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Visualizing Process Design, Operation and Failure Impacts through State Space Representations

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Abstract

Visualization can improve insights into choices made in early stages of design, particularly in relation to the impact of system related failures. Improved decision making can lead to higher commitment to inherently safer designs, more fault tolerant systems and increased operational resilience.

This paper proposes a means to visualize the function of a design in terms of the state space defined by multiple capabilities possessed by the individual components that constitute the system. Capability is related to the abilities of the component to affect the states of the system, primarily the properties of mass and energy streams that flow through the system. A representation that is constructed from these capability vectors maps out the potential space in which the system can normally operate. It also shows the impact on that space when selected capabilities are degraded or lost.

The visualization benefits of the proposed methodology will be displayed with an industrial case study. A typical supply line configuration to a fuel storage facility is investigated to show the fundamental concepts and to assess the utility of the ideas within conceptual process design and operations.

Introduction

New insights into the implications of design decisions at both the front-end engineering design (FEED) and operational stages of the process life cycle are needed for improved risk management practices. This work proposes new geometric representations of the evolving system function that permits real-time analysis of both function, failure and performance degradation as the design takes place. The methodology can also be used for existing operations through extraction of information from existing Piping and Instrumentation Diagrams (P&IDs).

Describing and understanding *function* is critical in hazard identification, risk management and fault diagnosis. Based on previous developments that led to the Blended Hazard Identification (BLHAZID) methodology, the idea emerged that plant components have an associated set of capabilities [2]. A capability is defined as an *action* on a system property, such as <increase><pressure>. Here *increase* is the action and *pressure* is the property. As the pressure is increased, the state of the system is altered, since the state is described by a set of properties that are principally associated with process streams. Certain sets of capabilities deliver the overall *function* of the system. Affecting the values of these properties is what a process system is designed to do, in order to meet its operational goals. As such, if the desired capabilities are not activated to the required extent to provide the desired functions, the production, safety, environmental and/or economic goals of a process system will most likely not be met.

The full set of component capabilities defines the Capability State Space (CSS) within the Lawful State Space (LSS), where thermodynamic and physical feasibility applies. See Figure 1. Since system function is related to certain activated component capabilities, the Functional State Space (FSS) of the design is then contained within the CSS. In operating the process system, the Operating State Space (OSS) depends on both the process stream properties and component function. This space can be visualized within the FSS.

Various geometric representations of the effects of capabilities on system properties can be generated. Each system property can be represented as a line interval with constraints. Any of the state spaces can be aggregated and visualized in radial and line interval forms. Failure and/or degradation of capabilities change the CSS and FSS respectively. Such changes might show whether the designed OSS remains feasible, or if latent capabilities should be activated to retain feasible operation. Alternatively, changes in the actual OSS can suggest process design changes for improved operational performance.

Fundamental system's concepts

A comprehensive systems approach involves the use of the *state space* concept. The fundamental notion of the *state space* and its various subsets was described by Mario Bunge in his *Treatise on Basic Philosophy* [1], and it is this interpretation that is applied here. The following state space concepts are considered:

- The *Lawful State Space (LSS)*, which constitutes a space where the laws of physics and thermodynamics are valid.

- The *Capability State Space (CSS)*, which is the space defined by the *activated* and non-activated, or *latent*, capabilities of the components that make up the designed entity. It encompasses all possible capabilities of components and the system.

- The *Functional State Space (FSS)*, which is the space defined by the purposely *activated* capabilities of the system components so that the system possesses the requisite functions to deliver the design and operational goals.

- The *Operational State Space (OSS)*, which is defined by the stream properties reflecting the space mapped out by the desired region of operations. This normally is bounded by the functional state space.

It is important to realise that the OSS is directly determined by the FSS. This is because the FSS provides the desired capabilities to affect the properties of the streams. However, it is possible that the boundaries between the FSS and OSS can coincide, or even be breached under abnormal operational conditions which include system disturbances and component failures.

The concept of a LSS has been directly taken from Bunge's work [1], whereas the CSS, FSS and OSS are newly defined here. Figure 1 shows the relationship amongst the state spaces of interest.

