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New Visualizations in the Development of Function and Failure in Process Design and Operations

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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 considers useful ways 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, defines the potential space in which the system can normally operate. It can also quickly show the impact on that state space when selected capabilities are degraded or lost. It can be used in conjunction with process design tools to show in real-time the evolution of the design and the impacts of component failures on the operations.
An industrial case study drawn from crude oil processing illustrates the visualization insights and benefits of the proposed methodology.

1. 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 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. Function arises from the individual capabilities possessed by plant components (Seligmann et al., 2012). 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.

Failure and/or degradation of capabilities change the CSS and FSS respectively. Such changes show whether the designed OSS remains feasible, or if latent capabilities might be activated to retain feasible operation.

Alternatively, changes in the actual OSS can suggest process design changes for improved operational performance.

2. System concepts

Figure 1 shows the following state space concepts:

- The Lawful State Space (LSS), which constitutes a space where the laws of physics, chemistry and thermodynamics are valid (Bunge 1977).
- 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.

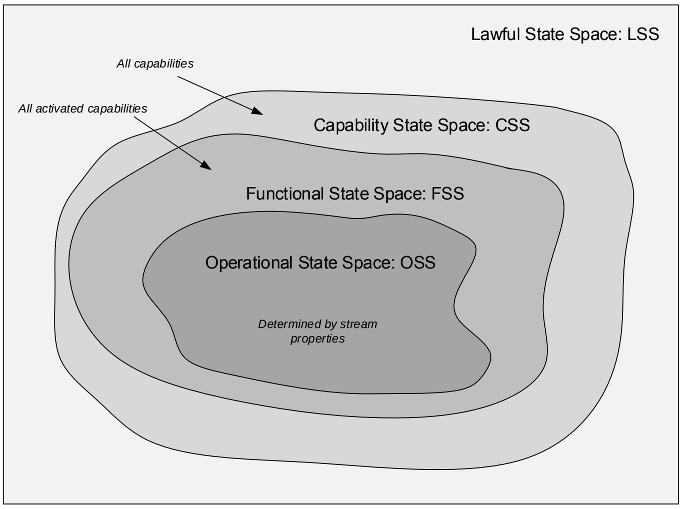

Figure 1. State space regions

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

2.1 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. Tables 1 and 2 describe the capability sets for some basic flowsheet components.

Table 1. Capability sets for basic flowsheet components

Component	Capability Set
Gate valve	{<contain><m>,<permit><Ff>,<stop><Ffr>}
Centrifugal pump	{<contain><m>,<permit>< Ff>,<increase><P>, …}
Control valve	{<contain><m>,<permit><Ff>,<regulate><Ff>, …}
In-line flow meter	{<contain><m>,<permit><Ff>,<observe><Ff>, …}
Non-return valve	{<contain><m>,<permit><Ff>,<stop><Fr>, …}
Pipe section	{<contain><m>,<permit><Ff>, …} or {<contain><M>,<permit><Ff>, …}
Pressure relief valve	{<contain><m>,<permit><Ff>,<stop><Fr>}
Dry oil tank	{<contain><m>,<permit><F>,<separate><Ø>}

Table 2. Symbol definitions for basic flowsheet components

Symbol	Definition	Symbol	Definition
F	Flow	m	Component mass:{m(i), i=1(1)n}
Ff	Forward flow	x	Composition:{x(i), i=1(1)n}
Fr	Reverse flow	M	Total mass
Ffr	Forward and reverse flow	Xs	Solids fraction
P	Pressure	Ø	Phase
T	Temperature		

2.2 Operation modes

Operational modes of the system are important. A gate valve has two main operational modes: ‘open’ or ‘closed’. Different sets of capabilities need to be activated for each operational mode. 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>.

2.3 Geometric representation of capability sets

Capabilities have two parts: action and property. The action part affects the range of the capability, such as <increase><pressure> in a pump. The action, ‘increase’, acts on the nominated stream property ‘pressure’ causing an increase in the fluid pressure. Visually a capability can be represented as a line interval with various constraints. Three capabilities are shown in Figure 2. The marking points are 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.

Various types of capabilities can be represented on a single diagram. Grouping and ordering arrangements can provide different meanings and/or better understanding. We examine the value of utilising this approach for visualising function.

