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A methodology for identifying flexible design opportunities in large-scale systems

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Abstract

Despite many uncertainties, industrial fields such as energy (eg, oil rigs), utilities infrastructure (eg, telecommunications), space systems, transportation systems, construction, and manufacturing make large and mostly irreversible investments in systems with potentially long life cycles. The life cycle value of such systems may be increased significantly by designing in the flexibility to make future changes. This paper presents a systematic methodology for designers to identify *flexible design opportunities* (FDOs) more comprehensively and earlier in the system design process. The methodology guides designers to generate flexible design concepts that can be assessed, selected, and integrated into a design during an early stage of the design process. We demonstrate and validate the FDO methodology on a case in the offshore drilling industry.

KEYWORDS
conceptual design, design for adaptability, design for flexibility, enduring systems, large-scale systems, product development

1 | INTRODUCTION

As political, market, legal, and environmental conditions change, enduring systems face uncertain futures. When several stakeholders contribute to a system's requirements and design, a lack of stakeholder alignment often creates disagreements.[1-3] Especially in designer-/builder-dominated systems, where the end user is not directly involved, operational requirements and life cycle considerations often have lower priority than minimizing initial capital expenditures. Moreover, the division of design tasks in organizations hinders multistakeholder thinking about life cycle value,[56] as well as anticipation of, and proactivity toward, uncertainty. Multiple suppliers contribute to large, complex systems; piecewise requirements specification leads to individual subsystems specified by local experts who do not consider the overall capability.[4] Design and operational expertise are typically siloed, and suppliers may provide technical knowledge, while contractors provide a proxy for users. System suppliers, represented by

their designers and sales engineers, have limited involvement during the early stages of design: Sales engineers usually bundle resources to meet the articulated needs of customers without challenging them exhaustively, just to get the job done and avoid the risk of diverging from those needs. Often, designers do not explore how changes in specifications and market factors might affect the design,[5(p.6)] and operational uncertainties are frequently ignored in early design phases. In such situations, uncertainty is most often dealt with reactively, once a system is already built, deployed, and operating.[6] However, this postponement significantly increases costs: In each subsequent program phase, the implementation of a change becomes about 10 times more costly.[7(p.49)]

Confronting this situation requires more proactive anticipation.[8] Within each engineering organization, "anticipatory capacity" must be established to increase life cycle value. This can be achieved through active or passive means, the latter akin to traditional, robust approaches, and the former embracing changeability as a

dynamic strategy for value sustainment.[9] According to de Neuffville and Scholtes,[5(p.39)] accounting for flexibility early, during the design phase, can increase financial performance by at least 25% over standard design procedures (even when accounting for the costs [eg, extra design effort and potential performance reductions] that flexibility sometimes adds). A flexible system enables the exercise of options for smaller, more frequent upgrades that extend the system's useful life.[2]

This paper targets the potential of increasing life cycle value by designing systems for flexibility, early in the design process, during need identification and conceptual design, to embed *flexible design opportunities* (FDOs) that enable its users to deal with unfolding uncertainty during system operations. Embedded flexibility provides the most value for industries with expensive, unique, enduring systems that face large uncertainty in user needs.[10,11]

This paper addresses the need for flexible design methods, organized into a consolidated framework,[1] with an extended perspective of the technical system that includes external interactions—ie, an "end-to-end" methodology[12] that guides the user from change initiation to *flexible design concepts* (FDCs) and solutions. We focus on the concept generation phase, where "more research is needed to develop new procedures or adapt existing ones."[13] We derived the method based on the need in the upstream oil and gas industry, where—due to social, technical, and environmental complexity, and the limits in planning operations strategically during design—a strong lack of uncertainty handling was observed, leading to design changes throughout the life cycle and making upgrades very expensive and suboptimal, especially postdeployment.[14] Hence, this paper presents a systematic methodology for designers to identify FDOs more comprehensively and earlier in the system design process. The methodology guides designers to generate FDCs that can be assessed, selected, and integrated into a design during an early stage of design. Due to space constraints, this paper presents only an overview of the FDO methodology; many further details are available in the first author's dissertation.[15]

2 | CONTEXT AND RELATED WORK

We organize our review of related work around Cardin's[1] five-phase framework for enabling and managing flexibility in engineering systems (Figure 1). The initial phase, Baseline Design, bases desirable flexibility on an existing design concept (eg, captured by a detailed sketch, computer-aided design model, etc.). Phase 2, Uncertainty Recognition, focuses on identifying and modeling the major sources of uncertainty anticipated to affect life cycle performance. Phase 3, Concept Generation, generates FDCs that deal proactively with the changing operating conditions identified in phase 2. Phase 4, Design Space Exploration, involves exploring the design space for the most valuable design concepts and decision rules to operate the system. Cardin[1] emphasized the use of quantitative techniques in this phase, resulting in a recommended set of FDCs (with more precise design specifications) and decision rules. Phase 5, Process Management, seeks to establish favorable conditions in the social and collaborative environment in which flex-
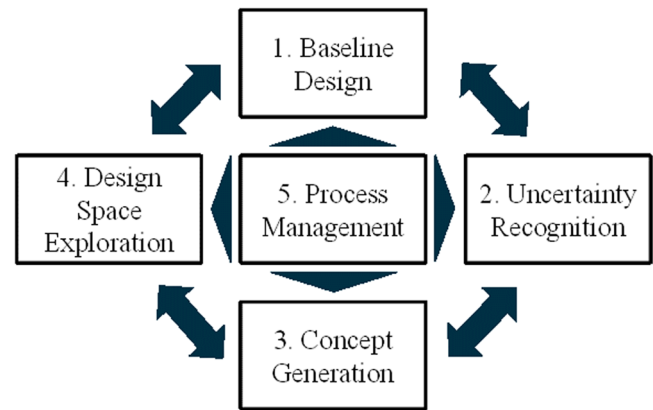

FIGURE 1 A five-phase framework to support the design of engineering systems for flexibility[1]

ibility may be generated, evaluated, and deployed. As the arrows in Figure 1 indicate, designers do not have to follow this process sequentially; rather, they may go back and forth between phases or explore the phases in any suitable order.