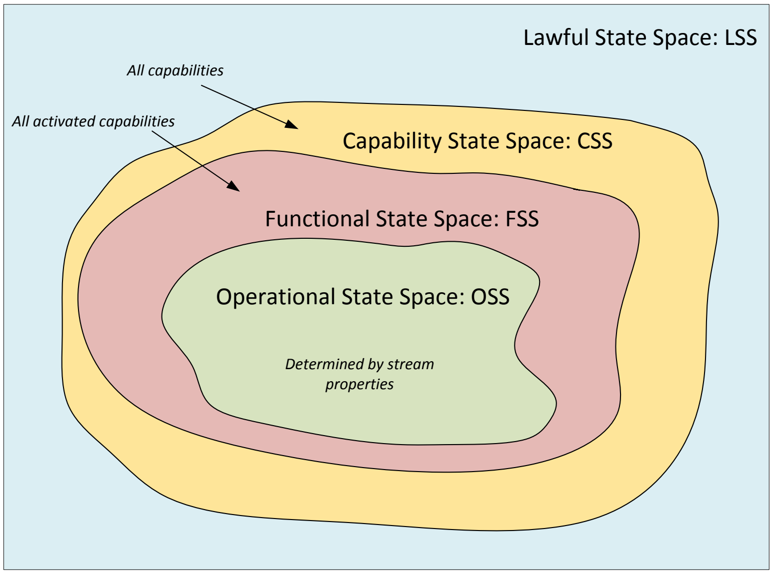


Figure 1. State space regions

There are important additional features that can be identified by such a set of state space representation particularly as the capability sets related to components is clearly defined.

Capability sets and the evolution of sub-system function

As the components and streams of a process system interact, different capabilities are activated to deliver the *function* of the system. Table 1 describes the capability sets for some basic flowsheet components.

Table 1. Capability sets for basic flowsheet components

Capability Sets	
Component	**Capability Set**
Gate valve	{<contain><m>, <permit><F_f>, <stop><F_{fr}>}
Centrifugal pump	{<contain><m>, <permit>< F_f>, <increase><P>, …}
Control valve	{<contain><m>, <permit><F_f>, <regulate><F_f>, …}
In-line flow meter	{<contain><m>, <permit><F_f>, <observe><F_f>, …}
Non-return valve	{<contain><m>, <permit><F_f>, <stop><F_r>, …}
Pipe section	{<contain><m>, <permit><F_f>, …} or {<contain><M>, <permit><F_f>, …}
Pressure relief valve	{<contain><m>, <permit><F_f>, <stop><F_r>}

Properties	
Symbol	**Definition**
F	Flow
F_f	Forward flow
F_r	Reverse flow
F_{fr}	Forward and reverse flow
P	Pressure
T	Temperature
x	Composition: {x(i), i=1(1)n}
m	Component mass: {m(i), i=1(1)n}
M	Total mass

Operation modes

There is a need to consider the specific *operational mode* of the system when attempting to represent the functional state space of the design. For example, a gate valve, or ball valve can be in two main operational modes: 'open' or 'closed'. This means that a different set of capabilities need to be activated for each operational mode. For example, if the mode of a gate valve switches to "open" instead of "closed", then the capabilities that should be activated are <*contain*><*mass*> and <*permit*><*flow*> instead of <*contain*><*mass*> and <*stop*><*flow*>.

As the design progresses, or the way the system is operated changes, the set of activated capabilities will change as well. This evolution of sub-system function, reflected in the changing shape of the FSS and/or OSS, could give insights into how the process is changing in a simplified form, to support designer decision making or, timely operator intervention if it becomes apparent that a failure scenario is developing. These changes in the capability sets can be displayed visually if each capability is expressed in *interval* form. Additionally, the ability to represent changes in the operational mode of a system or a component should also be incorporated into the representation, to enhance the description of functional evolution.

Geometric representation of capability sets

Conceptually, capabilities have two parts: *action* and *property*. It is possible to conceive of the action part as affecting the range of the capability. Consider the capability of <*increase*><*pressure*> in a pump. The action, '*increase*', acts on the nominated stream property '*pressure*' causing an increase in the fluid pressure. Given that the state space of a system is constructed from the values of key system properties, visually a capability can be represented as a line interval with various constraints. These constraints are ultimately determined by the specific component used and the nature of the stream passing through it.

Several representations can be adopted when organising the capabilities for visualization with two being highlighted.

- *Linear representation:* all of the capability intervals lie in sequence, forming a horizontal representation of the function space. Three capabilities are shown in Figure 2. The marking points used for indicating the range(s) or specific values, like zero datum or a hard constraint. In keeping with normal mathematical set theory, we adopt the square brackets […] to signify a closed interval.
- *Radial representation:* the capabilities of the components are attached to an anchor point and are distributed clockwise around a circle consistent with the flow regime in the actual design. An example can be seen in Figure 3, where the minus infinity point of each capability is anchored.

