Platform identification using Design Structure Matrices

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Abstract: This paper introduces a methodology and algorithm for the qualitative identification of platform components at multiple levels of system aggregation, among variants within a family of systems. We assume that the architectural concept and the functional requirements for the variants are pre-determined, and use Sensitivity Design Structure Matrices (SDSM) to represent the sensitivities between the design variables of the variants. We then introduce a novel algorithm for the identification of platform variables given the SDSM for each variant. Finally, the methodology is extended to the qualitative identification of platforms at various levels of system aggregation, i.e., between systems, subsystems and components. The process is demonstrated in an example of platform identification among topsides facilities of Floating Production, Storage and Offloading (FPSO) units.

Keywords: Design Structure Matrix (DSM), platform, standardization, Design Rules

Introduction

Increasingly, a big contributor to competitive advantage is a firm's ability to balance between requirements for highly customized products and systems and standardized platforms. The motivation for customization comes from necessary change in product portfolios, embracement of new technology and evolution of product lines to changing consumer requirements. At the same time, production costs must be driven down using economies of scale, lead times must be shortened, and inventory must be minimized. Besides static goals such as the above, firms also strive to minimize risks (Ulrich 1995) and increase flexibility (Suh 2005) to respond to environmental threats and opportunities. Fricke and Schultz (2005) cite many examples from the automotive and other industries where product variety has increased over the past 20 years, while production costs have declined. This is the result of a relatively new and evolving body of literature, emanating both from the industry and academia, that advances and integrates concepts and methodologies, traditionally "owned" by disciplinary fields such as systems optimization or management science. Fricke and Schultz provide an excellent account under the name "Design

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for Changeability." A subset of these methodologies provides a solution approach to address the trade-off between customization and differentiation across multiple product lines, and the minimization of fixed and variable costs. An inclusive name for these methods is *product platforming*.

A *product platform* is a common set of subsystems, components, processes, interfaces etc. shared by all *variants* in a product family (Meyer & Lehnerd 1997). Platforms may emerge as product families evolve; in this case, the platform components and processes are those that are simply found to be common between variants. Alternatively, platforms may be imposed as a conscious decision on a collection of variants. In either case, platform components, systems or processes end up constraining the variants' design: because of the requirement that a platform component or process is identical in all variants, customized components are necessarily designed to be compatible with the platform; indeed, the range of possible (or desirable) customization in the entire product family is dictated by the platform (de Weck 2006).

For some systems, the choice of the platform systems or processes between variants is straight forward: it may be intuitive or emerge naturally from the historical evolution of multiple variants. Potential platforms are those systems that act as "buses" in some way (Yu et al. 2003), or those that provide interfaces between other, customized systems. On the other hand, the deliberate identification of platforms is more difficult in network-like systems or systems in which platforms are comprised of subsystems and components from various levels of system aggregation. Platform identification is equally cumbersome in very large and complex systems.

This paper introduces a methodology for the qualitative identification of collections of subsystems and components that comprise feasible platforms. This contribution is relevant for systems in which platform identification is not intuitive or historically emergent. It is assumed that the architectural concept and the specifications for the product variants are given. The methodology is based on Design Structure Matrices (DSM, Steward 1981, 1991) and specifically the Sensitivity-DSM (Yassine and Falkenburg, 1999) to model how exogenous effects propagate through the interdependent components of a system. Related concept was presented in a seminal work by Sullivan et al. (2001). The main concept in this work is that the elements of the DSM that are not sensitive, directly or indirectly and within a certain tolerance, to exogenous changes, are potentially members of the platform collection of components. In short, the platform provides the *Design Rules* for the product family (Baldwin & Clark 2000).

The paper develops the concepts by first identifying platforms as collections of design variables using a novel algorithm. We then take a more qualitative approach to describe how the methodology can be used to identify platforms on multiple levels of system aggregation. The methodology is demonstrated using an example from the oil industry.

Platforms as collections of design variables

All variants in a product family will share some commonality in the arrangement of components, their interactions, and their mapping between function and form (Martin and Ishii 2002). Variants in a product family thus share a *platform architecture*, i.e., a common "scheme by which the function of a product is allocated to physical components" (Ulrich 1995). This common architecture will most often be reflected in an identical system model between variants of a product line, i.e., an identical set of equations and variables that describe the system's response. Given a common set of variables that describe the family architecture for each variant, it is possible to represent the architecture of all variants within a product line in a Design Structure Matrix (DSM).

System Representation

DSM's provide a structured methodology for representing systems and processes. The term DSM summarizes a variety of different uses of essentially the same structure, i.e., a square matrix where each row (and the respective column) corresponds to a single "element." Interactions between elements are represented as "1" (or another mark, often "x") in the off-diagonal entries of the matrix body. Depending on what the elements represent, DSMs are usually referred to as "component-based," "variable-based," "activity-based" or "team-based." Interactions between components represent material or energy flows or even spatial relationships in a static system. A symmetric interaction between two variables means that they are coupled and need to be determined jointly; such interactions do not include any notion of time. Finally, interactions in activity-based DSMs represent precedence between tasks, therefore the order of the activities corresponds to the order in which activities are performed (Browning 2001).

A mapping usually exists between component, activity and team-based DSMs (Eppinger and Salminen 2001): system components are regarded as distinct line items in a work breakdown structure and are therefore treated as separate design activities. In turn, these design activities are assigned to separate teams. Furthermore, the relationship between a component-based and a parameter-based DSM is usually at the level of aggregation in describing a system. Consider for example a DSM representing the design of a system where each component is fully characterized by a single parameter: the component-DSM and parameter-DSM for such a representation would coincide. Establishing these links between the different DSM types will prove explanatory for the later part of the paper; this section focuses on parameter-based DSMs only.

Consider a system whose response and performance can be fully described using *n* variables $\mathbf{x} = \{x_1, x_2, \ldots x_n\}$, which are coupled in a model of equations. The corresponding variable-based DSM is the square matrix with *n* rows and columns, whose entries *i,j* and *j,i* are equal to "1" (symbolically, $DSM(i, j) = DSM(j, i) = 1$) if the two variables *i* and *j* are coupled. In this sense, a variable-based DSM is an N^2 matrix, and represents the architecture of a system. Particular values of the variables correspond to variants $\mathbf{x}^* = \{x_1^*, x_2^*, \ldots x_n^*\}$ within the architecture described by the DSM.

A sensitivity DSM (SDSM) is also a square matrix with *n* rows and columns. The entry i, j of an SDSM, however, represents the normalized sensitivity of parameter i to unit changes in parameter j in the neighborhood of the particular solution: $SDSM(i, j) = (\partial x_i^* / \partial x_j^*)(x_j^* / x_i^*)$. In other words, entry i, j represents the percent change in variable i caused by a percent change in variable j. For this reason, a sensitivity DSM is always more sparsely populated than a variable-DSM: a variable may depend on another variable, but its sensitivity to changes in the latter may be zero.