3. Case study

Figure 3 shows the system under consideration. Crude oil, gas and residual sand enter into a dry oil tank (DOT101) from bulk oil treatment. In the vessel, gas and oil are separated, sand is retained by a weir. Crude oil is pumped downstream under level control through the LACT booster pumps and other processing facilities. Gas is discharged to compression facilities. A purge and LP blanket gas feed maintains the operating pressure. The design pressure of DOT101 is 1050kPag at 120ºC. Multiple pressure safety valves are incorporated. Figure 3 shows the capability sets and the dashed, highlighted plant section under study.

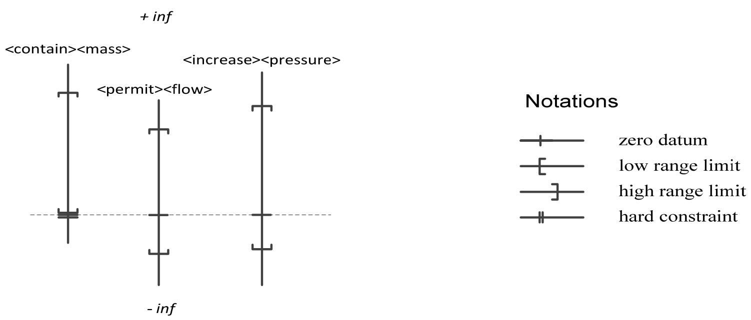

Figure 2. Example of linear representation of a set of capabilities

Some capabilities are ‘latent’, but they play a vital role in system integrity. Most components have two key latent capabilities: <withstand><pressure> and <withstand><temperature>. Note that in Figure 3 the capabilities are described as the triplet: <component><action><property>, e.g. DOT101.p.F. Figure 4 shows the numeric capability intervals. Mass holdup, pressure and flow are key system properties and Figure 5 shows the shape and profile of these key properties.

The charts show the capability profiles across the subsystem from L101 to L112. The functional state space (FSS) can be seen in relation to the OSS. It is now possible to observe the effect of failures in any component and the resultant impact on the FSS and OSS.

3.1 Visualizing component failure

To see how a component failure influences the FSS and the OSS representations we look at a failure mode in the emergency shutdown valve ESDV2 of 'failed closed' when operating in 'open' mode. Figure 6 shows that the ESDV2 closure leads to significantly reduced inventories downstream of the closed ESDV2 component, and a rise in the operating liquid inventory within the dry oil tank.