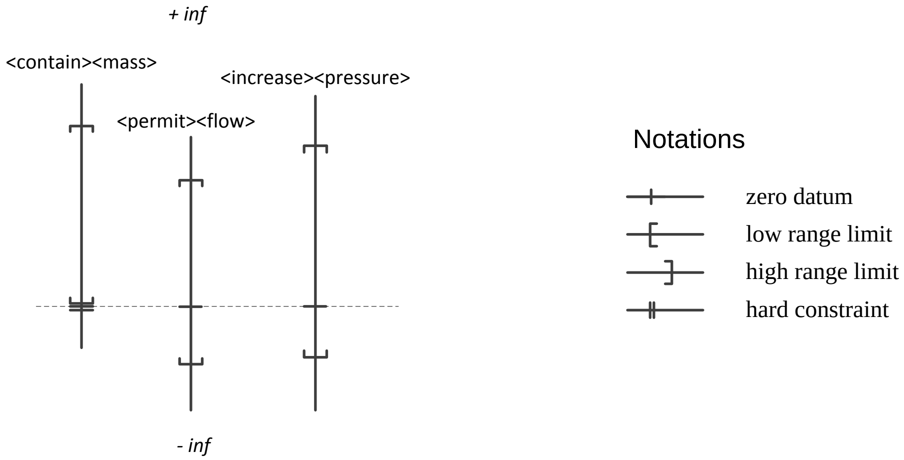


Figure 2. Example of linear representation of a set of capabilities

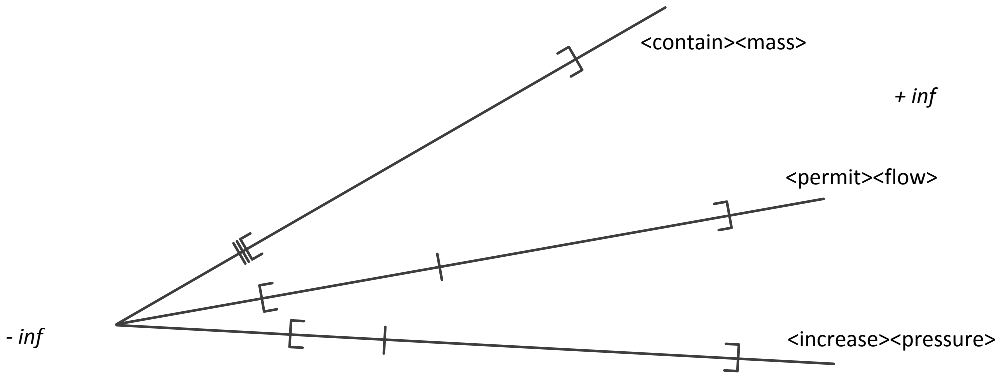


Figure 3. Example radial representation form for capabilities

Various types of capabilities can be represented on a single diagram. Grouping and ordering arrangements can provide different meanings and/or better understanding. At this stage of development, a number of display options have been investigated as usable representations of function/failure visualisation. To explore the value of utilising this approach for visualising function, a case study is developed in the next section.

Case study

A fuel feed line to a storage terminal is considered as a typical example of the application of the methodology and the visualization. Figure 4 shows a delivery line to a major fuel transport terminal storage tank. In this transfer system are 11 components, each providing a set of capabilities that together generate the function(s) that allow transfers of fuel to take place from production to bulk storage.

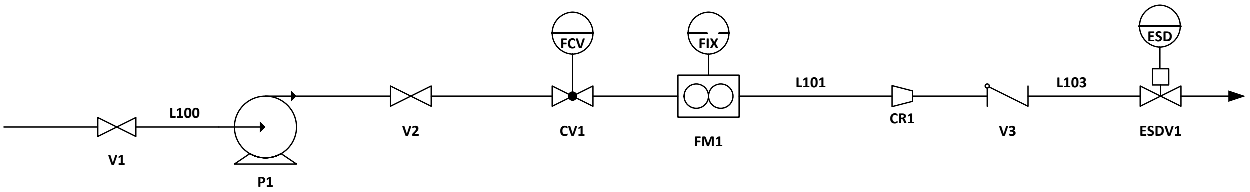


Figure 4. Fuel transfer system to a bulk storage tank

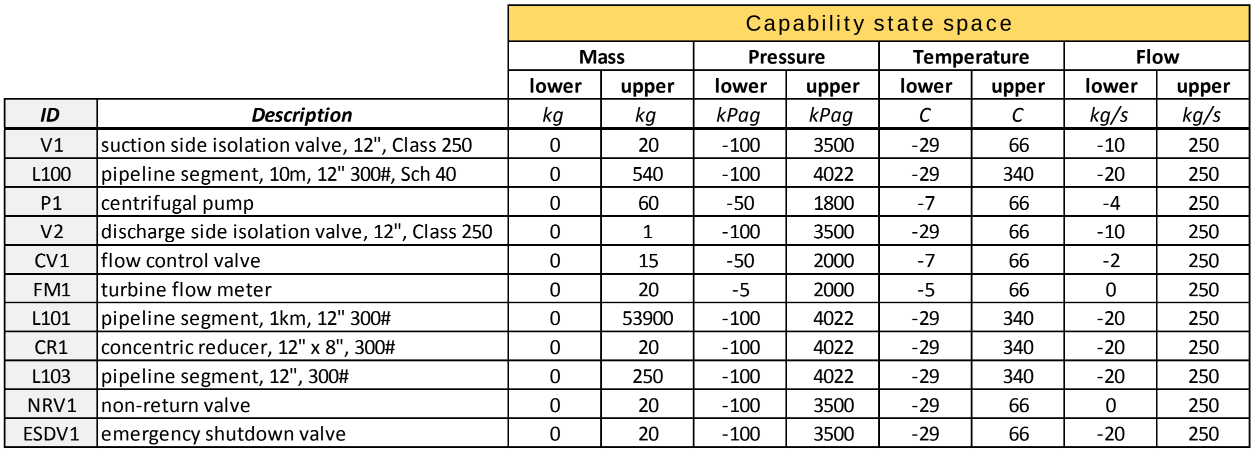
If we were assembling such a transfer system then as components such as pipelines, valves, pump and other items are placed and joined together we can track how the Functional State Space and Operational State Space evolves. In this case we use the linear representation and consider key physical properties that include mass, pressure, temperature and flow. Figure 6 shows the transfer system as well as the key capabilities of the 11 components.

