Dynamic and Classic PSA Model Comparison for a Plant Internal Flooding Scenario

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Different classic and dynamic PSA (*P*robabilistic *S*afety *A*ssessment) codes have different capabilities. However, few comparisons between codes have been published. GRS compares two classic PSA codes, RiskSpectrum® and SAPHIRE, and the dynamic PSA tool MCDET (*M*onte *C*arlo *D*ynamic *E*vent *T*ree) by GRS. MCDET includes the Crew Module which allows simulating human interactions. The plant internal flooding scenario chosen results from a extinguishing water pipe leakage within the reactor building annulus of a pressurized water reactor. After the leakage, leak detection and human actions are needed to interrupt the water flow before items important to safety are damaged. An available and validated RiskSpectrum® PSA plant model of the scenario was used and automatically transferred to SAPHIRE by applying the GRS tool pyRiskRobot. For the Crew Module, the scenario was extended by different steps and more time-dependent elements. The comparison shows: Both classic models lead to nearly identical flooding induced damage probabilities of the systems. However, qualitative differences between the codes exist. Preliminary results with the dynamic model show a lower probability because of the additional steps and large time available for mitigation measures. Concluding, dynamic PSA codes can enhance results from classic ones, particularly regarding aggravating conditions delaying mitigation measures outside buildings. It has been demonstrated that pyRiskRobot can transfer the most relevant parts of a classic PSA model increasing the analysists' flexibility.

Keywords: aggravating conditions, code development, dynamic model, human action, internal flooding, probabilistic safety analysis.

1. Introduction

Human actions often contribute significantly to mitigating the consequences of various internal or external hazards in nuclear power plants (NPPs). These actions can be interrelated with other human actions, time dependent system states, or developing phenomena of the hazard, see Gonzalez and Siu (2021). Internal flooding is a typical example of such hazards. Detailed guidance for treatment of internal flooding within Probabilistic Safety Assessment (PSA) is provided in the IAEA Specific Safety Guide SSG-3 and its update DS523, see IAEA (2022), paras. 7.90 ff.

Few comparisons exist between different classic PSA codes, e.g., Prassad et al. (2021), particularly for the mitigation of internal or external hazards involving human actions. Hence, one objective of this paper is to compare the results of a plant internal flooding scenario modelled by the two classic PSA codes RiskSpectrum® and SAPHIRE. RiskSpectrum® is a commercial software tool developed by the industry for modelling, and quantifying risk and reliability in the context of a PSA. SAPHIRE has been developed by the Idaho National Laboratory (INL) for the U.S. Nuclear Regulatory Commission (NRC) Office of Nuclear Regulatory Research also representing the primary sponsor of the SAPHIRE software.

In addition to the comparison of different classic PSA codes, their results are compared to those of

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a dynamic one. Such a comparison, particularly with respect to human actions outside buildings and aggravating conditions have been rarely published and is therefore the other objective of this paper. It is motivated by the IAEA Safety Guide SSG-3, which describes the relevance of dynamic elements in the analysis of plant internal flooding scenarios that can only be indirectly considered by classic PSA models. In this regard, the flooding scenario analysed comprises several time dependent elements and various interactions between humans, systems and components, and the hazard (see Section 2.1).

Different dynamic PSA codes have been developed and are still the subject of current research, e.g., Mandelli et al. (2019) or Park and Lee (2021). Dynamic PSA codes allow for a detailed analysis of time dependent human actions and their complex and dynamic interrelations. In this context, GRS has developed the dynamic PSA code MCDET (*M*onte *C*arlo *D*ynamic *E*vent *T*ree) for dynamic event trees, including the so-called Crew Module for human interactions, see Peschke et al. (2018). Several analyses have been carried out with the Crew Module, Berchtold et al. (2021) or Mayer, et al. (2022).

The classic RiskSpectrum® plant model for this scenario was already available from earlier work in Röwekamp et. al. (2017). This model has been already validated and verified for different applications. For this study, the model has been extended by different temporal aspects for the dynamic model in the Crew Module (see Sections 2.2 and 2.4). These aspects have been derived from operating experience or other known parameters such as distances. In addition, the GRS tool pyRiskRobot, see Berner (2020), has been extended to allow an automatized transfer of the RiskSpectrum® plant model to the SAPHIRE plant model (Section 2.3). Qualitative and quantitative comparisons are presented in Section 3. First preliminary conclusions have been drawn from the results (Section 4).