In addition to Cardin,[1] several others have explored "end-to-end" methodologies for identifying FDOs by guiding a user from exogenous *Change Drivers (CDs)* toward FDCs and solutions. (The Appendix contains a list and definitions of the italicized terms used throughout this paper.) These methodologies generally emanate from the fields of "engineering systems" and "manufacturing and factory planning" (Table 1). Moreover, several matrix-based methodologies (introduced in the next subsection) include the literature from the field of product development. The methodologies of engineering systems often target specific application contexts (eg, construction), although they may apply across various other domains as well. Based on the definition by Chmarra et al,[16] they all relate to "lifetime adaptability" (prolonging the product's service life in its normal operational mode and adapting it to new operational modes) and also partially to "runtime adaptability" (increasing utility through flexibility when the product performs a task, such as the ease of switching between two tasks). Some of the methods, eg, Refs. 17 and 18 target operational flexibility by easing the configurational changes of "systems of systems."

The FDO methodologies in Table 1 led us to several observations regarding the five phases in Figure 1:

- All of the FDO methodologies in Table 1 focus mainly on phases 2-4 in Figure 1.
- The FDO methodologies begin variously in phases 1-3, although these phases are not performed in a strict, consecutive order (as allowed by Cardin[1]).
- All FDO methodologies in Table 1 aim to specify FDCs. Most also yield evaluated solutions that provide a starting point for embodiment design.
- Although the FDO methodologies in Table 1 all require a Baseline Design (phase 1), its selection is usually *ad hoc*, without an explicit description. Only Nilchiani and Hastings[17] explicitly address

TABLE 1 Overview of literature pertaining to FDO methodologies

		Hernández[19]	Clarkson et al.[20]	Greden[21]	Nyhuis et al.[22]	Kalligeros[23]	Bartolomei[12]	Nilchiani & Hastings[17]	Suh et al.[24]	Wilds[25]	Schuh et al.[26]	de Neufville & Scholtes[5]	Mikaelian et al.[18]	Mikaelian et al.[27]	Koh et al.[28]	Koh et al.[29]	Baudzus et al.[30]	Cardin[1]	Francalanza et al.[31]	Klemke[32]	Hu & Cardin[33]
Application context	Engineering systems (general)			●	●	●	●		●		●	●	●	●		●		●			●
	Product development (general)		●						●						●	●					
	Building / Construction			●		●															●
	(Aero-)space system		●			●	●		●			●	●	●							
	Automotive							●								●					
	Factory planning (general)	●			●															●	
	Manufacturing system										●								●		
	(Manual) assembly system																●				
Lifecycle perspective on flexibility	Flexibility of a design under development		●			●	●	●	●	●	●				●	●					
	Flexibility of a design after fielding - Runtime adaptability			●					●				●	●			●		●		
	Flexibility of a design after fielding - Lifetime adaptability	●		●	●				●		●	●	●				●	●	●	●	●

the identification of a suitable Baseline Design to motivate FDCs, although they do not detail the substeps and criteria.

- Process management (phase 5) is only considered by certain FDO methodologies from the field of engineering systems.
- In the FDO methodologies from the field of engineering systems, the emphasis often lies on the extensive, quantitative assessment of a high number of FDCs (based on a limited number of design variables and for a limited number of objects to address change), whereas FDO methodologies from the field of manufacturing and factory planning tend to stress the gradual identification and containment of various FDCs based on many alternative design variables for numerous objects.
- Some FDO methodologies[17,31] intentionally embed the selection of flexibility-relevant aspects (eg, selecting changeability type, suitable evaluation methodology) as an output of a separate step, while others constrain such aspects and pursue a specific goal from the beginning (eg, targeting "modularity" of *Change Objects* only[26]).

These observations point to the need for a more comprehensive, "end-to-end" FDO methodology that better spans and aligns with Figure 1. Furthermore, comparing the available FDO methodologies against the needs of industry (mentioned in Section 1)—including support for system suppliers in early design phases to embed flexibility successfully into technical systems—also reveals many shortcomings and motivates the need for further work in this area. In this paper, we take up this challenge and present an overview of such a FDO methodology.

As a key aspect of several of the available FDO methodologies, we also noted that many have employed matrix-based methods (Table 2) such as the design structure matrix (DSM)[34(p. 9)] to identify effective FDOs more systematically. Examples include: Mikaelian et al,[27] who sought to identify real options to enable operational flexibility for systems-of-systems (SoS); Koh et al,[28] who targeted "change options" in developing products; and Kalligeros,[23] who focused on customized components in developing products. Engel and Browning[35] and Engel et al[36] focused on modularity as a solution for dealing with future change by comparing alternative allocations of components to modules—in particular, merging or splitting modules of the initial baseline design—to find a product architecture better suited to future changes. The scope of these matrix-based methodologies varies as highlighted in Table 2—wherein the last column compares with the "end-to-end" FDO methodology presented in this paper.

All of the methodologies in Table 2 assume an initial, baseline design as an input for FDO identification—with the exception of Hu and Cardin,[33] who included identifying the best-performing baseline design before considering flexibility. Although most of the methodologies in Table 2 touch on uncertainty recognition and scenarios, only a couple embed them as core elements. With the exception of Mikaelian et al,[27] most of the approaches in Table 2 focus on the identification of *Change Objects*, direct change propagations among them (addressing indirect ones only partially), and their subsequent prioritization and selection—where "change propagations" entail knock-on effects to other objects and are especially important to consider in complex products with strong interconnections.[37] Meanwhile, the

TABLE 2   Comparing matrix-based methods for identifying *FDOs*

Legend:
- ▨ Matrix-based contribution
- ■ Core of methodology
- ○ Addressed briefly
- ◆ Ad hoc consideration only
- □ Unaccounted for