It should be recognised that some capabilities are "latent", as they are often not specifically activated but they play a vital role in system integrity. For most components the two key latent capabilities are:

- <withstand><pressure>
- <withstand><temperature>

These latent capabilities are important and are related to the choice of specific components that are temperature and pressure related. This refers to pipework components and also to some rotating machinery such as pumps and compressors. In this case we have set the upper range of pressure and temperature to the maximum allowable working pressure/temperature.

Figure 5 shows the adopted capability intervals for the components used in the fuel transfer system. These are based on a Class 300 DN300 Schedule 40 transfer pipeline and associated components.



		Capability state space							
		Mass		Pressure		Temperature		Flow	
		lower	upper	lower	upper	lower	upper	lower	upper
ID	***Description***	*kg*	*kg*	*kPag*	*kPag*	*C*	*C*	*kg/s*	*kg/s*
V1	suction side isolation valve, 12", Class 250	0	20	-100	3500	-29	66	-10	250
L100	pipeline segment, 10m, 12" 300#, Sch 40	0	540	-100	4022	-29	340	-20	250
P1	centrifugal pump	0	60	-50	1800	-7	66	-4	250
V2	discharge side isolation valve, 12", Class 250	0	1	-100	3500	-29	66	-10	250
CV1	flow control valve	0	15	-50	2000	-7	66	-2	250
FM1	turbine flow meter	0	20	-5	2000	-5	66	0	250
L101	pipeline segment, 1km, 12" 300#	0	53900	-100	4022	-29	340	-20	250
CR1	concentric reducer, 12" x 8", 300#	0	20	-100	4022	-29	340	-20	250
L103	pipeline segment, 12", 300#	0	250	-100	4022	-29	340	-20	250
NRV1	non-return valve	0	20	-100	3500	-29	66	0	250
ESDV1	emergency shutdown valve	0	20	-100	3500	-29	66	-20	250

Figure 5. Capability ranges for transfer pipeline components

Items such as ‘upper’ flow rates were based on flow levels that result in uneconomic pressure drop through the system. Other limits were based on maximum allowable working conditions of the components.

Using the capability sets it is now possible to construct the Functional State Space (FSS) for each of the key system properties, as well as the Operational State Space (OSS). In this case we choose the mass holdup, pressure and flow as key properties.

Consider the first few components being assembled. By following the normal flow direction we see how the FSS evolves as components are added to the system.