System or product variants exist to cover different commercial, marketing or societal needs and objectives that are completely exogenous to the system, i.e., design decisions cannot affect them. Examples of *exogenous factors* in the automotive industry are the condition of the roads in the region a vehicle is marketed and the typical weather. Marketing studies can translate exogenous factors to *functional requirements.* Functional requirements are performance or response targets the system has to meet, and as such they depend on both exogenous factors as well as the design variables of the system. Using the previous automotive example, a functional requirement affected both by the road quality as well as design variables is a measure of softness of a car's suspension system. Let the functional requirements for system variant $\mathbf{x}^*$ be denoted by a vector $\mathbf{FR}^* = \{FR_1^*, FR_2^*, ..., FR_m^*\}$.

The SDSM can be extended to include the vector of functional requirements (Figure 1). The south-western quadrant of the extended SDSM is populated by the sensitivities of design variables to exogenous parameters; the main body of the SDSM (south-east quadrant) contains the sensitivity of design variables to other design variables for the particular solution.

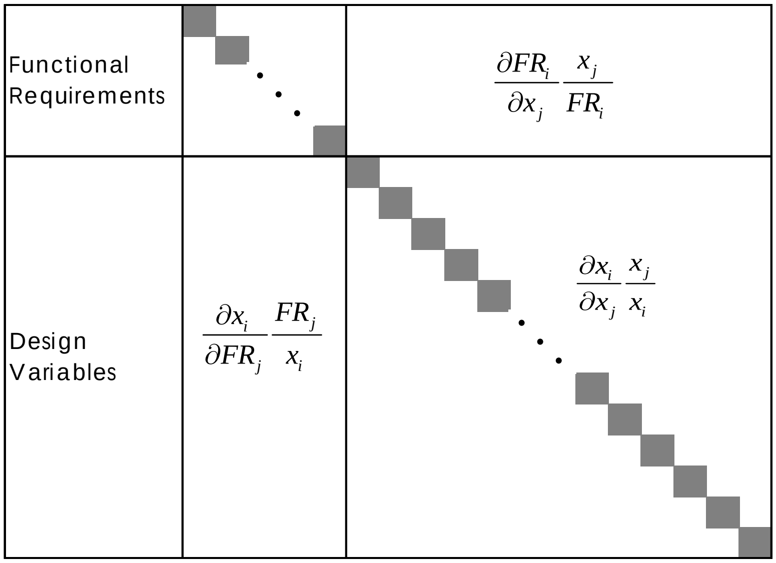

Functional Requirements
$\frac{\partial FR_i}{\partial x_j}\frac{x_j}{FR_i}$
Design Variables
$\frac{\partial x_i}{\partial FR_j}\frac{FR_j}{x_i}$
$\frac{\partial x_i}{\partial x_j}\frac{x_j}{x_i}$

Figure 1: Normalized SDSM, extended to include exogenous parameters

Change propagation

Consider a particular solution $\mathbf{x}^* = \{x_1^*, x_2^*, \ldots x_n^*\}$ to the system model, and a small change $\Delta\mathbf{FR}$ in some of the functional requirements $\mathbf{FR}^*$ on which this solution was based. The question is to find those design variables that will need to change to facilitate this perturbation in $\mathbf{FR}^*$, and those that may remain the same.

Assume the system model behaves linearly for the changes in design variables necessary to achieve a perturbation $\Delta\mathbf{FR}$ in the functional requirements. Then each design variable x_i will need to change by Δx_i:

$$\Delta x_i = \sum_{j=1}^{m} \frac{\partial x_i^*}{\partial FR_j^*} \Delta FR_j^* + \sum_{s=1}^{n} \frac{\partial x_i^*}{\partial x_s^*} \Delta x_s^* \qquad (1)$$

This simply says that the required change in x_i is the cumulative change caused by all the functional requirements and other design variables to which x_i is sensitive in the neighborhood of x_i^*.

If every term in the sums in equation (1) is zero, then Δx_i will be zero. Writing this separately for each summation we obtain conditions (2) and (3). These conditions are sufficient but not necessary: in theory, the sum of the terms in equation (1) can be zero without necessarily all the terms being zero.

$$\frac{\partial x_i}{\partial FR_j} \Delta FR_j = 0 \qquad \text{for all } j = 1...m \qquad (2)$$

$$\frac{\partial x_i}{\partial x_s}\Delta x_s = 0 \qquad \text{for all } s = 1...n \tag{3}$$

Conditions (2) and (3) indicate whether the change introduced in the functional requirements propagates to design variable x_i. A change can propagate to variable x_i because x_i directly depends on an affected functional requirement, or because x_i is sensitive to changes in some other variable that in turn is sensitive to changes. If both conditions (2) and (3) are satisfied for x_i, then the change does not propagate to variable x_i and therefore is common between the designs that satisfy functional requirements $\mathbf{FR}^*$ and $\mathbf{FR}^* + \Delta\mathbf{FR}$. In other words, it is a platform variable for these designs.

Platform identification

The problem is to find the partitioning of the design vector $\mathbf{x} = \{\mathbf{x}_p, \mathbf{x}_c\}$ that contains the greatest number of platform variables $\mathbf{x}_p$ (and the least number of customized variables $\mathbf{x}_c$), given the functional requirements $\mathbf{FR}^\alpha$ and $\mathbf{FR}^\beta$ corresponding to differences in exogenous factors affecting the two variants α and β. Given $\mathbf{x}_p$, the design variables of each variant can be written as in equation (4).

$$\begin{aligned} \mathbf{x}^\alpha &= \{\mathbf{x}_p, \mathbf{x}_c^\alpha\} \\ \mathbf{x}^\beta &= \{\mathbf{x}_p, \mathbf{x}_c^\beta\} \\ \mathbf{x}^* &= \{\mathbf{x}_p, \mathbf{x}_c^*\} \end{aligned} \tag{4}$$

Consider a variant $\mathbf{x}^*$ designed to functional requirements $\mathbf{FR}^*$ [1]. Variant $\mathbf{x}^*$ is essentially an unknown starting design point, from which variants are examined based on their differences in functional requirements according to the previous section. If each of the two $\mathbf{x}^\alpha$ and $\mathbf{x}^\beta$ share the same platform variables with $\mathbf{x}^*$, then they also share the same platform variables.