2. Methodology

2.1. Description of the scenario

The scenario is initiated by an assumed extinguishing water pipe leakage, either in the first or in the second of four redundant trains, i.e., the quadrants, of the reactor building annulus (see Figure 1). In both cases, the location of the leakage is located between the pipe entering the annulus and the entry valve, where the pipe is pressurized. After the leakage, the pumps for maintaining the water pressure start and provide a permanent water flow of about 500 m³/h into the annulus. This water flow cannot be stopped due to the difference in height between the locations of the leakage and the pumps. The leakage can be detected by several water level sensors in the reactor sumps. Once detected, the leakage must be properly diagnosed. Then the water flow must be stopped manually by closing an extinguishing water pipe valve (STS-11 or STS-21). If the closing of the valve fails, the water flow inside the containment can be stopped by closing both corresponding main ring valves. If the flow cannot be stopped, the operators will initiate a manual reactor scram. However, the procedure for the scram is not included in this paper. Failures of systems and components important to safety being located in the reactor building annulus, are only assumed if these are submerged. The systems and the corresponding water volumes up to their submergence are shown in Table 1. Only the residual heat removal (RHR) pumps are needed after the scram. Hence, if the water volume remains below the RHR pumps level of 1274 m³ the water flow is stopped successfully; otherwise, the annulus is assumed to be flooded.

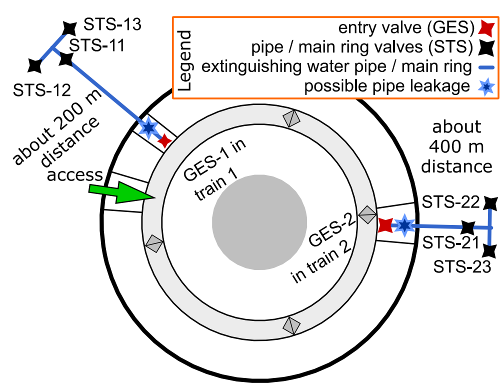

Fig. 1. Scheme of the reactor building annulus with the relevant extinguishing water supply facilities (figure not to scale).

The frequency of the assumed scenario is expected to be very low since the leakage must occur exactly between the building entry of the pipe and its entry valve with a length of less than 10 m for both redundant trains. Hence, the leakage in the pipe is a prerequisite for this study and the scenario frequency is not considered here.

Table 1. Submergence water volume limit for systems important to safety in the reactor building annulus.

System	Water Limit
Containment venting systems in the reactor building annulus	645 m³
High pressure safety injection pumps	738 m³
Liquid neutron absorber shutdown pumps	1175 m³
Residual heat removal (RHR) pumps	**1274 m³**
Spent fuel pool pumps	1367 m³
Component cooling pumps for safety related cooling	1367 m³

2.2. Classic and dynamic modelling of the scenario

The scenario chosen as basis for this study had already been implemented in a RiskSpectrum® plant model for other purposes and validated and verified for different applications. The event tree is shown in Figure 2. The accident sequence comprises the initiating event 'pipe leakage' (S50), the 'leak detection' (LE50), the 'leak diagnosis' (S50-DIA), and the 'valve closure' (AS501). The scenario ends as soon as the extinguishing water pipe valves are either closed successfully (sequence 1) or not (sequences 2, 3, 4). The corresponding end states are 'OK' in sequence 1 or 'annulus flooded' (AF) in the sequences 2, 3, or 4.

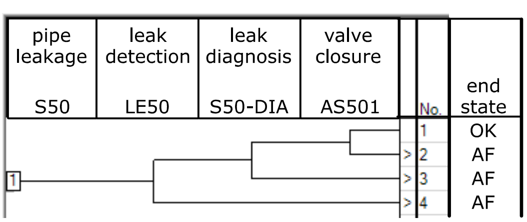

Fig. 2. RiskSpectrum® event tree (AF: annulus flooded).

The scenario includes the time-dependent elements required by IAEA (2022), namely the duration of event sequences, time dependent events, and human actions for mitigating the consequences. These characteristics cause several possible interrelations between human actions, signals, and component states. Furthermore, the use of a dynamic code allows more detailed modelling of the function events described above. For these reasons, the scenario is modelled in steps rather than function events as shown in Figure 3. However, the steps and function events are characterised together.