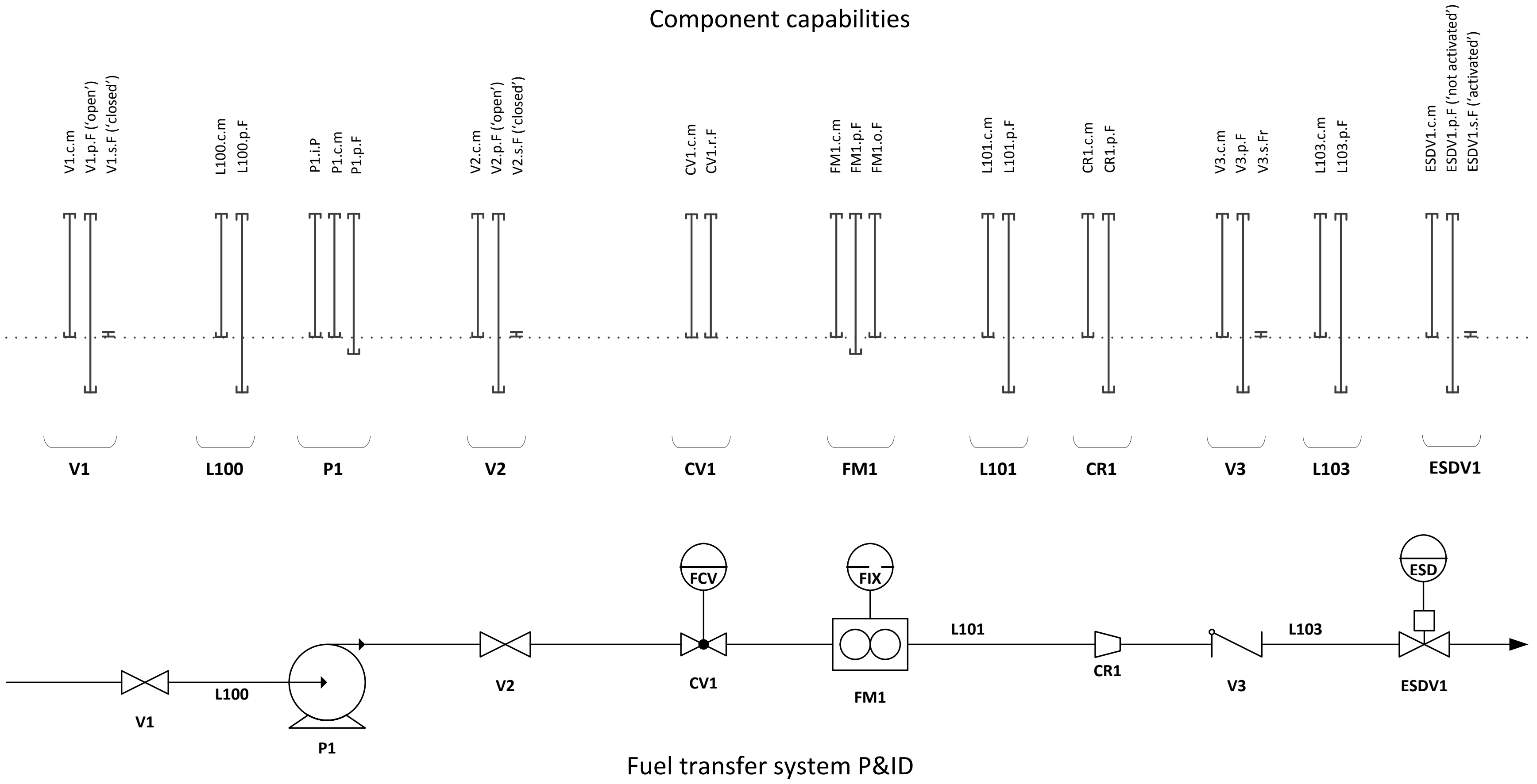
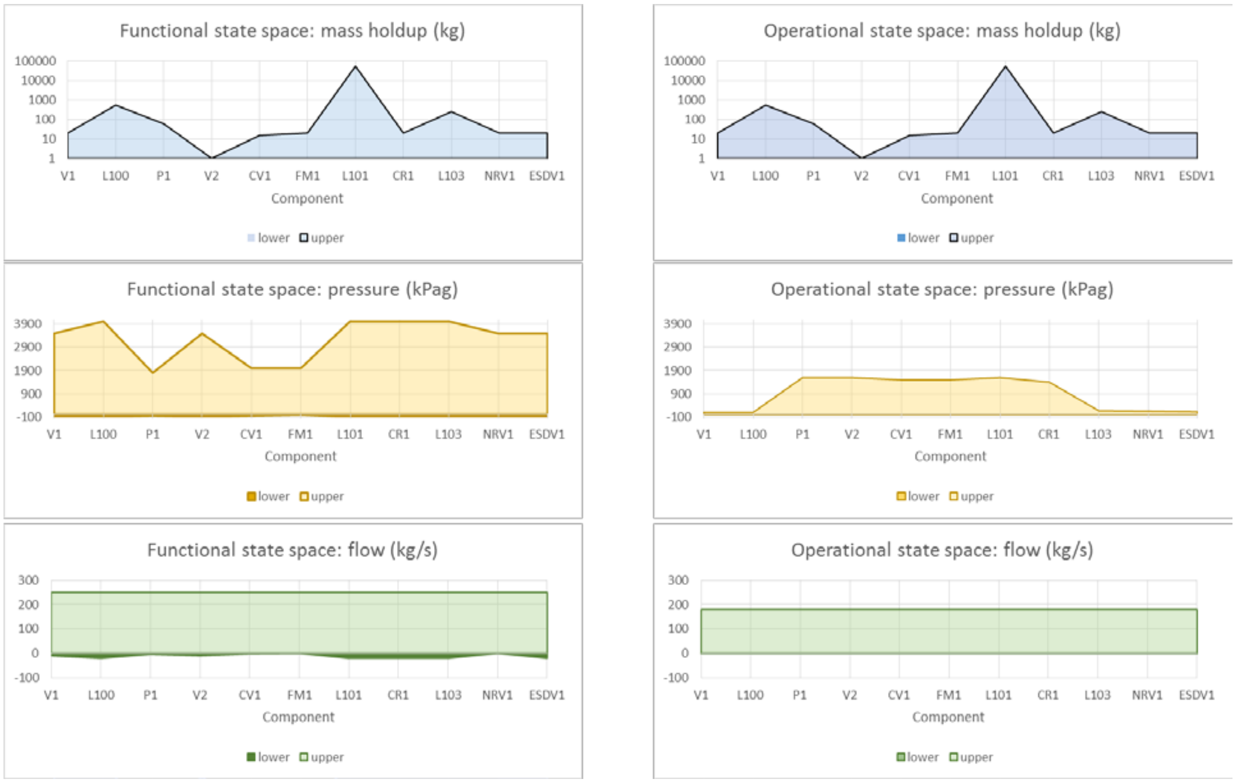


Figure 6. Fuel transfer system showing key component capabilities (with assumed latent capabilities for pressure/temperature limits)

FSS and OSS representations of the transfer system

Area plots can be used to show the various state spaces that are generated by the design. In this case it is the FSS and the OSS of the system. The FSS can be seen in Figure 7 across the first 3 components.