		Clarkson et al.[20]	Koh et al.[28]	Koh et al.[29]	Kalligeros[23]	Suh et al.[24]	Bartolomei[12]	Wilds[25]	Mikaelian et al.[27]	Hu & Cardin[33]	Engel et al.[36]	FDO Methodology
1. Baseline Design	Initial design basis	◆	◆	◆	◆	◆	◆	◆	◆	■	◆	■
2. Uncertainty Recognition	Uncertainty and scenario				◆	◆	○	■	◆	■	■	■
3. Concept Generation: Identification of *Change Objects*	Direct change-instigating objects (*Change Objects*)	◆	■	◆	■	■	○	■	◆	■		■
	Direct change propagation (direct change influence)	■	■	■	■	■	○	■		■		
	Indirect change propagation	■	■	■				■		■		■
	Prioritization of *Change Objects*	■		■	■	■	○	■	◆	■		
3. Concept Generation: Generation of *Flexible Design Concepts*	Change Strategies (*Transitions*)		■				◆	◆	■	◆	◆	■
	Change Enabler			◆			◆	◆	◆	■	◆	■
4. Design Space Exploration: Concept evaluation and decision-making	Qualitative design concept evaluation		■									■
	Quantitative design concept evaluation						■	◆		■	■	■

Right-side brackets: "End-to-end" FDO Methodology; Matrix-based FDO Methodology

generation of FDCs has received less consideration so far among the matrix-based methodologies. The selection of change strategies (*Transitions*) and *Change Enablers* (*CEs*) is usually performed in an ad hoc way that fails to consider how the flexibilities may be obtained.[27] As indicated by Cardin et al,[38] so far DSM methods have focused mainly on switching flexibility among product variants rather than considering other flexibility strategies. Koh et al[28] emphasized the identification of the most suitable "change options" that address possible *Transitions* for design phases; however, they did not address *CEs* to facilitate those changes. Mikaelian et al[27] offered the only matrix-based methodology that emphasized the integrated identification of suitable *Transitions* ("types") and *CEs* ("mechanisms"). However, their multidomain matrix (MDM) approach largely bypasses the identification of *Change Objects* and does not consider change propagation. Most FDC evaluations use "real option valuations" for large-scale systems as a means of quantifying the value of FDCs when performance parameters cannot be clearly assigned to monetary payback functions.[39 (p.6)] Of all of the methodologies in Table 2, Hu and Cardin[33] come closest to the more comprehensive, end-to-end (as described in Section 1), matrix-based FDO methodology presented in this paper. Although all of the other approaches in Table 2 are partially matrix-based, none of them maintains a matrix-based approach "end-to-end." Furthermore, they focus on the processing of empirically derived data, which are then used for analysis in the absence of domain experts, but this ignores the available, tacit knowledge of domain experts and limits applicability across varied industrial settings and projects.

The FDO methodology presented in this paper addresses these gaps by covering all of the early design phases—from baseline design and the sources of uncertainty to concept generation and the evaluation and decision on FDCs—with a more holistic, end-to-end perspective. Most of the FDO methodology (especially from uncertainty recognition to the generation of FDCs) is implemented via a consistent, integrated, and traceable DSM model. The methodology targets the "concept generation" phase by further exploring Mikaelian et al's[27] integrated concept of *Transitions* and *CEs* as change strategies. Hence, this work extends *Transitions* and *CE* constituents and also makes them more specific and applicable to the context of large-scale systems.

3 | PROPOSED FDO METHODOLOGY

Our proposed FDO methodology consists of three interrelated models: an eight-step procedural model, a data model, and an execution model. The following subsections describe each in turn. We realize that these descriptions involve many specialized terms (which, to note again, are summarized in the Appendix). Section 4 applies the FDO methodology to an example.

3.1 | Overview of the eight-step *FDO Procedural Model* (FDO-PM)

Drawing upon Figure 1, the procedural model identifies FDOs through three main stages containing eight subordinate steps, as shown in Figure 2's overview. Stage I identifies *Change Objects*. Stage II generates *FDCs* that connect the *Change Objects* to combinations of *Transitions* and *CEs*. Stage III determines *Flexible Design Solutions* by assessing the *FDCs* and integrating them into the initial reference design. In accordance with de Neufville and Scholtes,[5 (p.99-127)] this third stage emphasizes the efficient short-listing and selection of candidate designs.
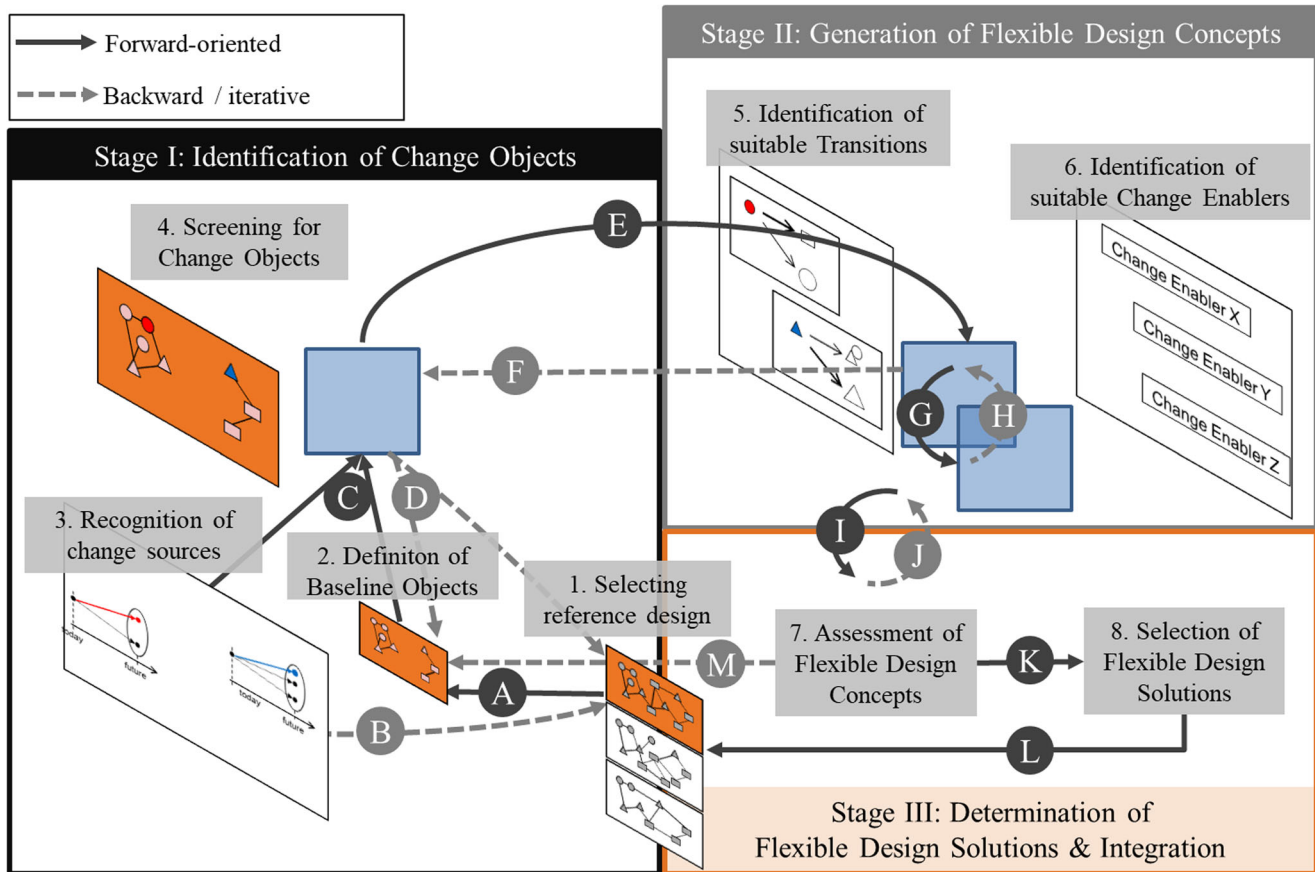
FIGURE 2 Overview of the *FDO-PM* with three main stages and eight subordinate steps

