDV 1, 2, 5**	0.5h	10.5h	**IDV 1, 2** - T1	36h	46h	**XMV 3** (97.5%)	72h
72	**XMV 3** (97.5%, 1h)	0.5h	1.5h	**IDV 1, 2** - T5	4h	14h	**XMV 3** (97.5%)	41h
73	**IDV 5** (95%, 48h)	0.5h	48.5h	**IDV 1, 5** - T2	52h	62h	**XMV 3** (97.5%)	80h
74	**IDV 2** (95%, 48h)	0.5h	48.5h	**IDV 1, 2** - T2	75h	85h	**XMV 3** (97.5%)	113h
75	**IDV 1, 2, 5**	0.5h	10.5h	**IDV 1, 5** - T1	39h	49h	**XMV 3** (97.5%)	69h
76	**IDV 1** (95%, 10h)	0.5h	10.5h	**IDV 1, 2** - T5	27h	37h	**XMV 3** (95%)	65h
77	**IDV 1, 5** - T2	0.5h	10.5	**IDV 5** (100%, 1h)	28h	29h	**XMV 3** (95%)	31h
78	**XMV 3** (97.5%, 1h)	0.5h	1.5h	**XMV 6** (5%, 1h)	6h	7h	**XMV 3** (95%)	10h
79	**IDV 5** (95%, 48h)	0.5h	48.5h	**IDV 1, 5** - T5	51h	61h	**XMV 3** (95%)	79h
80	**IDV 1** (95%, 10h)	0.5h	10.5h	**IDV 6** (75%, 15h)	27h	42h	**XMV 3** (95%)	90h
81	**IDV 1** (95%, 1h)	0.5h	1.5h	**IDV 1, 5** - T5	10h	20h	**XMV 4** (97.5%)	37h
82	**IDV 1, 2** - T2	0.5h	10.5h	**IDV 1, 2, 5**	39h	49h	**XMV 4** (97.5%)	77h
83	**IDV 1, 5** - T3	0.5h	10.5h	**IDV 1, 2** - T3	26h	36h	**XMV 4** (97.5%)	63h
84	**XMV 6** (5%, 1h)	0.5h	1.5h	**IDV 5** (95%, 48h)	7h	55h	**XMV 4** (97.5%)	56h
85	**IDV 1, 5** - T4	0.5h	10.5h	**IDV 2** (95%, 48h)	30h	78h	**XMV 4** (97.5%)	103h
86	**IDV 1** (95%, 10h)	0.5h	10.5h	**XMV 6** (5%, 1h)	26h	27h	**XMV 4** (95%)	29h
87	**IDV 1, 2, 5**	0.5h	10.5h	**IDV 6** (75%, 15h)	38h	53h	**XMV 4** (95%)	101h
88	**XMV 3** (97.5%, 1h)	0.5h	1.5h	**IDV 1, 5** - T3	5h	15h	**XMV 4** (95%)	33h
89	**IDV 1, 5** - T4	0.5h	10.5h	**IDV 1, 5** - T2	27h	37h	**XMV 4** (95%)	54h
90	**IDV 5** (100%, 1h)	0.5h	1.5h	**IDV 1, 2** - T1	2h	12h	**XMV 4** (95%)	40h
91	**IDV 1, 2** - T2	0.5h	10.5h	**IDV 1** (95%, 1h)	37h	38h	**XMV 6** (97.5%)	46h
92	**IDV 6** (75%, 15h)	0.5h	15.5h	**IDV 1, 2, 5**	64h	74h	**XMV 6** (97.5%)	104h
93	**IDV 1, 2** - T5	0.5h	10.5h	**IDV 2** (95%, 48h)	37h	85h	**XMV 6** (97.5%)	110h
94	**XMV 6** (5%, 1h)	0.5h	1.5h	**IDV 1, 5** - T1	4h	14h	**XMV 6** (97.5%)	31h
95	**IDV 5** (95%, 48h)	0.5h	48.5h	**IDV 1, 2** - T3	51h	61h	**XMV 6** (97.5%)	88h
96	**IDV 5** (100%, 1h)	0.5h	1.5h	**IDV 1, 2, 5**	3h	13h	**XMV 6** (95%)	42h
97	**IDV 1, 2** - T3	0.5h	10.5h	**IDV 1** (95%, 10h)	38h	48h	**XMV 6** (95%)	66h
98	**IDV 1, 2, 5**	0.5h	10.5h	**IDV 1** (95%, 1h)	40h	41h	**XMV 6** (95%)	48h
99	**IDV 2** (95%, 48h)	0.5h	48.5h	**IDV 1, 5** - T3	73h	83h	**XMV 6** (95%)	100h
100	**XMV 3** (97.5%, 1h)	0.5h	1.5h	**IDV 1, 2** - T4	6h	16h	**XMV 6** (95%)	44h

E: Ground-Truth Partitions

To allow for the systematic evaluation of methods for the clustering of similar alarm flood situations, a set of six different ground-truth partitions is provided, i.e., *GTP-1* to *GTP-6*. Each partition is created using a different set of rules to determine the exact definition of similarity regarding alarm flood situations and their dynamic properties.