Functional state space: mass holdup (kg)

Operational state space: mass holdup (kg)

Functional state space: pressure (kPag)

Operational state space: pressure (kPag)

Functional state space: flow (kg/s)

Operational state space: flow (kg/s)

Figure 7. FSS and OSS for mass, pressure and flow

The following observations on Figure 7 can be made:

1. The FSS area plots represent the limits in mass, pressure and flow that are allowable for the selected components.
2. The FSS profiles show the variation across the transfer system (V1, L100, … , ESDV1).
3. The large mass holdups at L100 and L101 represent the inventory of the 10m and 1000m pipe segments.
4. The OSS area plot for mass is the same as the FSS for mass.
5. The OSS for pressure and flow show that the OSS boundary lies inside the equivalent FSS. This is an operational choice.

Figure 8 shows the comparative FSS-OSS capability profiles for pressure and flow. It clearly shows the operational “back-off” from the maximum allowable limits.

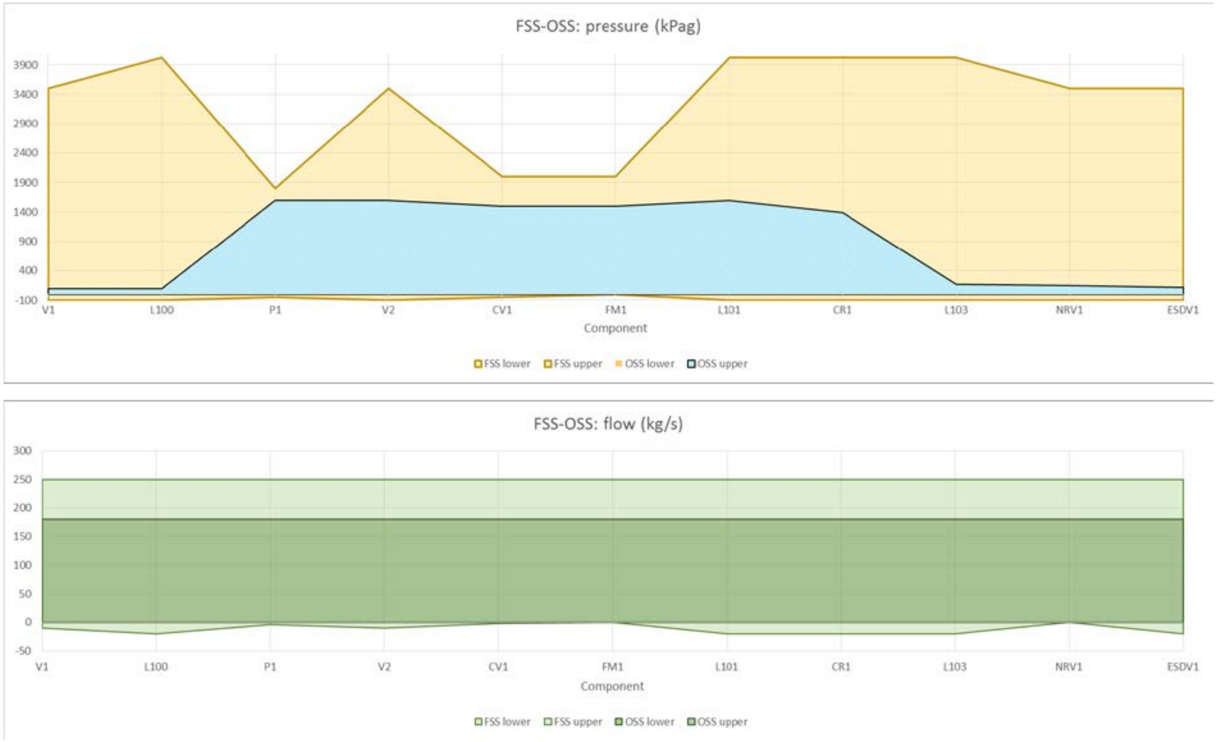


Figure 8. FSS-OSS comparison and degree of operational "back-off"

Visualizing failure scenarios

To illustrate the visualization of failure we consider two possible component failures:

- Failure case #1: A rupture of the flow meter component (FM1)
- Failure case #2: A failure of the control valve (CV1) to remain open (fail ‘closed’)

These two failures lead to changes in both the FSS and OSS of the system due to failure or loss of capabilities.

In case #1, the capability of <contain><mass> is lost with a subsequent change in the Functional State Space contribution of FM1. There is also by implication an immediate effect on the process stream, in that the failure generates a high flow to the environment. This is clearly a loss of containment event.