According to condition (2), a design variable x_i may be a platform variable between $\mathbf{x}^*$ and $\mathbf{x}^\alpha$ if

$$\left.\frac{\partial x_i}{\partial FR_j}\right|_* (FR_j^\alpha - FR_j^*) = 0 \qquad \text{for all } j = 1...m \tag{5}$$

where $\cdot\,|_*$ denotes that the quantity is evaluated in the neighborhood signified by $*$. If condition (2) applies as well between variants $\mathbf{x}^*$ and $\mathbf{x}^\beta$,

$$\left.\frac{\partial x_i}{\partial FR_j}\right|_* (FR_j^\beta - FR_j^*) = 0 \qquad \text{for all } j = 1...m \tag{6}$$

then variant $\mathbf{x}^*$ can be operated under either functional requirements $\mathbf{FR}^\alpha$ or $\mathbf{FR}^\beta$, and design

[1] This variant can coincide with α or β, or be a completely different design conforming to either functional requirements $\mathbf{FR}^\alpha$ and $\mathbf{FR}^\beta$. If $\mathbf{x}^\alpha = \mathbf{x}^\beta$ then $\mathbf{x}^\alpha$ is meant to be the “base” design and $\mathbf{x}^\beta$ is its evolution, and vice-versa.

variable x_i^* will not be directly impacted by this change. This is shown by subtracting condition (6) from (5):

$$\left.\frac{\partial x_i}{\partial FR_j}\right|_* (FR_j^{\beta} - FR_j^{\alpha}) = 0 \qquad \text{for all } j = 1...m \tag{7}$$

Similarly, condition (3), written for design variable x_i, between variants $\mathbf{x}^*$ and $\mathbf{x}^{\beta}$ becomes

$$\left.\frac{\partial x_i}{\partial x_s}\right|_* (x_s^{\beta} - x_s^*) = 0 \qquad \text{for all } s = 1...n \tag{8}$$

Written for design variable x_i, between variants $\mathbf{x}^*$ and $\mathbf{x}^{\alpha}$, condition (3) becomes

$$\left.\frac{\partial x_i}{\partial x_s}\right|_* (x_s^{\alpha} - x_s^*) = 0 \qquad \text{for all } s = 1...n \tag{9}$$

Subtracting (9) from (8) yields the condition for insensitivity of variable x_i^* to changes in any other variable in the range $\mathbf{x}^{\beta} - \mathbf{x}^{\alpha}$:

$$\left.\frac{\partial x_i}{\partial x_s}\right|_* (x_s^{\beta} - x_s^{\alpha}) = 0 \qquad \text{for all } s = 1...n \tag{10}$$

Together, equations (7) and (10) are the sufficient conditions for design variable x_i^* to be part of the shared platform between variants $\mathbf{x}^*$, $\mathbf{x}^{\alpha}$ and $\mathbf{x}^{\beta}$. For each j, condition (7) will be true if (a) $FR_j^{\beta} - FR_j^{\alpha} = 0$, i.e., functional requirement j does not change despite changes in exogenous factors, or (b) if the partial derivative $[\partial x_i / \partial FR_j]_*$ is zero. Therefore, platform components can only be sensitive to changes in functional requirements that are invariant to changes in exogenous factors. Likewise, condition (10) will be true for variable s if $x_s^{\beta} - x_s^{\alpha} = 0$ or $\left.\partial x_i / \partial x_s\right|_* = 0$. Therefore, platform components can only be sensitive to unit changes in the design specifications of other platform components. Conditions (11) and (12) define the set of platform variables. Condition (11) says that all platform variables must be insensitive to changes in functional requirements between the variants considered. Condition (12) says that platform variables must be insensitive to customized variables for the variants considered.

$$\left.\frac{\partial x_p}{\partial FR_c}\right|_* = 0 \qquad \forall c, p \tag{11}$$

$$\left.\frac{\partial x_p}{\partial x_c}\right|_* = 0 \qquad \forall c, p \tag{12}$$

A sensitivity DSM of the variant $\mathbf{x}^*$ can be partitioned to isolate the platform variables, as Figure 2 shows. The functional requirements that change between the variants are listed first, followed by the platform variables. Last are the customized design variables. Conditions (11) and (12) imply that the blocks East and West of the diagonal block of platform variables must be equal to zero by definition.[2]

[2] Or almost equal to zero, depending on the accepted tolerance.

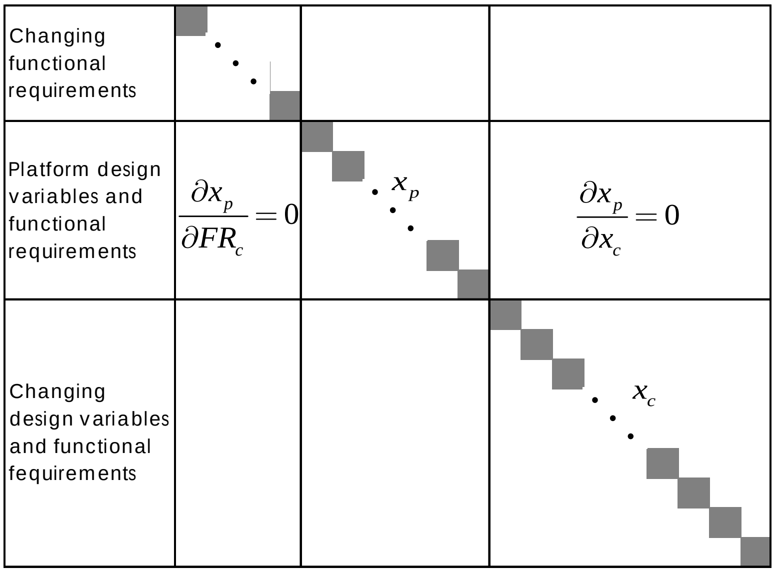

Changing functional requirements
Platform design variables and functional requirements
$\frac{\partial x_p}{\partial FR_c} = 0$
x_p
$\frac{\partial x_p}{\partial x_c} = 0$
Changing design variables and functional fequirements
x_c

Figure 2: Invariant Design Rules on an S-DSM

The re-arrangement of the SDSM in Figure 2 shows why the platform variables provide the design rules for the variants in the product family. Design rules is the name coined by Baldwin and Clark (2000) to refer to the system components or variables that are established first in the design process and dictate the design of other components of variables. Therefore, design rules are unaffected by other variables, while at the same time they constrain the design of other variables. Platform components are thus design rules as the block on their East is zero and the block right below them, denoting sensitivity of the customized variables to platform variables, is generally non-zero.

Algorithm for platform identification

This section presents an algorithm for the identification of the largest set of platform variables. The algorithm operates on the SDSM of Figure 1 and partitions it in such a way so that the blocks East and West of the block of platform variables are equal to zero within tolerance limits (Figure 2).

Conditions (7) and (10) or equations (11) and (12) cannot be used directly for determining the platform variables between variants. If conditions (7) and (10) are satisfied, a design variable i is necessarily part of a platform between variants $\mathbf{x}^{\alpha}$ and $\mathbf{x}^{\beta}$. However, conditions (7) and (10) are only useful for *checking* whether a design variable belongs to the platform subset, not *locating* the platform subset. Also, equations (11) and (12) that hold for all platform and customized variables, are not directly useful for determining what the partitioning of the design vector should be, given the sensitivity DSM at a solution $\mathbf{x}^{*}$ and the functional requirements of the variants, $\mathbf{FR}^{\alpha}$ or $\mathbf{FR}^{\beta}$.