Consistent selections within and across these three stages are pursued to ensure satisfactory results, which is why these stages' subordinate steps are represented in Figure 2 as layers connected in series or parallel. The following subsections present each of the eight steps in greater detail, with full details available elsewhere.[15] Section 4 follows with an example implementation.

3.1.1 | Step 1: Select and adapt the most suitable reference design

The reference design must first be proven to fulfill the main requirements. Because requirements for large-scale systems usually vary, and efforts for complete redesigns are impractical, inefficient, and at risk of introducing system malfunctions, the starting point for step 1 is to determine a reference design that best meets the requirements for the project under consideration. Similar designs are usually created by modifying the existing designs based on varying requirements.[40] Hence, after (i) determining a suitable reference system and layout, the reference design is modified where requirements are violated, which includes the modification of (ii) system-specific items such as products and bulk items and (iii) the system configuration or layout. These activities result in a tentative solution, consisting of a set of *Objects* that may already include some

flexible *Objects* (as the initial reference design usually accounts for some requirements concerning future changes from the previous project). For instance, some machinery such as cranes might already be overdimensioned for dealing with larger functional or environmental loads than currently necessary. Hence, in step 4, those *Objects* might not become *Change Objects* because they already handle future changes without requiring additional *CEs* (eg, over-dimensioning, modularity).

3.1.2 | Step 2: Define *Baseline Objects*

Baseline Objects are the subset of the reference design *Objects* that belong in the flexibility solution space. The reference design may initially include *Objects* that are irrelevant for embedding flexibility, because they have a very low risk of being subject to future changes—ie, they are unlikely to be affected (low likelihood of being changed), they may be changed quite easily (low impact of being changed), or some of both. Although it is easier to estimate a change risk for some components, the risk of changes to bulk items such as piping and electrical cabling is highly specific to the product architecture and the indirect impacts of change propagation. Hence, bulk items are always included among the *Baseline Objects*. The degree of filtering at this stage depends on the stakeholders' preferences. Hence, based on the

Objects of the reference design (path A in Figure 2), designers assess the general need for making those *Objects* flexible and remove irrelevant *Objects*, yielding a set of *Baseline Objects* relevant to flexibility.

3.1.3 | Step 3: Recognize change sources

This step involves identifying the "change sources," the underlying factors potentially causing *Objects* to change. Change sources include both exogenous *CD*s and endogenous *System Requirements* (*SR*s). First, the set of *CD*s (or "system drivers"[12(p.73)]) represents both root causes and resulting ones that lead to nonfulfillment of *SR*s, and thus, system change. They "represent uncertainty sources that are known to engineers to have significant impact on anticipated life cycle performance"[38] but can also include knowable unknown-unknowns—ie, "knowable unk-unks."[41] They come from outside the system and will be resolved in the future—eg, oil price fluctuations, health safety environment (HSE) requirement changes, etc. Second, the set of *SR*s defines the capabilities the system must demonstrate. Meeting a *SR* provides both value and utility to the system's customer or user.

*CD*s may be modeled as a cause-and-effect network of uncertain factors, whose changes can affect particular *SR*s, which, in turn, can affect physical *Objects*. Designers can systematically identify *CD*s by determining the relevant factors and building a representative and consistent scenario. The outputs of Step 3 are the directly affected *SR*s and the ones affected indirectly by other *SR*s.

Iterations may be required (path B in Figure 2) when a scenario identifies new *SR*s that were unaccounted for in the reference design from Step 1. *Objects* of dedicated capability would have been omitted from the reference design as future scenarios were not yet accounted for, and consequently, were also not part of the imported *Baseline Objects*. If reference designs from previous projects cannot be found with such a capability, "Object placeholders" must be added to the existing *Baseline Objects* (in Step 2) to ensure that flexibility is considered for those *Objects*.

At the next stage, it must be determined if the defined *Baseline Objects* (Step 2) are significantly affected by the changing *SR*s.

3.1.4 | Step 4: Screen for *Change Objects*

The *Baseline Objects* now confront the affected *SR*s (path C in Figure 2). Each *Baseline Object* represents a potential *Change Object*—ie, an *Object* where a changing *SR* may lead to its nonfulfillment, with *Change Objects* ∈ *Baseline Objects*. This nonfulfillment indicates a *Change Trigger*, and the *Change Object* would have to be changed to continue to run within the allowed ranges. In this regard, a *Change Trigger* may result from adding or removing a *SR*, or from changing certain *SR* characteristics (conditions, such as "lifting capacity," or limits or constraints, such as "max. noise level"). Such Change Triggers may be driven by exogenous *CD*s. If many *Change Objects* have unfulfilled *SR*s, it may be necessary to reconsider the initially selected reference designs and *Baseline Objects* (path D in Figure 2) in order to maintain focus going forward.