Figure 9 shows the mass holdup situation for failure case #1, where the OSS profile for failure changes significantly where FM1 is located in the transfer system. It should be noted that the FSS changes only at the FM1 component and other downstream components are unaffected in their functionality. Other plots can easily show the failure in flow through the system as well as loss of pressure downstream.

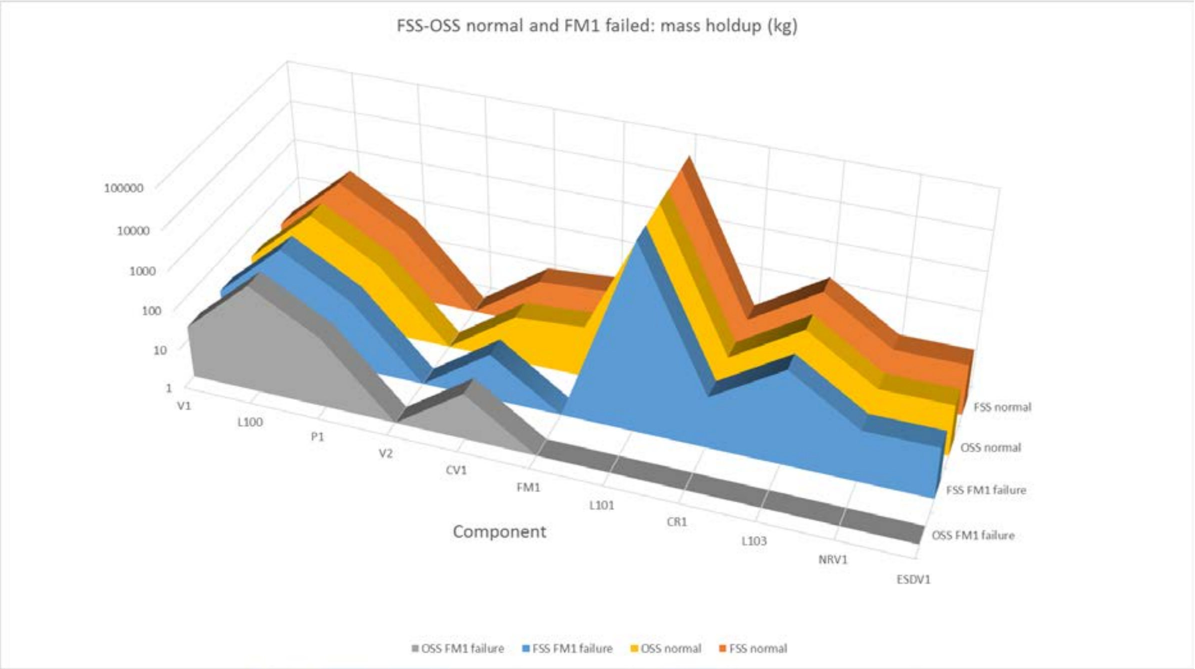


Figure 9. Comparison of "normal" and "failure" conditions related to FM1 operations

In Case #2, there is no loss of containment but there is a loss of capability to *<permit><flow>*. Figure 10 shows the pressure profiles for the FSS and OSS in normal and failed states. It clearly shows a major change in system pressure downstream of the failed control valve. Figure 11 shows the various state spaces for the equivalent flow property.

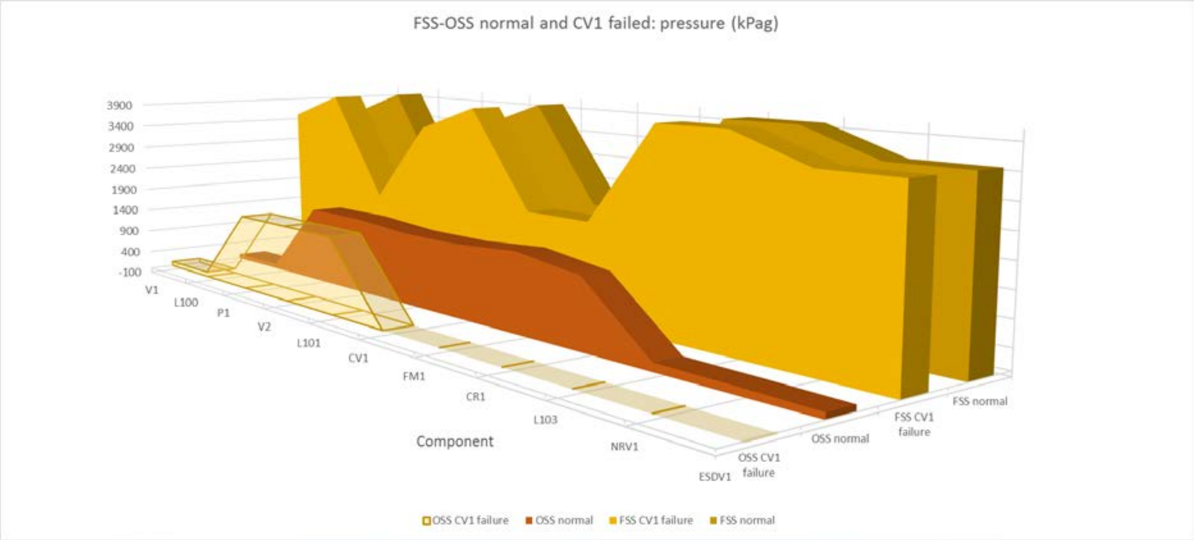


Figure 10. Comparison of "normal" and "failure" pressure situations for CV1 failed 'closed'