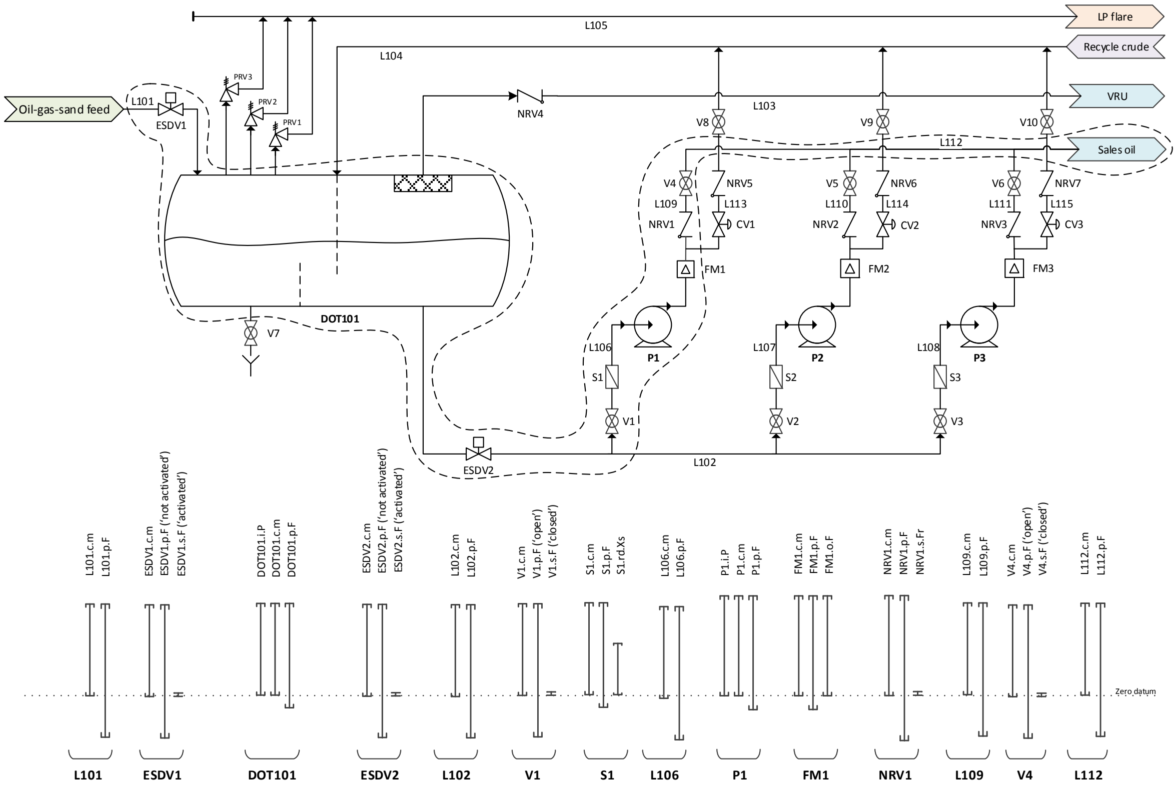

Figure 3. Dry oil tank and crude oil transfer system with component capability sets

		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
L101	pipeline segment: 30m DN750, Class 150	0	9278	-100	1700	-29	150	-10	250
ESDV1	emergency shutdown valve, Class 150	0	93	-50	1700	-29	150	-20	250
DOT101	dry oil tank, 85m3 capacity, Class 150	0	84673	-20	1870	0	150	-4	250
L102	pipeline segment: 15m DN400, Class 150	0	1319	-100	1700	-29	150	-10	250
ESDV2	emergency shutdown valve, Class 150	0	26	-50	1700	0	150	-2	250
V1	isolation gate valve, Class 150	0	15	-5	1700	0	150	0	250
S1	line strainer, Class 150	0	15	-50	1700	-29	150	-20	250
L106	pipeline segment: 3m DN300, Class 150	0	148	-100	1700	-29	150	-20	250
P1	centrifugal pump, Class 300	0	25	-20	3500	-29	150	-20	250
FM1	flow meter, Class 300	0	15	-50	3500	-29	150	0	250
NRV1	non-return valve, Class 300	0	15	-50	3500	-29	150	-20	250
L109	Class 300 pipeline segment: 3m DN250	0	103	-100	3500	-29	150	-20	250
V4	line isolation valve, Class 300	0	10	-50	3500	-29	150	-20	250
L112	pipeline segment: 10m DN400, Class 300	0	880	-100	3500	-29	150	-20	250