Considering only direct but not indirect relationships among elements ignores valuable opportunities to embed flexibility.[33] Hence, changes may include "planned changes" triggered by exogenous uncertainties as well as those induced by change propagation.[29] When *Objects* are coupled, especially physically, a change made to one typically requires changing the other.[42] Thus, *Change Objects* may be affected directly by *SR*s changes and indirectly by physical or logical changes propagating across *Objects*. Change propagation depends on the selected *Transition* (Step 5). For instance, changing an entire *Object* is more likely to have physical implications on connected *Objects* than merely replacing subassemblies of that *Object*. Consequently, an iteration, whose scope strongly depends on the product architecture of the reference design, is required between the first and second stages to identify indirectly affected *Objects* (path F in Figure 2) based on the selected *Transition*. The identified *Change Objects* are now transferred to Stage II (path E in Figure 2) to generate FDCs.

3.1.5 | Steps 5 and 6: Identify suitable *Transitions* and *Change Enablers*

With the set of *Change Objects* identified, designers can now select relevant *Transitions*. *Transitions* are change strategies performed on physical *Change Objects* to make them refulfill any violated *SR*s. Designers must always consider *Transitions* in relation to the entire *Change Object*. For instance, a change might be an "Entire Replacement" or a "Relocation" of the *Change Object*. The suitable *Transition*, in turn, is always specific to the *Change Object*, unless designers can attribute it to a class of similar *Change Objects* (eg, manifolds).

*CE*s, in contrast, are inherent features or properties that enable the physical *Change Objects* to facilitate *Transitions* in a timely and cost-efficient manner once the system is in use. "Modularity" and "mobility" are two examples of underlying principles attributable to *CE*s. As with *Transitions*, suitable *CE*s are also specific to the *Change Object* or suitable for a class of *Change Objects* with similar characteristics. The selected *Change Object* and *Transition* are both transferred to Step 6 (path G in Figure 2) to finalize the *FDC*. Here, designers select the suitable *CE*s, which might also require other specific *CE*s as a prerequisite—ie, they cannot be embedded without other *CE*s in place.

Transitions and *CE*s both represent "design variables" to generate *FDC*s for the previously defined *Change Objects*. In this regard, two alternative approaches for *FDC* generation apply, depending on the project's boundary conditions. In the first, a *Transition*-driven approach, the *CE*s are selected (Step 6) based on previously identified *Transitions* for each *Change Object* that is frozen in Step 5. By feeding the *FDC*s to Stage III, they are assessed (Step 7) and provide the basis for decision-making (path K in Figure 2). The best performing *FDC*s are then determined (Step 8), which represent or can be combined into *Flexible Design Solutions*. This *Transition*-driven approach is recommended when upgrade preferences are well established, upgrades have a fixed schedule, and/or the project faces strong time pressure.

In the second, *Enabler*-driven approach, *Transitions* (Step 5) and *CE*s (Step 6) are regarded simultaneously, resulting in a highly iterative

process (paths G and H in Figure 2). This allows the identification of best-performing combinations of *Transitions* and *CE*s for the identified *Change Object*. Here, *Transitions* are considered to be design variables that may be reset and can vary for a specific *Change Object* in the search for the best *CE-Transition* combinations. However, to attain a single *Transition*, which is required for the consideration of change propagation (path F in Figure 2), designers must perform an intermediate assessment (Step 7) to decide on the best *Transition*(s) for the *Change Object* with respect to the interdependent *CE*s. In contrast to the first, *Transition*-driven approach, where the *Transition* is defined at the very beginning, the *Enabler*-driven approach requires returning to Stage II postassessment (path J in Figure 2), where, based on the assessment results, the most suitable *Transition*(s) are then selected for the *Change Object* (Step 5). This is the basis for identifying downstream *Objects* affected by change propagation as they depend upon the *Transition* (path F in Figure 2). Those indirectly affected *Change Objects*, in turn, would then be subject to the same, iterative process. The *Enabler*-driven approach is recommended when high-performing solutions should be embedded and/or the project faces less cost and schedule pressure.

3.1.6 | Step 7: Assess *Flexible Design Concepts*

When applying the *Transition*-driven approach in Step 6, the assessment of *FDC*s is performed sequentially, without returning to Stage II. When applying the *Enabler*-driven approach, the selection of the final, suitable *Transition*(s) depends on the outcome of the intermediate assessment during this step. The assessment can be performed across different stages, and by applying different criteria, but we do not elaborate on these possibilities here. See Allaverdi[15] for further details.

3.1.7 | Step 8: Select *Flexible Design Solutions*

Based on the assessment results, designers filter and integrate high-performance *FDC*s to arrive at *Flexible Design Solutions*, which they may then integrate into the reference design (path L in Figure 2). However, further iterations of the *FDO-PM* may still be useful.[43(p.32)] As each *Change Object* might still have insufficient solutions, initially neglected *Baseline Objects* may be reconsidered by lowering the critical risk threshold (path M in Figure 2). Less critical *Change Objects* could also prove worthwhile for embedding flexibility, as they might still provide positive value across the life cycle.

3.2 | *FDO Data Model (FDO-DM)*

The *FDO-PM* incorporates five domains, each with its own sets of internal and external dependencies: *Change Drivers* (*CD*s), *SR*s, *Objects*, *CE*s, and *Transitions*. We model this scope of consideration in a MDM called the *FDO Data Model* (*FDO-DM*). Figure 3 shows its metamodel,[28,44(p.109)] where each diagonal cell represents a DSM (not

shown in detail) and each off-diagonal cell represents a potential domain mapping matrix (DMM), only some of which apply. For example, *CD*s affect *SR*s, which affect *Objects*, and so on.