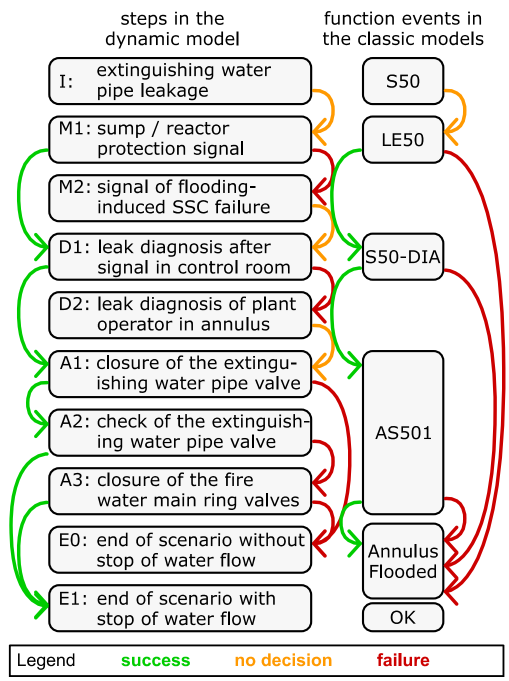

Fig. 3. Steps with the required function events in the dynamic and the classic PSA plant model.

'I, pipe leakage' / 'S50': This step begins with the leakage of the extinguishing water pipe and comprises the activation of the pumps for maintaining the water pressure as well as their alarm in the control room. The water flow is between $dV = 490 \ldots 520$ m³/h. The entire control room staff and three further plant operators are present in the main control room and available for carrying out different tasks. At the time of the leakage two firefighters are present in a distance of approximately 100 m to 500 m to the location of the relevant extinguishing water pipe valve. This step takes only a few seconds and directly leads to step ‘M1’.

‘M1, sump or reactor protection signal’ / ‘LE50’: The water fills the sumps and spreads over the entire reactor building annulus. The sensors in the sumps trigger a signal within less than a minute, the reactor protection system leads to a signal within 55 to 60 min. The failure probability of the signal is 1 E-04. There are two options: either at least one signal is triggered and recognized in the main control room leading to step ‘D1’ within the time period mentioned above, or all signals fail leading to step ‘M2’.

‘M2, signal of flooding induced SSC failure’ / not included in the classic PSA plant models: The leakage resulting from the pipe leakage has not yet been correctly diagnosed. Thus, the water flow will cause a failure of the containment venting systems as soon as a water volume of 645 m³ is reached in the annulus, which triggers an alarm in the control room after about 75 to 80 min. The alarm leads to step ‘D1’.

‘D1, diagnosis after signal in main control room’ / ‘S50-DIA’: After the signal, the diagnosis is assumed to take 50 to 70 min. There are two options: either the diagnosis is successful, which leads to step ‘A1’, or the diagnosis is not successful without suitable subsequent measures (failure probability of 1.7 E-03) leading to step ‘D2’.

‘D2, diagnosis by plant operator in the reactor building annulus’ / not included in the classic PSA plant models: Since there is no correct diagnosis two plant operators are sent to the annulus. They certainly recognize the leakage and inform the control room. This step takes more than 30 min and leads to step ‘A1’.

‘A1, closure of the extinguishing water pipe valve’ / ‘AS501’: One plant operator and two firefighters are sent to close the correct extinguishing water pipe valve (STS-11 or STS-21). The time period for reaching the valve and closing it is less than 12 min. There are two options: either the action is carried out successfully at the time t_{close} leading to A2, or the action is not carried out correctly (probability of 4.8 E-06) leading to step ‘E0’.

‘A2, check of the extinguishing water pipe valve’ / ‘AS501’: The flow through the pipe is checked by the control room personnel. There are two options: either the extinguishing water pipe valve closed successfully leading to step ‘E1’, or the valve did not close (probability of 5.9 E-04) leading to step ‘A3’.

‘A3, closure of the fire water main ring valves’ / ‘AS501’: The plant operator and two firefighters go to the corresponding valves (STS-12/STS-13 or STS-22/STS-23) of the fire water main ring and close them in less than 7 min. There are two options: either both valves are closed successfully at the time t_{close} leading to step ‘E1’, or at least one of the two valves did not close (see ‘A2’ for the failure probability) leading to step ‘E0’.