Table 1 describes the algorithm steps. The algorithm involves a running list $LIST_k$ (subscript k denotes iteration k) of variables, initially consisting of all elements of the SDSM that are directly insensitive to the changing functional requirements. By the end of the first loop (Step 2), $LIST_k$ contains the maximum possible number of platform variables. In this $LIST_k$, it is very likely that some variables are sensitive to changes in customized variables (not in $LIST_k$). On a second loop, each potential platform variable is examined and removed from $LIST_k$ if it is sensitive to a customized variable. The algorithm terminates when the IDR list remains unchanged, or if $LIST_k$ is empty.

Table 1: Algorithm for the location of invariant design rules

STEP	Description	Variables
1	Establish running list of variables that are potential design rules	$LIST_k$
2	Examine S-DSM element i. If i is not affected by changes in the changing functional requirements, then add element i to $LIST_k$.	
3	Repeat Step 2 for next element until all elements have been examined.	
4	Store running $LIST_k$	$LIST_k$ contains maximum set of potential design rules
5	Check each element i against each element j. If $SDSM_{i,j} = 1$ and $x_i \in LIST_k$ and $x_j \notin LIST_k$ then remove element i from $LIST_k$ and go to Step 6. Otherwise, examine for next element $j = j + 1$.	$LIST_k = LIST_k - \{x_i\}$
6	Repeat step 4 for next element i until all elements have been examined.	
7	If $LIST_k = LIST_{k-1}$ or $LIST_k = \varnothing$ then the algorithm has converged; terminate. Otherwise, go to Step 4	

The algorithm in Table 1 is guaranteed to find the largest set of platform variables, not just any set. To show this, it is enough to show that $LIST_k$ at iteration k always contains the largest set of platform variables $\mathbf{x}_p$.

When the first loop is finished, at step 2, the running list $LIST_k$ indeed contains the largest $\mathbf{x}_p$. To show this, consider the complementary set to $LIST_k$, $\overline{LIST_k}$. $\overline{LIST_k}$ contains all variables that do not satisfy condition (11). Since the variables in $\mathbf{x}_p$ must satisfy both conditions (11) and (12), it follows that $\overline{LIST_k}$ is the smallest possible $\mathbf{x}_c$; therefore, $LIST_k$ contains the largest possible set of platform variables. So, $\mathbf{x}_p \subset LIST_k$.

The second loop (steps 4-6) starts with $\overline{LIST_k}$, and in every iteration k an element is removed so that $LIST_k \subseteq LIST_{k-1}$. Because in each iteration the element removed does not satisfy condition (12)it also follows that

$$\mathbf{x}_p \subseteq LIST_k \subseteq LIST_{k-1} \tag{13}$$

From equation (13) it follows that the first feasible $LIST_k$ will be the largest set of platform variables.

Platform identification at higher system levels: application

In the final part of this paper we extend the previously presented concepts to a higher level of system aggregation, so that the process can be used as a design management tool. We illustrate such use of the concepts with an example from standardizing systems and components between Floating Production, Storage and Offloading (FPSO) facilities.

FPSO Technology

An FPSO is a multi-functioning production system that has become an increasingly attractive engineering solution for the development of oilfields remote from export pipeline infrastructure. An FPSO is essentially an anchored tanker which receives produced fluids from multiple underwater wells. The incoming fluids from the sub-sea wells are essentially a mix of oil, gas and water. The topsides facilities' main function is to separate the gas and water from the oil; "treat" the gas to meet specifications for export, re-use on board as fuel, and/or re-injection into the reservoir; and separate and deoxygenate the produced water before it is pumped back into the reservoir. The degassed and dewatered oil is stored in the hull of the vessel and periodically offloaded to shuttle tankers.

The main equipment for these functions is shown in Figure 3, a simplified fairly typical process flow diagram. Incoming fluids first meet the slug catcher, whose main function is to act as a buffer that establishes a steady flow of liquids through the rest of the system. Nevertheless, a coarse gas/oil separation also takes place in the slug catcher. The oil stream out of the slug catcher is heated prior to entering a high pressure separation system, where water and solution gas are removed. This is followed by a low pressure separation stage, which performs secondary separation necessary to achieve the oil export specifications. The solution gas streams are compressed prior to dehydration and re-injection into the reservoir to enhance oil recovery, or exported via pipelines. Besides this primary equipment, FPSO topsides involve numerous support and utility systems.

For the preliminary costing and sizing of FPSO topsides, the information needed can be captured in a limited number of parameters, which we treat as the *functional requirements* for a facility. The *Inlet Gas Rate, Inlet Fluids Rate*, *Inlet Pressure* and *Temperature* are all characteristics of the fluids that reach the slug catcher through the *risers*. They are determined largely by the stage of production and the physical and chemical characteristics of the hydrocarbon fluids. The produced gas can be exported, re-injected into the reservoir or used as "lift gas." This system recycles gas and mixes it with the incoming fluids at the point of the sub-sea well to effect a lower specific gravity and enhance flow. The use of produced gas at any point on the field's life determines *Gas Lift Rate, Gas Injection Rate* and *Gas Injection Pressure*. Similarly, the water produced at each separation and gas treatment stage determines the *Produced Water Rate*. This water (as well as sea-water) is often re-injected into the reservoir at the *Water Injection Rate* and *Water Injection Pressure*.

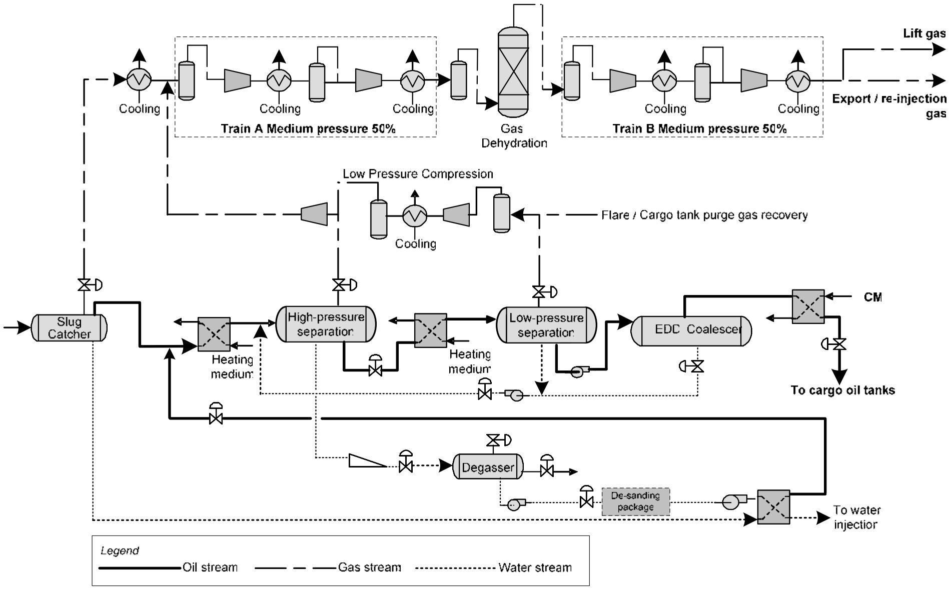


Figure 3: Typical main topsides functions and equipment (simplified)

FPSO platform identification

Some recent programs of FPSOs and other oil production facilities have been developed according to a new design paradigm of complete standardization. For example, the Kizomba A and Kizomba B developments offshore Angola are built almost entirely on the same identical design. The ACG development in the Caspian Sea offshore Baku, Azerbaijan, consisted of 6 almost identical fixed platforms. The almost identical design for these and other facilities was enabled by the alignment of a number of conditions. Generally, the technical specifications, architectural concept, economic conditions and development time frame were very similar for these projects, allowing maximum design re-use and standardization of systems and components across facilities.