*CD*s are built up as <Type of change><Subject of change>, such as "change rate of penetration," "depletion of formation," "demand of mud logging," etc. "Demand for" *CD*s are usually the last in the *CD* causal network. Hence, they are usually related directly to *SR*s, which are built up as <*SR*><[Capability],[Condition],[Constraint]>. While capabilities describe the ability of the system to perform a function (eg, "managed pressure drilling" [MPD]), conditions describe either the manner of function fulfillment (eg, methods such as alternative heavy equipment guiding principles) or parameters within allowable borders for functions or features (eg, changes in mud storage volume). Constraints, in contrast, indicate externally imposed limits for functions or features (eg, specific "tubular specifications" or limits in "indoor toxic fumes exposure").

Objects are physical constituents of the system that its designers can influence (ie, they belong to the solution space). If a *Baseline Object* in the *Object* domain does not fulfill a *SR*, then a *Change Trigger* (not shown in Figure 3) occurs and the *Object* becomes a *Change Object*. The *Object* domain contains all possible *Objects* that could be fed as *Baseline Objects* when identifying FDOs. It is the central domain as it represents the linking element between the reasons for change and the changes themselves. Domain elements must have an unambiguous name (eg, *Object* "derrick drilling machine").

*CE*s are inherent features or properties embedded in physical *Enabler Reference Objects* to facilitate *Transitions* of physical *Change Objects* in a time- and cost-efficient manner during system operation in the field. *CE* elements are built up as <Design guideline identifier><Design guideline><Enabler Reference Object>. A design guideline, in turn, also follows a formal description including the action, the subject and—to avoid ambiguity—an optional indication of the purpose, which indicates what to do with the *Enabler Reference Object*. For clarity and systematization of design guidelines, each is assigned to a superior category of *CE* principles (Universality [UNI], Scalability [SCA], Modularity [MOD], Mobility [MOB], Connectivity [CON], or Compatibility [COM]) and defined by a number to form a unique identifier (eg, "MOB_1" for a specific, mobility-related design guideline). The syntax also includes an *Enabler Reference Object* that identifies where the design guidelines are embedded, as it may not correspond to the *Change Object* to be facilitated. For instance, "more available space in a room," with the "room" being an *Enabler Reference Object*, may support the relocation of a pump (*Change Object*).

Transitions are externally imposed change strategies for physical *Change Objects* to make them refulfill any violated *SR*s. We define a set of eight *Transition* operators (Table 3) to span designers' relevant change strategies.

The *FDO-DM* provides the basis for both defining the system and applying the *FDO Execution Model* (*FDO-EM*, described in the next subsection). The *FDO-DM* is built up generically (ie, without a specific architecture in mind) at a higher level of abstraction, as it is intended to be reused across, and adapted for, specific projects while running in early design phases, when "detailed change information is not readily
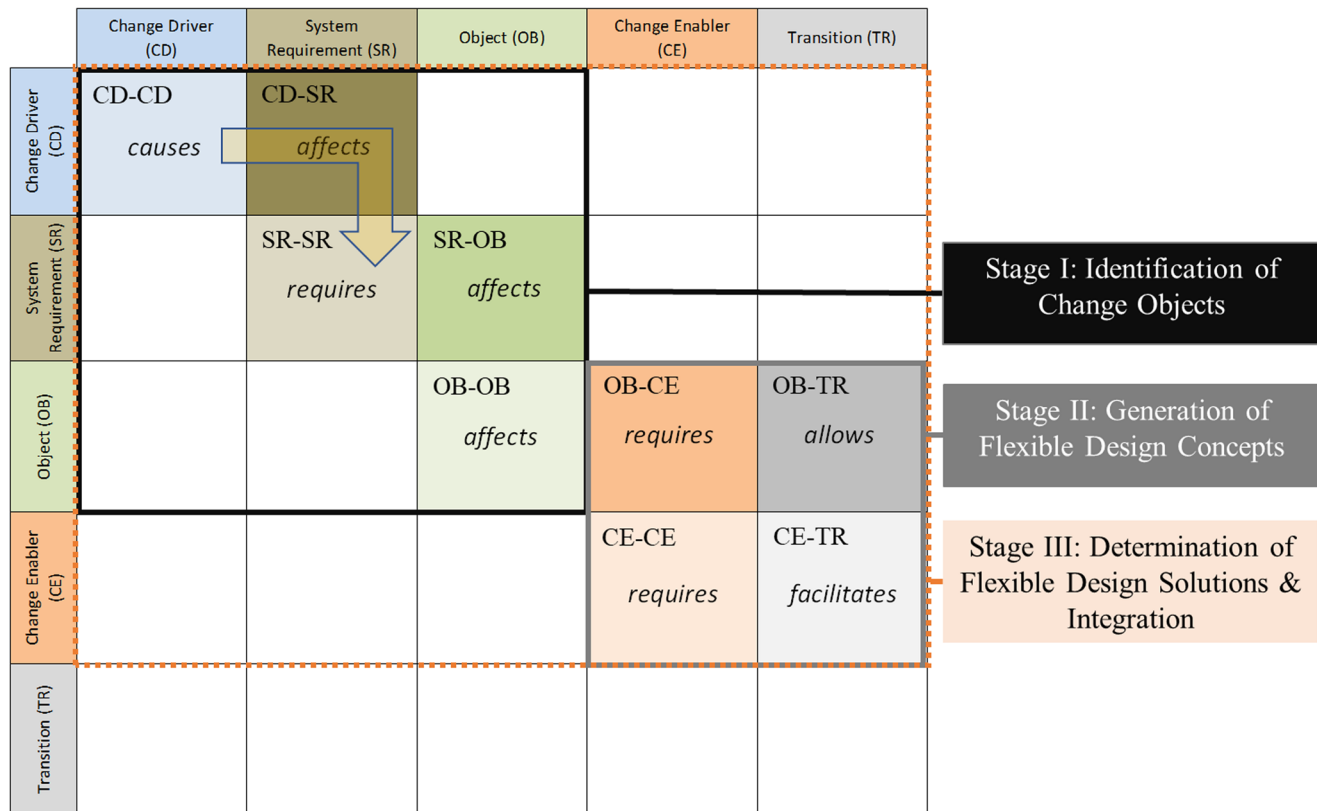
FIGURE 3 *FDO Data Model* (*FDO-DM*) as a MDM metamodel

available and an estimation of change impact is sufficient for further planning."[46] This implies, on one hand, a high level of elements' abstraction (eg, *Objects*), while, on the other hand, documented relations being only *potentially* relevant to the context of a particular project, thus requiring confirmation in the project's specific context when running the *FDO-EM*.