‘E0, end of scenario without stop of water flow’ / ‘AF’: The leakage with water flowing into the reactor building annulus could not be stopped. Further measures are not considered. Therefore, all systems shown in Table 1 are assumed to be failed.

‘E1, end of scenario with stop of water flow’ / ‘OK’: The water flow into the reactor building annulus could be successfully stopped at the time t_{close}. The water volume in the annulus is $V = dV \cdot t_{close}$ (see steps ‘I’ and ‘A1’ / ‘A3’). The water level in the annulus results in failures of systems important to safety as shown in Table 1. While the end state of both classic PSA plant models is ‘OK’, the dynamic model provides two options: either the RHR pumps are not damaged representing a safe end state, or the pumps are damaged.

In case of steps ‘E0’ and ‘E1’ with the damage of the RHR pumps, the scenario will continue with a manual reactor scram, which is not further considered hereafter.

2.3. Transfer of the RiskSpectrum® plant model to SAPHIRE applying pyRiskRobot

The event trees shown in Figure 2 and the subsequent event tree up to core damage have been transferred from RiskSpectrum® to SAPHIRE applying GRS pyRiskRobot. This tool was developed by GRS to simplify the generation, modification, and duplication of PSA fault trees.

It is particularly useful when repetitive tasks need to be carried out within a classic PSA plant model. Although pyRiskRobot has historically been used only for RiskSpectrum® PSA models its underlying layered structure can facilitate the extension to other types of classic PSA codes, such as SAPHIRE. The data format of pyRiskRobot consists of sqlalchemy objects. Using sqlalchemy, pyRiskRobot implements and extracts information from SQL databases such as the RiskSpectrum® 1.3 MSSQL database. Meanwhile, pyRiskRobot has been extended to allow translation of these sqlalchemy objects into the SAPHIRE MARD flat file format. For this translation, following differences between SAPHIRE and RiskSpectrum® require special treatment:

- special characters accepted in element ID and element descriptions,
- modelling of house event,
- modelling of negated basic events, and
- available probabilistic distribution of parameters and failure models.

2.4. Modelling approach in the Crew Module

The GRS Crew Module allows modelling complex time-dependent sequences of human actions. The analyst can specify potential branching points in these sequences as well as uncertain input parameters, e.g., the duration and probability of different actions or the parameters which influence the next human action taken at a branching point. The Crew Module can simulate an action sequence based on a set of input parameters and the provided model. In combination with MCDET, the analyst can also specify the uncertainty distribution for each input parameter. Simulation parameter sets get sampled from the distributions provided in a combined MCDET / Crew Module run and are applied as Crew Module input. Each potential action sequence is simulated, the duration and probability of the action sequences are calculated and stored. Based on the information stored, the dependency between aleatoric and epistemic uncertainties and the final duration and probability of the action sequences can be analysed.

The Crew Module input can be modelled using the software tool FreeMind. Actions following each other without intermediate branching points are summarized in one FreeMind knot. The knots are connected following the links shown in Figure 3. All uncertain parameters described in Section 2.2, the duration of different actions, the walking distance for the firefighters in step ‘A1’ and the water flow per time period have been sampled using the GRS software tool SUSA (*S*oftware for *U*ncertainty and *S*ensitivity *A*nalyses), see Kloos and Berner (2017).

The probability of all uncertain parameters is assumed to be uniformly distributed. Special cases are the duration of ‘M1’, the period until the sump signal or the reactor protection signal is triggered, and the time period needed until either the plant operators or the firefighters reach the correct extinguishing water pipe valve (‘A1’). The duration of ‘M1’ is modelled as dependent on the water flow per time period and the redundant train of the reactor building annulus. The period until the first person (plant operator or firefighter) reaches the valve depends on the respective distance to the valve and on the walking speed. Since the starting point of the two firefighters in ‘A1’ is not fully known, a uniform distribution between 100 and 500 m has been assumed. In addition, a walking speed of 1.2 m/s has been assumed.

3. Results

As outlined in Section 2.1, the extinguishing water leakage in the reactor building annulus is a prerequisite in this study without considering its occurrence frequency. Moreover, the scenario does not comprise the reactor scram procedure after the failure to interrupt the water flowing then leakage. Therefore, the analysis of the three PSA plant models is focused on the probability of the end state ‘annulus flooded’ due to the leakage.