Number of clusters in each partition:

- *GTP-1*: 29 clusters.
- *GTP-2*: 21 clusters.
- *GTP-3*: 16 clusters.
- *GTP-4*: 14 clusters.
- *GTP-5*: 13 clusters.
- *GTP-6*: 9 clusters.

Fault Description	Cluster Labels					
	GTP-1	GTP-2	GTP-3	GTP-4	GTP-5	GTP-6
IDV1 (100%, 7h 45min – 10h 00min)	0	0	0	0	0	0
IDV1 (95%, 10h 00min)	1	0	0	0	0	0
IDV1 (95%, 1h 00min)	2	1	1	1	1	0
IDV2 (100%, 43h 30min – 48h 00min)	3	2	2	2	2	1
IDV2 (95%, 48h 00min)	4	2	2	2	2	1
IDV5 (100%, 43h 30min – 48h 00min)	5	3	3	3	3	2
IDV5 (95%, 48h 00min)	6	3	3	3	3	2
IDV5 (100%, 1h 00min)	7	3	4	4	4	2
IDV6 (100%)	8	4	5	5	5	3
IDV6 (90%)	9	5	5	5	5	3
IDV6 (80%, 12h 45min – 15h 00min)	10	6	6	6	6	4
IDV6 (75%, 15h 00min)	11	7	6	6	6	4
IDV1, 2 (T1 – T5)	12	8	7	7	7	5
IDV1, 5 (T1 – T5)	13	9	8	0	0	0
IDV1, 2, 5 (T1 – T5)	14	10	9	7	7	5
XMV2 (100%)	15	11	10	8	8	6
XMV2 (97.5%)	16	12	10	8	8	6
XMV2 (95%)	17	12	10	8	8	6
XMV3 (100%)	18	13	11	9	5	3
XMV3 (97.5%)	19	14	11	9	5	3
XMV3 (95%)	20	14	11	9	5	3
XMV3 (97.5%, 1h 00min)	21	15	12	10	9	3
XMV4 (100%)	22	16	13	11	10	7
XMV4 (97.5%)	23	17	13	11	10	7
XMV4 (95%)	24	17	13	11	10	7
XMV6 (100%)	25	18	14	12	11	8
XMV6 (97.5%)	26	19	14	12	11	8
XMV6 (95%)	27	19	14	12	11	8
XMV6 (95%, 1h 00min)	28	20	15	13	12	8

Description of the partitions:

- ***GTP-1*****:** Least agglomerated partition. Each variant of the tested disturbances is grouped in an individual cluster, thus assuming that there are no relevant similarities between them.
- ***GTP-2*****:** Different scaling and duration of identical IDV disturbance types are grouped together in one cluster if the impact on the alarm dynamics (alarm activations and deactivations) is insignificant. XMV disturbance types are grouped together in one cluster if the disturbance affects the same valve and if the valve opening is similar, i.e., 97.5% and 95% are grouped together since they represent a low flow through the valve, whereas 100% indicates a full blockage.
- ***GTP-3*****:** Different scaling of identical disturbance types (IDV and XMV) are grouped together in one cluster if the underlying abnormal situations have the same outcome, i.e., either a normalization or emergency shutdown of the TEP.
- ***GTP-4*****:** In addition to GTP-3, the combined disturbance type IDV 1_5 is grouped together with IDV 1 since the effect of IDV 5 in IDV 1_5 is insignificant, i.e., two alarms that do not affect any propagation throughout the TEP. Moreover, for the same reason, IDV 1_2 and IDV 1_2_5 are grouped in one cluster.
- ***GTP-5*****:** In addition to GTP-4, IDV 6 and XMV 3 are grouped in one cluster if the underlying abnormal situations have the same outcome. This is justified by IDV 6 and XMV 3 affecting the same material inlet flow of the TEP, i.e., Feed A.
- ***GTP-6*****:** Most agglomerated partition. In addition to GTP-5, all short variants of the disturbances, i.e., those that are active for one hour, are clustered together with their respective disturbance types.