An exception is the *CE*s representing heuristics, which can vary in their level of abstraction from general design principles to very specific design guidelines,[47–49] and thus, are applicable for both variant design (changes within defined parameter ranges, such as "add crossbracings to a derrick structure") and adaptive design (changes involving new parameters or new parameter ranges, such as "provide space around Object for spatial expansion"), as suggested by Koh.[46] This also applies to *Enabler Reference Objects*, which can be a specific *Object* or a generically defined part of the system (eg, structure or room). This leaves users with several degrees of freedom in applying *CE*s or *Enabler Reference Objects* in the application context while ensuring maximum reuse of project-independent knowledge.

Whereas the procedural aspects (*FDO-PM*) are application-context-independent, the data stored within the domains (elements, relations) are not. Nevertheless, insights, especially *Transitions* and *CE*s, can be said to apply across different but similar contexts (eg, across plant engineering). In general, the extension of elements and relations of domains (eg, *CD*s and *CE*s) in the *FDO-DM* is a continuous process for the application context of concern to increase the value of the FDO methodology once it is applied in projects.

The next subsection provides an example of the DSMs and DMMs in stages I and II of the *FDO-PM* as they develop through the *FDO-EM*.

3.3 | *FDO Execution Model* (*FDO-EM*)

The *FDO-EM* applies the data stored in the *FDO-DM* to a specific project by running through the *FDO-PM*, as exemplified in Figure 4. This generates multiple instances of the various matrices, either original or transposed (the latter evidenced by the vertical labeling of the influence), to account for the various possibilities of how the *Objects* can be affected and enabled, while providing an unambiguous representation of those results as a means for assessment. Each matrix has a singular identification handle for clear referencing. For instance, the dependency type "*SR affects Objects*" (*SR-OB*) is represented twice, by matrices M_3 and M_7 (the latter being the transposed version of M_3), which are numbered according to the order of steps within and across each path. Based on the *FDO-DM*, where the domains, dependency types, and data (elements and relationships) are stored, the *FDO-EM* represents a running model that uses both the originally oriented and transposed matrices to enable the identification of FDOs.

Matrices *OB-TR* and *CE-TR* are not shown in Figure 4, because they are added "on top" (ie, as a third domain in particular matrices), enabling the generation of *FDC*s (stage II). The generation of *FDC*s can be divided into the selections made in:

TABLE 3 *Transition* operators for *Change Objects* with examples

Transition Operator	Description	Example(s)
Passive	Delivers its intended functionality despite varying operational conditions,[45] so requires no further actions in response to changing *SR*s	Overdimensioning of hydraulic power unit (*Change Object*) by providing two additional slots and subunits than currently required (required capacities might increase due to longer drilling paths in the future)
Relocating	Changes the *Change Object*'s position and/or the system's configuration	Due to expected increases in environmental loads on the drilling rig, large handling cranes (*Change Objects*) that are very sensitive to rig accelerations are moved to lower decks to increase operating windows (preventing shutdown), efficiency, and safely
Adding	Increases the number of existing *Objects* or introduces entirely new *Objects* to the system, usually when adding entirely new capabilities	Adding a backpressure pump (*Change Object*) to the system as a new drilling method ("Managed Pressure Drilling") is introduced to an existing rig that previously lacked that capability
Reducing	Reducing the number of existing *Objects* or removing them entirely from the system, usually when certain capabilities are no longer required	Removing a handling crane (*Change Object*) due to stricter Health Safety Environment (HSE) requirements
Extending	Adding only major parts of *Objects* (eg, due to added functionality or capacity)	Adding cross-bracings to a derrick structure (*Change Object*) or adding a stronger and larger derrick drilling machine motor (*Change Object*) due to higher lifting load requirements
Contracting	Removing only major parts of *Objects* (eg, due to reduced functionality or capacity, high-resource consumption)	Removing two out of eight compensation cylinders from the compensation system (*Change Object*) due to reduced compensation capacity (and higher weight, maintenance efforts, space, etc.) requirements when moving from harsh to benign waters
Partial Replacement	Replaces some parts of the *Change Object* (combines Contracting and Extending)	Replacing the hydraulic motor or gearbox of an already-embedded derrick drilling machine (*Change Object*)
Total Replacement	Replaces the entire *Change Object* (combines Reducing and Adding)	Replacing an already-embedded derrick drilling machine (*Change Object*)

- matrices *SR-OB* (M_3) and *OB-OB* (eg, M_{10}) with the superposed matrix *OB-TR*, to make both the decisions on the affected *Objects* and the suitable *Transitions*, and
- matrix *OB-CE* (eg, M_4) with the superposed matrix *CE-TR*, to make both the decisions on the affected objects' *CEs* and the suitable *Transitions*.

3.3.1 | FDO-EM scaling

The *FDO-EM* is scalable to four cumulative paths of increasing scope and fidelity, depending on a project's circumstances. The higher paths build on the lower ones, including their results (eg, the Advanced path builds on the Light one). Figure 4 illustrates the path gradations with two types of tracing: "interdomain tracing" (identification of elements within DMMs) and "intradomain tracing" (identification of elements within DSMs).

The Light path runs through only the bare essentials of the *FDO-EM*. It allows the identification of directly affected *SR*s (M_1 and M_2), related *Change Objects* (M_3), and *CEs* (M_4), with the superimposed matrices *OB-TR* in M_3 and *CE-TR* in M_4, to choose suitable *Transitions*. The identification of indirectly required *CEs* (in M_5) is also included, as they must be considered simultaneously with *OB-CE* (M_4) to identify suitable

solutions. Generally, the consideration of *Prerequisite CEs* applies to all four paths in either M_5, M_9, M_{12}, or M_{15}.