Figure 4. Capability ranges for oil transfer section

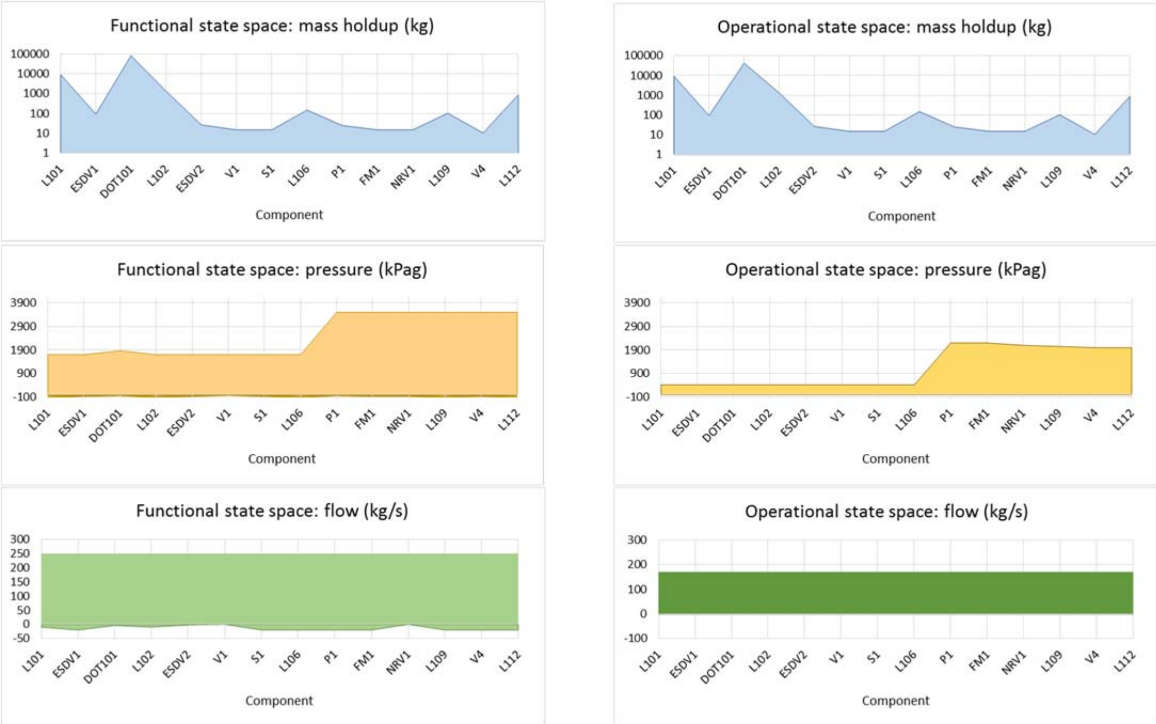

Figure 5. Functional State Space and Operational State Space for mass, pressure and flow

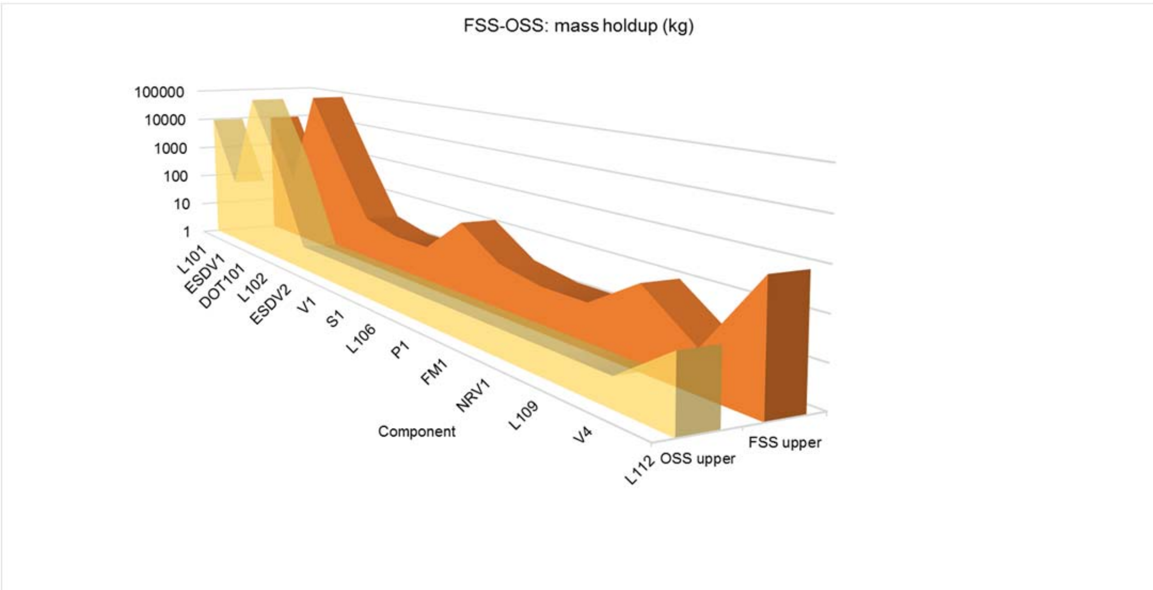

Figure 6. FSS-OSS mass holdup (kg) across system after ESDV2 'fails closed'

In Figure 7 we see that the ESDV2 'failed closed' situation has impacted significantly on the downstream pressure reducing this to almost zero. The ESDV2 component is now unable to fulfil the capability of <permit><flow> and the pump P1 is starved of liquid feed and hence cannot generate a pressure head.