However, what happens if these conditions are not entirely aligned for the development of multiple facilities? For example, Figure 4 shows the differences in terms of functional requirements between two FPSOs, denoted α and β. In such cases, the design paradigm so far has been to customize and individually optimize each facility, even if their design specifications and project requirements are as similar as those between α and β. However, significant benefits can be realized even from partial standardization of facilities designed to fairly different specifications. The application of the methodology presented in the previous section has helped BP, a major integrated energy company, identify which systems may or may not be standardized as part of a platform between two topsides facilities (FPSO α and β) with different gas processing capacity requirements, as shown in Figure 4.

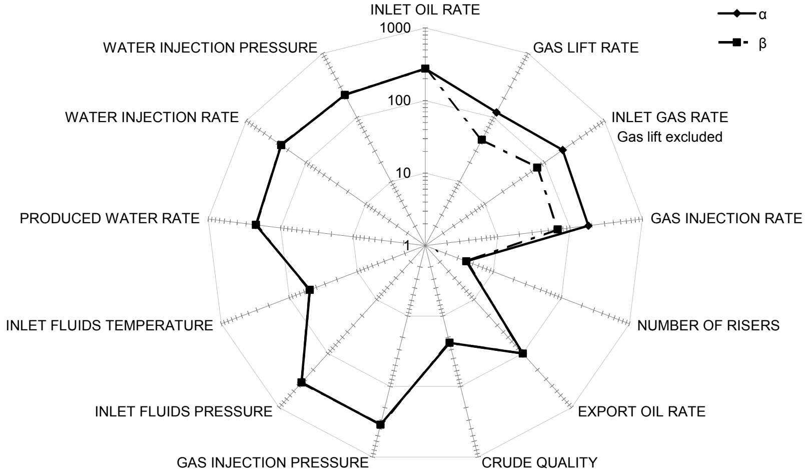
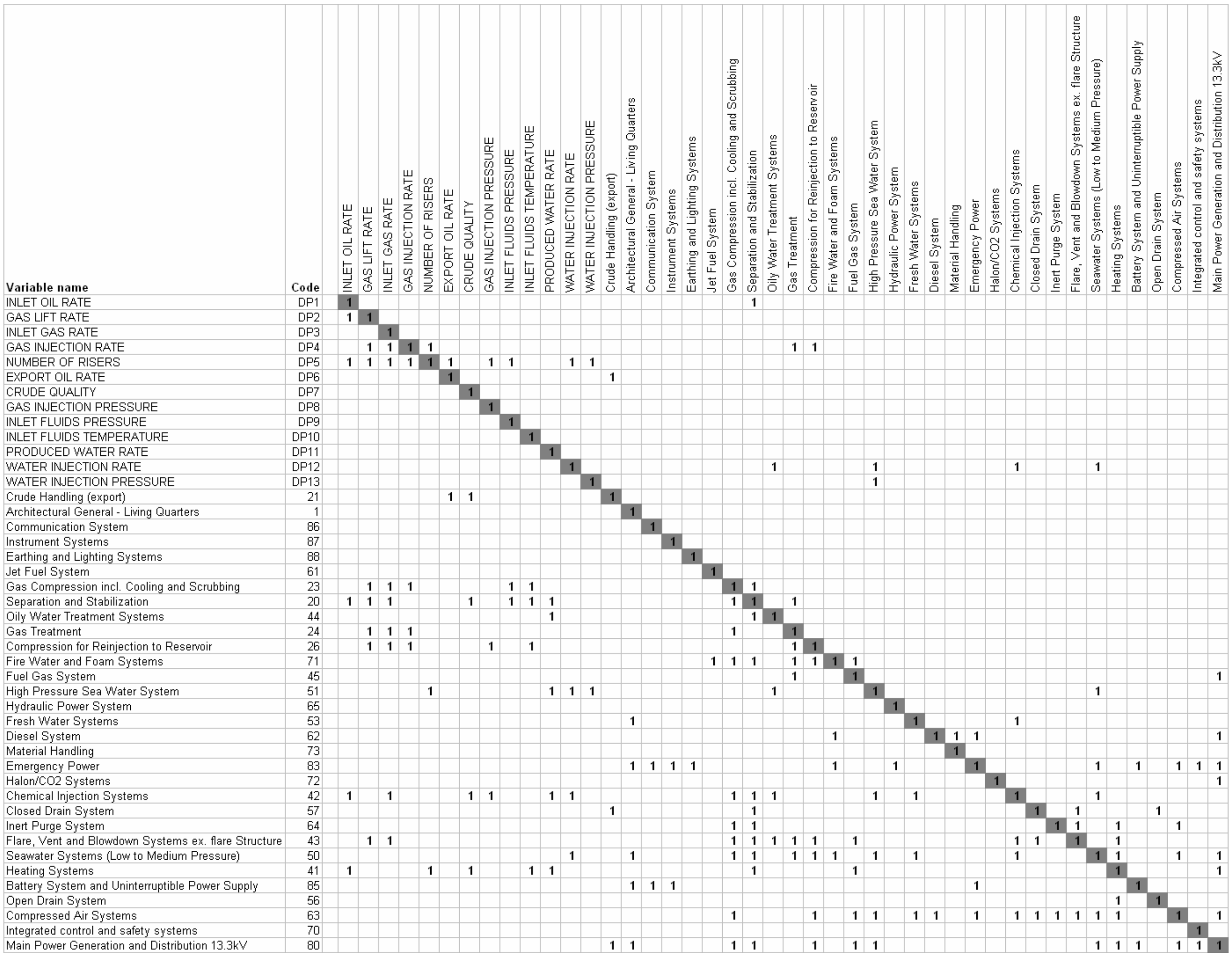