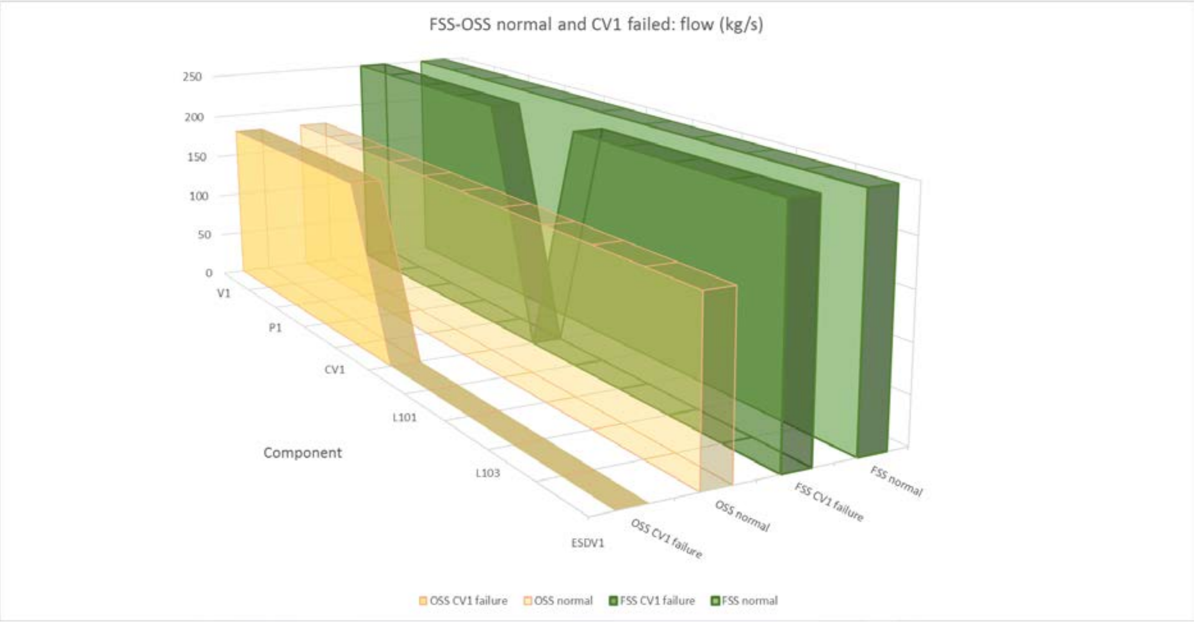


Figure 11. Comparison of "normal" and "failure" flow situations for CV1 failed 'closed'

Figure 11 shows how the FSS for flow drops to zero at CV1 due to the ‘fail closed’ condition, whilst other components remain functional. The impact of the CV1 failure leads to no flow downstream from CV1 as seen in the OSS CV1 failure profile.

All these results show visually how using the underlying capability sets for each component it is possible to visualize very clearly the effects of failures.

Conclusions

Displaying activated capability sets and property values of a process system gives access to a clear and simple representation of instantaneous system operation. The simplicity of the visual display is a great strength, where interpretation of the area plots can be done quickly and accurately to understand the current state of the system.

The ability to display the functional state space and the corresponding operational state space in the same visualisation has the benefit of showing the observed values from measured variables and the current status of each equipment item. This supports online operations for improving fault detection and diagnosis, since the effect of failures on downstream operations can be observed and linked to specific equipment failures, shown in terms of deactivated capabilities. Future applications include linking of the visualisation engine to distributed control system (DCS) data. This would allow for the detailed testing of this method to establish its utility for supporting operational decision making during failure scenarios.

Simultaneously observing the current function and operational state also provides insight for supporting process design. The capability sets and corresponding area plots will change as equipment is added to an existing design. This feature allows many potential design scenarios to be developed and the resilience of the system tested, where the proportion of activated to latent capabilities can be altered to investigate the redundancy and robustness of the system to failures. Future applications in the design space could include developing a software plugin to process simulators to show the evolving design as the flowsheet is built. This visual approach to design would also help guide chemical engineering students as they develop fundamental knowledge and skills in process design.

The method presented here for visualising the state space of a process system gives insight into current functional and/or failure scenarios, providing support for process design development and operational decision making across the life cycle.

References

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