3.1. Comparison of both classic PSA plant models

The RiskSpectrum® plant model has been transferred into SAPHIRE by applying the GRS tool pyRiskRobot. Therefore, the focus is first on the qualitative differences between RiskSpectrum® and SAPHIRE and how pyRiskRobot copes with these. In addition, the quantitative results of both classic PSA codes are compared.

3.1.1. Qualitative comparison

There are differences in the two classic PSA codes with respect to five relevant aspects:

- SAPHIRE is less flexible regarding special characters; e.g., the '@' frequently used in Risk-Spectrum® is not allowed.
- RiskSpectrum® provides a larger variety of element types, such as house events and different types of parameters such as failure probability or mean time for repair.
- Different basic events in RiskSpectrum® can be linked to the same parameter. This reduces the number of parameters a user needs to specify. To achieve the same goal SAPHIRE provides so-called 'template events' which can be used as templates for different events throughout the model.
- RiskSpectrum® allows the use of exchange events within a basic event. An exchange event can be linked to another basic event replacing the original one by activating a house event. A similar feature is not available in SAPHIRE.
- RiskSpectrum® and SAPHIRE use identical definitions for uniform, normal, lognormal, beta, and gamma distribution types. However, the distribution types shown in Table 2 are either defined differently in both PSA codes or they are only available in only one.

Table 2. Deviating distribution types for probabilistic models between RiskSpectrum® and SAPHIRE.

Distribution Type	RiskSpectrum®	SAPHIRE
lognormal uniform	yes	no
discrete / histogram	different approaches	
linear interpolation	arbitrary number of points	triangular
chi-squared	no	yes
constrained non-informative	no	yes
Dirichlet	no	yes
exponential	no	yes
gamma	no	yes
maximum entropy	no	yes

Consequently, the following procedures have been performed by pyRiskRobot:

- Special characters in the element IDs of a RiskSpectrum® plant model are replaced.
- Prefixes are introduced in the basic event IDs for distinguishing between the different element types of RiskSpectrum® (e.g., 'HO_' for house events).
- RiskSpectrum® parameters are replaced by SAPHIRE template events.
- Identical distribution types are transferred, and others are transformed appropriately.

The following procedures are not yet available in pyRiskRobot and have to be carried out manually:

- the activation of template events,
- the translation of RiskSpectrum® exchange events into the corresponding fault trees (see Figure 4), and
- the translation of event trees.

In conclusion, pyRiskRobot has been successfully applied for the transfer of all fault trees, the required basic events, their parameters, and the house events from the RiskSpectrum® plant model to the SAPHIRE plant model.

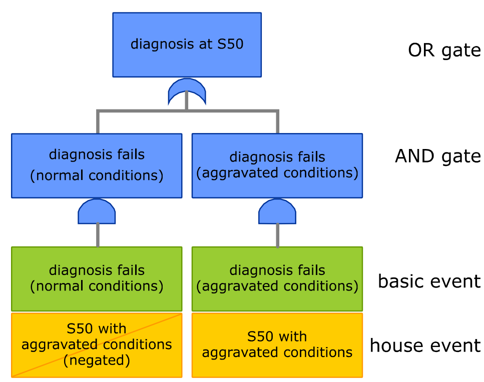

Fig. 4. Fault tree in SAPHIRE used to model the exchange event 'diagnosis fails (aggravated condition)' for the basic event 'diagnosis fails (normal condition)' in RiskSpectrum®.

3.1.2. Quantitative evaluation

Due to the automatised transfer using the GRS tool pyRiskRobot and few manual extensions, the event trees, fault trees, basic events, and parameters of the scenario are the same in the RiskSpectrum® plant model and the SAPHIRE plant model. Hence, both classic PSA plant models led to nearly identical results in terms of point estimates from the minimal cut set analyses and to very similar results from the uncertainty analysis. More precisely, the conditional probabilities for the end state 'annulus flooded' are for RiskSpectrum® and SAPHIRE listed in Table 3. Figure 5 illustrates the corresponding cumulative density function of the mean result for RiskSpectrum®.