Figure 4: specifications for FPSOs α and β



Variable name	Code	INLET OIL RATE	GAS LIFT RATE	INLET GAS RATE	GAS INJECTION RATE	NUMBER OF RISERS	EXPORT OIL RATE	CRUDE QUALITY	GAS INJECTION PRESSURE	INLET FLUIDS PRESSURE	INLET FLUIDS TEMPERATURE	PRODUCED WATER RATE	WATER INJECTION RATE	WATER INJECTION PRESSURE	Crude Handling (export)	Architectural General - Living Quarters	Communication System	Instrument Systems	Earthing and Lighting Systems	Jet Fuel System	Gas Compression incl. Cooling and Scrubbing	Separation and Stabilization	Oily Water Treatment Systems	Gas Treatment	Compression for Reinjection to Reservoir	Fire Water and Foam Systems	Fuel Gas System	High Pressure Sea Water System	Hydraulic Power System	Fresh Water Systems	Diesel System	Material Handling	Emergency Power	Halon/CO2 Systems	Chemical Injection Systems	Closed Drain System	Inert Purge System	Flare, Vent and Blowdown Systems ex. flare Structure	Seawater Systems (Low to Medium Pressure)	Heating Systems	Battery System and Uninterruptible Power Supply	Open Drain System	Compressed Air Systems	Integrated control and safety systems	Main Power Generation and Distribution 13.3kV
INLET OIL RATE	DP1	1																				1																							
GAS LIFT RATE	DP2	1	1																																										
INLET GAS RATE	DP3			1																																									
GAS INJECTION RATE	DP4		1	1	1	1																		1	1																				
NUMBER OF RISERS	DP5	1	1	1	1	1	1		1	1			1	1																															
EXPORT OIL RATE	DP6						1								1																														
CRUDE QUALITY	DP7							1																																					
GAS INJECTION PRESSURE	DP8								1																																				
INLET FLUIDS PRESSURE	DP9									1																																			
INLET FLUIDS TEMPERATURE	DP10										1																																		
PRODUCED WATER RATE	DP11											1																																	
WATER INJECTION RATE	DP12												1										1					1							1				1						
WATER INJECTION PRESSURE	DP13													1														1																	
Crude Handling (export)	21						1	1							1																														
Architectural General - Living Quarters	1															1																													
Communication System	86																1																												
Instrument Systems	87																	1																											
Earthing and Lighting Systems	88																		1																										
Jet Fuel System	61																			1																									
Gas Compression incl. Cooling and Scrubbing	23		1	1	1					1	1										1	1																							
Separation and Stabilization	20	1	1	1				1		1	1	1									1	1		1																					
Oily Water Treatment Systems	44											1										1	1																						
Gas Treatment	24		1	1	1																1			1																					
Compression for Reinjection to Reservoir	26		1	1	1				1		1													1	1																				
Fire Water and Foam Systems	71																			1	1	1		1	1	1	1																		
Fuel Gas System	45																							1			1																		1
High Pressure Sea Water System	51					1						1	1	1									1					1											1						
Hydraulic Power System	65																												1																
Fresh Water Systems	53															1														1					1										
Diesel System	62																									1					1	1	1												1
Material Handling	73																															1													
Emergency Power	83															1	1	1	1							1			1				1						1		1		1	1	1
Halon/CO2 Systems	72																																	1											1
Chemical Injection Systems	42	1		1				1	1			1	1								1	1	1					1		1					1				1						
Closed Drain System	57														1							1														1		1				1			
Inert Purge System	64																				1	1															1	1		1			1		
Flare, Vent and Blowdown Systems ex. flare Structure	43		1	1																	1	1	1	1	1		1								1	1		1		1					
Seawater Systems (Low to Medium Pressure)	50												1			1					1	1		1	1	1		1		1					1				1	1			1		1
Heating Systems	41	1				1		1			1	1										1					1													1					1
Battery System and Uninterruptible Power Supply	85															1	1	1															1								1				
Open Drain System	56																																							1		1			
Compressed Air Systems	63																				1				1		1	1		1	1		1		1	1	1	1	1	1			1		1
Integrated control and safety systems	70																																											1	
Main Power Generation and Distribution 13.3kV	80													1	1						1	1			1		1	1											1	1	1		1	1	1

Figure 5: System-level SDSM for FPSO β, original

Thousands of design variables are needed to characterize the topsides of an FPSO, even at a very aggregate level. Clearly, building a DSM (and much less an S-DSM) for thousands of variables is impractical. However, a variable-based DSM can be *clustered* so that subsystems and components are defined (e.g., see Browning 2001). This clustering is not unique: drawing boundaries around sets of design variables and considering these sets as subsystems involves a trade-off: the larger the subsystems, the fewer interactions are left outside the boundaries; the smaller the subsystems, the more interactions exist between their variables and outside their boundaries. Similarly, variables can belong to two or more systems simultaneously, so that these overlap; alternatively, sets of common variables can be regarded as separate "link" subsystems that provide the interface between the other subsystems (e.g., see Sharman et al, 2002 and Yu et al, 2003). In this application, the FPSO design variables were clustered into subsystems and their interactions according to the specifications required by suppliers and engineers for the design of specific *line items* in a pre-defined system/equipment list. Just as in the case of parameter-based DSMs, formulating the Sensitivity-DSM requires that the interaction in row i and column j be interpreted as "the change necessary to line item i because of a unit change in line item j. In other words, if the design variables of component i are not (significantly) constraining those of component j in the neighborhood of the specific solution in mind, then the entry i, j should be zero.

With this convention, all the concepts developed in the first part of the paper are transferable to component-based DSM's; the difference is limited to the way sensitivities are quantified. In the variable-based SDSM, sensitivity is objectively defined to be the relative change in one variable as a consequence of a change in another. In the component-based SDSM, sensitivity is subjectively defined as the change necessary in one component as a consequence of change in another. In other words, since components are described by many variables, designers should use expert judgment as to whether the design of a component influences the design of another. Figure 5 shows the system-level SDSM, formulated for the FPSO with the more ominous functional requirements (FPSO α). The matrix entries are 1 or 0 (empty), denoting sensitivity between items or lack thereof.

By applying the IDR methodology, the SDSM in Figure 5 can be re-arranged so that the changing functional requirements (i.e., inlet oil rate, gas lift rate and inlet gas rate) are placed first, followed by the invariant decision rules (Figure 6). The platform systems are isolated from the customized elements by the fact that the rectangular blocks on their East and West on the SDSM are zero. Finally, the customized systems can be sequenced so that the feedback interactions above the diagonal are minimized. These interactions define clusters of coupled systems that need to be designed simultaneously, and are enclosed in rectangles in Figure 6.

In this example, systems 1, 21, 86, 87, 88, 61, 65, 73 and 70 are shown to present potential platform opportunities between FPSOs α and β. These are mostly utility systems whose specifications are logically not affected by the differences in the functional requirements, e.g., system 1 represents the design of architectural elements and living quarters. On the other hand, the methodology also reveals less obvious examples of potentially standardized systems.