Likewise in Figure 8 we see that no liquid flow proceeds from the DOT101 liquid discharge but the tank can still fill with liquid as seen in Figure 6.

The visualizations are informative and reflect the implications from component failures. These can be linked to other causal representation such as directed graphs as discussed by Németh and Cameron (2013).

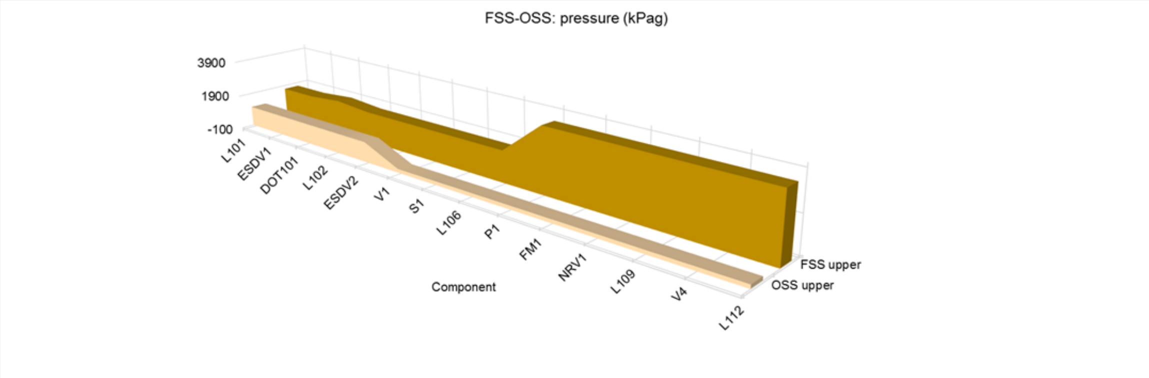

Figure 7. FSS-OSS pressure change across system after ESDV2 'fails closed'

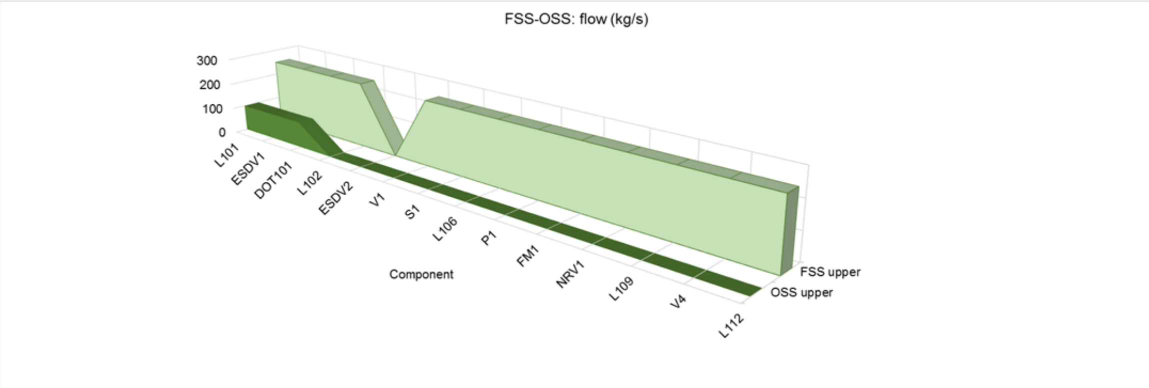

Figure 8. FSS-OSS flow (kg/s) across system after ESDV2 'fails closed'

4. Conclusions

This work has shown that it is feasible to take component capability sets related to flowsheet equipment and represent them by three primary state spaces that can then be easily visualized. These state spaces can then be used by designers and operators to inform them of the implications of process component choices. This is particularly the case when failures occur that disrupt the functional state space through loss of component capabilities.

The ability to augment traditional design tools such as process simulators and CAD tools with real-time visualizations of the capability, functional and operating state spaces can provide immediate insights into design decisions and would lead to concurrent engineering practices that would enhance design efficiencies and provide early indications of the failure scenarios within a design. The visualization capabilities can be enhanced to consider the role of latent capabilities within the design that can be activated to enhance resilience in the system against system failures and major disturbances on the system. These insights should help towards enhancement of process safety at both design and operational phases of the process life cycle.

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