The identical minimal cut sets of both classic PSA plant models show that sequence 3 of the event tree in Figure 2 contributes about 99.6 % to the result. Accordingly, function event S50 with the fault tree in Figure 4 and the basic event failure of the diagnosis are most relevant. This corresponds to the importance measures Fussel-Vessely Importance (0.996), Risk Decrease Factor (275), and Risk Increase Factor (586).

Table 3. Conditional probabilities for the end state annulus flooded for RiskSpectrum® and SAPHIRE.

	RiskSpectrum®	**SAPHIRE**
Point estimate	1.71 E-03	1.71 E-03
Mean	1.72 E-03	1.71 E-03
Median	2.12 E-04	2.06 E-04
5% quantile	1.32 E-05	1.22 E-05
95% quantile	5.90 E-03	6.16 E-03

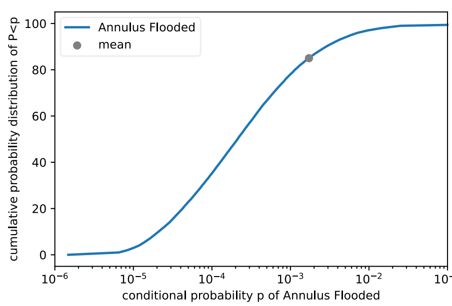

Fig. 5. Cumulative density function of the conditional probability for the end state 'annulus flooded' of the RiskSpectrum® plant model.

3.2. Comparison of the Crew Module model with the classic PSA plant models

First of all, it has to be taken into account that some scenario steps have been modelled differently between the classic PSA plant models and the dynamic model.

Qualitatively, the steps 'D2' and 'M2' of the scenario considered in the Crew Module model cannot be included in the classic PSA plant models. The step 'D2' within a classic model would always lead to a successful detection since the plant operator always goes to the reactor building annulus and detects the leakage after a diagnosis failure in step 'D1'. Similarly, step 'M2' would also certainly trigger a signal/alarm in the control room. Thus, the function events 'S50-DIA' and 'LE50' would be obsolete in a classic PSA plant model due to 'D2' and 'M2' while the time dependent event sequence in the Crew Module suggests modelling these steps.

Preliminary quantitative analyses indicate that the Crew Module model leads to lower probabilities for event sequences with the reactor building annulus being flooded than the classic PSA plant models, as visible in Table 4. The probability is dominated by sequences in which the extinguishing water pipe valve and the fire water main ring valves could not be closed, i.e., the overlap between 'E1' and 'annulus flooded' in Figure 3 is expected to be very small.

Table 4. Preliminary point estimate probability of the end state 'annulus flooded' for classic PSA and dynamic PSA, the latter with the valves closed or not.

RiskSpectrum®	**MCDET**	
	valves not closed	valves closed
1.71 E-03	4.80 E-06	0.17 E-06

It seems that this lower probability for the end state 'annulus flooded' in the dynamic model results from the additional detection and diagnosis steps 'M2' and 'D2' as well as from the long time period available for closing the valves ('M1' to 'M3'). These two reasons can even lead to safe end states when both steps, first detection 'M1' and first diagnosis 'D1' fail (mean probabilities of 1 E-04 and 1.7 E-03, respectively). This is not the case in the classic PSA model. These are only preliminary results and further studies are currently being conducted.

4. Conclusions and outlook

Dynamic PSA codes can support and enhance results from classic PSA plant models by resolving time dependent elements more precisely (e.g., considering additional sequences, time dependency of failures). The preliminary investigations have demonstrated that a reliable diagnosis of the pipe leak by the control room staff is essential. However, in case of aggravated conditions, e.g., outside buildings, the time period required for mitigation measures may dominate the results. The respective effects can be further analysed applying dynamic PSA codes.

Moreover, the classic PSA codes RiskSpectrum® and SAPHIRE lead to similar results for the scenario analysed. Consequently, it seems that the code can be freely chosen only with regard to the qualitative differences such as usability or flexibility. In this context, it has been shown that the GRS tool pyRiskRobot is able to transfer the most parts of a PSA plant model, i.e., fault trees and related elements, from RiskSpectrum® to SAPHIRE and vice versa, increasing the flexibility of the analyst.

The comprehensive comparison of the dynamic and classic PSA plant models is ongoing. Particularly the analysis of effects from aggravated conditions will be part of this work. A comparison of classic and dynamic PSA methods can thus enable a broader view on the PSA results.

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