Variable name	Code	GAS INJECTION RATE	INLET GAS RATE	GAS LIFT RATE	EXPORT OIL RATE	CRUDE QUALITY	GAS INJECTION PRESSURE	INLET FLUIDS PRESSURE	INLET FLUIDS TEMPERATURE	PRODUCED WATER RATE	Crude Handling (export)	Architectural General - Living Quarters	Communication System	Instrument Systems	Earthing and Lighting Systems	Jet Fuel System	Hydraulic Power System	Material Handling	Integrated control and safety systems	INLET OIL RATE	Gas Compression incl. Cooling and Scrubbing	Separation and Stabilization	Gas Treatment	Oily Water Treatment Systems	Compression for Reinjection to Reservoir	NUMBER OF RISERS	WATER INJECTION RATE	WATER INJECTION PRESSURE	Fire Water and Foam Systems	Fuel Gas System	High Pressure Sea Water System	Fresh Water Systems	Diesel System	Emergency Power	Chemical Injection Systems	Closed Drain System	Inert Purge System	Flare, Vent and Blowdown Systems ex. flare Structure	Seawater Systems (Low to Medium Pressure)	Heating Systems	Battery System and Uninterruptible Power Supply	Open Drain System	Compressed Air Systems	Main Power Generation and Distribution 13.3kV	Halon/CO2 Systems
GAS INJECTION RATE	DP4	1	1	1																			1		1	1																			
INLET GAS RATE	DP3		1																																										
GAS LIFT RATE	DP2			1																1																									
EXPORT OIL RATE	DP6				1						1																																		
CRUDE QUALITY	DP7					1																																							
GAS INJECTION PRESSURE	DP8						1																																						
INLET FLUIDS PRESSURE	DP9							1																																					
INLET FLUIDS TEMPERATURE	DP10								1																																				
PRODUCED WATER RATE	DP11									1																																			
Crude Handling (export)	21				1	1					1																																		
Architectural General - Living Quarters	1											1																																	
Communication System	86												1																																
Instrument Systems	87													1																															
Earthing and Lighting Systems	88														1																														
Jet Fuel System	61															1																													
Hydraulic Power System	65																1																												
Material Handling	73																	1																											
Integrated control and safety systems	70																		1																										
INLET OIL RATE	DP1																			1		1																							
Gas Compression incl. Cooling and Scrubbing	23	1	1	1				1	1												1	1																							
Separation and Stabilization	20		1	1		1		1	1	1										1	1	1	1																						
Gas Treatment	24	1	1	1																	1		1																						
Oily Water Treatment Systems	44									1												1		1																					
Compression for Reinjection to Reservoir	26	1	1	1			1		1														1		1																				
NUMBER OF RISERS	DP5	1	1	1	1		1	1												1						1	1	1																	
WATER INJECTION RATE	DP12																							1			1				1				1				1						
WATER INJECTION PRESSURE	DP13																											1			1														
Fire Water and Foam Systems	71															1					1	1	1		1				1	1															
Fuel Gas System	45																						1							1														1	
High Pressure Sea Water System	51									1														1		1	1	1			1								1						
Fresh Water Systems	53											1																				1			1										
Diesel System	62																	1											1				1	1										1	
Emergency Power	83											1	1	1	1		1		1										1					1					1		1		1	1	
Chemical Injection Systems	42		1			1	1			1										1	1	1		1			1				1	1			1				1						
Closed Drain System	57										1											1														1		1				1			
Inert Purge System	64																				1	1															1	1		1			1		
Flare, Vent and Blowdown Systems ex. flare Structure	43		1	1																	1	1	1	1	1					1						1	1		1		1					
Seawater Systems (Low to Medium Pressure)	50											1									1	1	1		1		1		1		1	1			1				1	1				1	1	
Heating Systems	41					1			1	1										1		1				1				1										1					1	
Battery System and Uninterruptible Power Supply	85											1	1	1																				1							1				
Open Drain System	56																																							1		1			
Compressed Air Systems	63																				1				1					1	1	1	1	1	1	1	1	1	1	1				1	1	
Main Power Generation and Distribution 13.3kV	80										1	1							1		1	1			1					1	1								1	1	1		1	1	
Halon/CO2 Systems	72																																											1	1

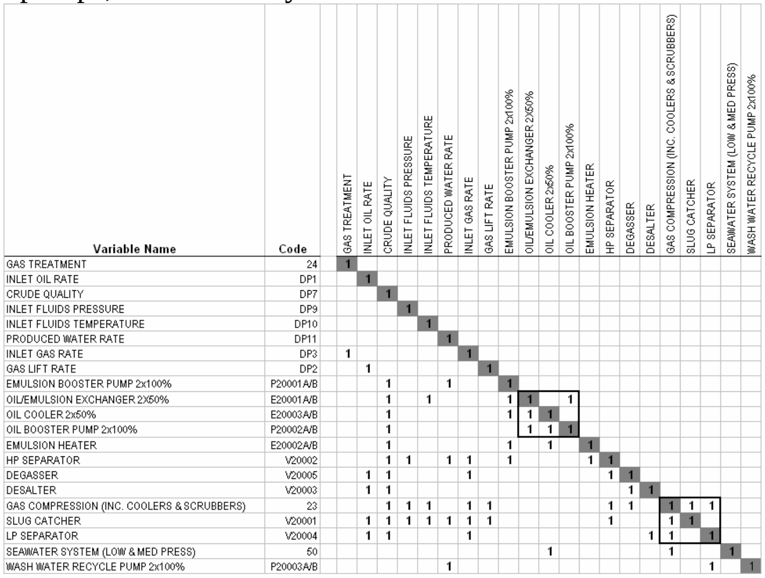
Figure 6: S-DSM for FPSO β, partitioned to show the invariant design rules

Multi-level platforms

According to Figure 6, system 20 (Separation and Stabilization) is customized, because its design is directly sensitive to changes in the changing functional requirements and systems 23 and 24 (gas compression and treatment respectively). System 20 includes the entire train of slug catcher, high-pressure and low-pressure separators, as well as electrostatic coalescer. Additionally, a number of pumps, pipes and smaller-scale equipment are included in system 20. Even if the entire system is modeled to be sensitive to changes in these specifications, it is reasonable to assume that some of its components may be more sensitive than others. This implies that there may be standardization opportunities at a lower system level, i.e., components within system 20.

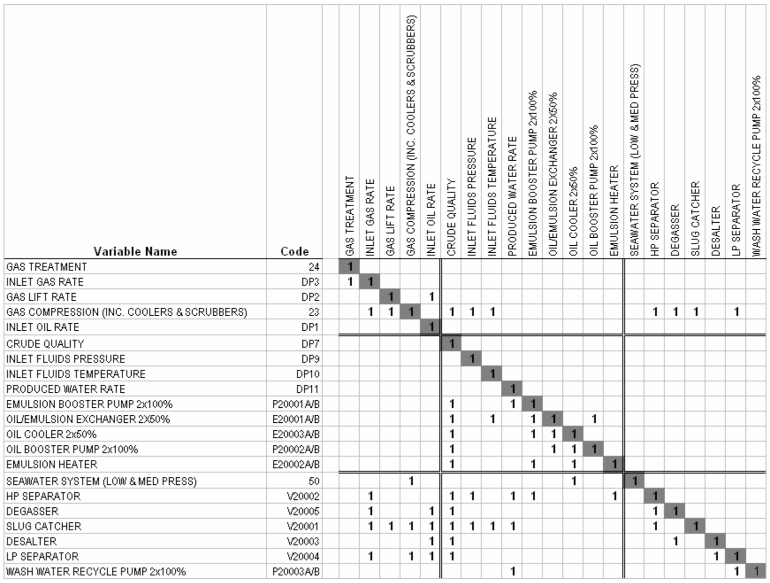
A component-level SDSM of system 20 can be constructed following the same logic as before. The constituent components of system 20 and their sensitivities must be included, as well as the system-level line items to which separation and stabilization is sensitive to (from the SDSM in Figure 6). The system-level items that are sensitive to changes in system 20 components do not need to be included. This SDSM is shown in Figure 7.

To partition this SDSM and reveal standardization opportunities within system 20, the changing functional requirements must first be defined. These should include the original functional requirements that change between FPSOs α and β; they should also include all the customized systems that affect the design of system 20: for the purposes of examining system 20, these systems cause exogenous changes in specifications. In this case, these are systems 23 and 24. Given these exogenous changes, the SDSM of system 20 can be partitioned so that the platform components are isolated as shown in Figure 8. Evidently, there is no need to customize the entire system 20 based on these matrices: some secondary systems, such a heat exchangers, coolers, heaters and pumps, can be readily standardized between the two FPSOs.



Variable Name	Code	GAS TREATMENT	INLET OIL RATE	CRUDE QUALITY	INLET FLUIDS PRESSURE	INLET FLUIDS TEMPERATURE	PRODUCED WATER RATE	INLET GAS RATE	GAS LIFT RATE	EMULSION BOOSTER PUMP 2x100%	OIL/EMULSION EXCHANGER 2X50%	OIL COOLER 2x50%	OIL BOOSTER PUMP 2x100%	EMULSION HEATER	HP SEPARATOR	DEGASSER	DESALTER	GAS COMPRESSION (INC. COOLERS & SCRUBBERS)	SLUG CATCHER	LP SEPARATOR	SEAWATER SYSTEM (LOW & MED PRESS)	WASH WATER RECYCLE PUMP 2x100%
GAS TREATMENT	24	1																				
INLET OIL RATE	DP1		1																			
CRUDE QUALITY	DP7			1																		
INLET FLUIDS PRESSURE	DP9				1																	
INLET FLUIDS TEMPERATURE	DP10					1																
PRODUCED WATER RATE	DP11						1															
INLET GAS RATE	DP3	1						1														
GAS LIFT RATE	DP2		1						1													
EMULSION BOOSTER PUMP 2x100%	P20001A/B			1			1			1												
OIL/EMULSION EXCHANGER 2X50%	E20001A/B			1		1				1	1		1									
OIL COOLER 2x50%	E20003A/B			1						1	1	1										
OIL BOOSTER PUMP 2x100%	P20002A/B			1							1	1	1									
EMULSION HEATER	E20002A/B			1						1		1		1								
HP SEPARATOR	V20002			1	1		1	1		1				1	1							
DEGASSER	V20005		1	1				1							1	1						
DESALTER	V20003		1	1												1	1					
GAS COMPRESSION (INC. COOLERS & SCRUBBERS)	23			1	1	1		1	1						1	1		1	1	1		
SLUG CATCHER	V20001		1	1	1	1	1	1	1						1			1	1			
LP SEPARATOR	V20004		1	1				1									1	1		1		
SEAWATER SYSTEM (LOW & MED PRESS)	50											1						1			1	
WASH WATER RECYCLE PUMP 2x100%	P20003A/B						1													1		1

Figure 7: Component-based SDSM for system 20



Variable Name	Code	GAS TREATMENT	INLET GAS RATE	GAS LIFT RATE	GAS COMPRESSION (INC. COOLERS & SCRUBBERS)	INLET OIL RATE	CRUDE QUALITY	INLET FLUIDS PRESSURE	INLET FLUIDS TEMPERATURE	PRODUCED WATER RATE	EMULSION BOOSTER PUMP 2x100%	OIL/EMULSION EXCHANGER 2X50%	OIL COOLER 2x50%	OIL BOOSTER PUMP 2x100%	EMULSION HEATER	SEAWATER SYSTEM (LOW & MED PRESS)	HP SEPARATOR	DEGASSER	SLUG CATCHER	DESALTER	LP SEPARATOR	WASH WATER RECYCLE PUMP 2x100%
GAS TREATMENT	24	1																				
INLET GAS RATE	DP3	1	1																			
GAS LIFT RATE	DP2			1		1																
GAS COMPRESSION (INC. COOLERS & SCRUBBERS)	23		1	1	1		1	1	1								1	1	1		1	
INLET OIL RATE	DP1					1																
CRUDE QUALITY	DP7						1															
INLET FLUIDS PRESSURE	DP9							1														
INLET FLUIDS TEMPERATURE	DP10								1													
PRODUCED WATER RATE	DP11									1												
EMULSION BOOSTER PUMP 2x100%	P20001A/B						1			1	1											
OIL/EMULSION EXCHANGER 2X50%	E20001A/B						1		1		1	1		1								
OIL COOLER 2x50%	E20003A/B						1				1	1	1									
OIL BOOSTER PUMP 2x100%	P20002A/B						1					1	1	1								
EMULSION HEATER	E20002A/B						1				1		1		1							
SEAWATER SYSTEM (LOW & MED PRESS)	50				1								1			1						
HP SEPARATOR	V20002		1				1	1		1	1				1		1					
DEGASSER	V20005		1			1	1										1	1				
SLUG CATCHER	V20001		1	1	1	1	1	1	1	1							1		1			
DESALTER	V20003					1	1											1		1		
LP SEPARATOR	V20004		1		1	1	1													1	1	
WASH WATER RECYCLE PUMP 2x100%	P20003A/B									1											1	1

Figure 8: Component-based SDSM for system 20, partitioned

Finally, the component-level SDSM in Figure 8 can be embedded back into the system-level SDSM, resulting in a matrix consisting of line items at both levels of aggregation (not shown here). This way, potential standardization can be explored at different degrees for multiple systems.

Discussion

This paper introduced a DSM-based methodology and algorithm for the qualitative identification of platform components at multiple levels of system aggregation, between variants that are intended to fulfill different functional requirements. The concept and theory of the methodology is shown at the design variable level of aggregation, by considering a model of the sensitivity in changes between variables. This was structured as a Sensitivity Design Structure Matrices (SDSM) that included the external functional requirements and factors affecting the design. We then introduce a novel algorithm for the identification of platform variables given the SDSM for each variant. The logic of the algorithm is to identify the largest set of design variables that are (1) not directly sensitive to the changing functional requirements, and (2) insensitive to customized design variables. Finally, the methodology is extended to the qualitative identification of platforms at higher levels of system aggregation, i.e., between systems, subsystems and components. Such semi-qualitative SDSMs can be constructed by design teams for the purpose of exploring platform opportunities.

The process is demonstrated in an example of platform identification among topsides facilities of Floating Production, Storage and Offloading (FPSO) units. The application of the methodology and the algorithm achieved more than its nominal objectives: it served as a standardized and transparent vehicle for communicating design ideas and platforming opportunities among inter-disciplinary engineering teams in a very complex system.

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