Building on the Light path, the Advanced path additionally identifies indirectly affected *SR*s (M_6), which, in turn, affect *Objects* (M_7) also requiring *CEs* (M_8) and *Prerequisite CEs* (M_9). In this case, the superimposed matrix *OB-TR* applies to M_7, and *CE-TR* applies to M_8. The Profound path further considers physical change propagations from upgraded *Objects*. Based on the *Change Objects* directly affected by *SR*s (M_3), indirectly affected *Objects* are identified (M_{10}). As before for those *Change Objects*, *CEs* (M_{11}) and *Prerequisite CEs* are determined (M_{12}), again with the superimposed matrices *OB-TR* in M_{10} and *CE-TR* in M_{11}. The Complete path also considers propagations of *Change Objects* that are indirectly affected by *SR*s. Hence, the *Change Objects* (M_7) directly affected by indirectly affected *SR*s (M_6) are used to identify indirectly affected *Objects* (M_{13}), *CEs* (M_{14}), and *Prerequisite CEs* (M_{15}). In this case, the superimposed matrices *OB-TR* and *CE-TR* apply to M_{13} and M_{14}, respectively. This last path utilizes the full set of data from the *FDO-DM*.

Change propagations depend on the selection of *Transitions* in the superimposed matrices *OB-TR* and *CE-TR*. Hence, a homogenization of *Transitions* or a decomposition of the *Change Object* into multiple instances with heterogeneous *Transitions* is required. The latter is
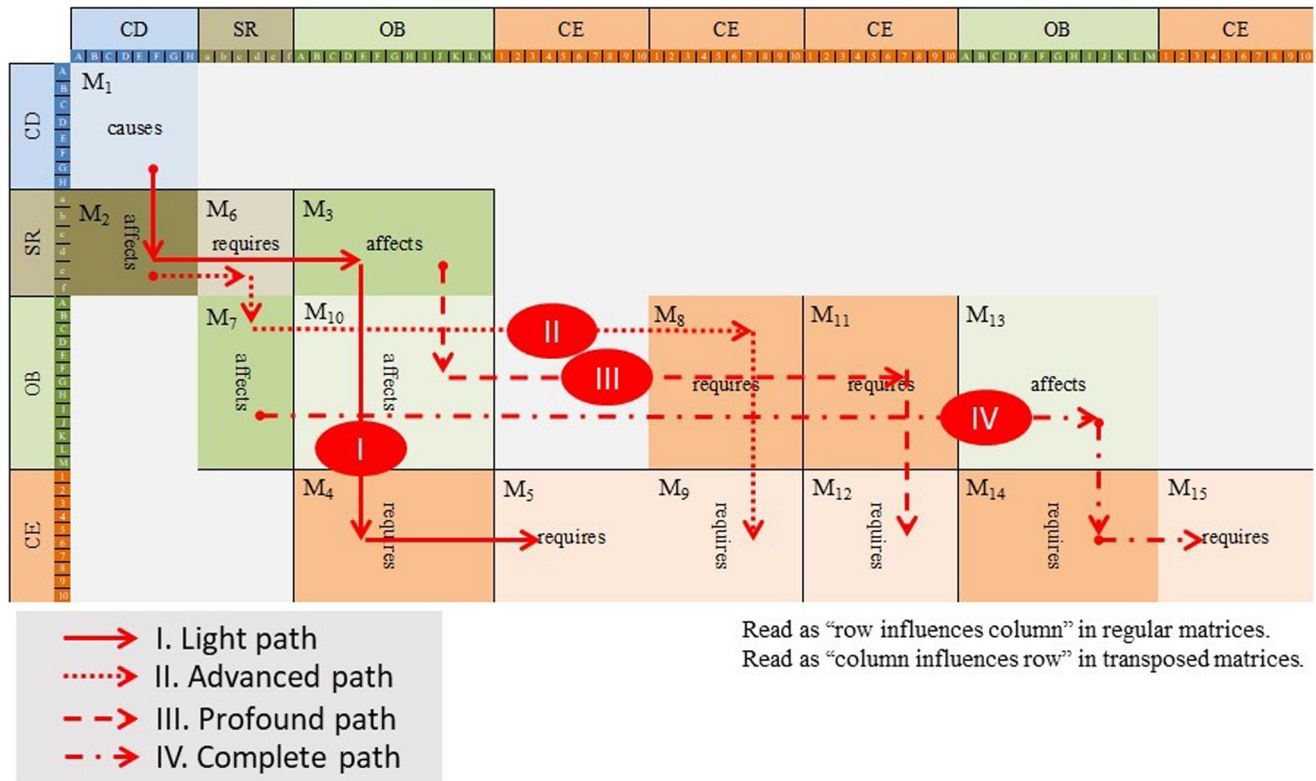
FIGURE 4 FDO Execution Model (FDO-EM) with original matrices, transposed matrices, and paths

realized by splitting/duplicating the *Change Objects* in matrices M_3, M_7, M_{10}, and M_{13}.

Because some paths build upon others, one of the following two sequences must be followed to move beyond the Light path:

1) Light path → Profound path
2) Light path → Advanced path → Complete path

This means, for instance, that running the Complete path requires having already run the Light and Advanced paths.

Besides these particular path dependencies, we advise first considering externally imposed changes and *SR* changes before accounting for internally imposed changes due to change propagation (*FDO-PM*). That is, account for indirectly affected *Change Objects*, such as accounting for the indirect relationships among *SRs* (M_6), before change propagations among *Change Objects* (M_{10}). Hence, the natural order of the cumulative paths is: Light path → Advanced path → Profound path → Complete path.

However, the relevancy, order, and actual thoroughness of the paths strongly depends on several factors, such as:

- The stakeholder constellation, the type of stakeholder using the model, and the decision-making criteria: For instance, operator-dominated tendering constellations, where the operator (eg, an oil company) is paying for the life cycle changes, may be more apt to

undertake the additional effort of running all of the paths (including change propagations), compared to "Builder Furnished Equipment" constellations (eg, a shipyard as a buyer), where initial CAPEX decisions dominate and only the most obvious future changes are taken into account.
- The scope of the *FDO-DM*, which sets boundary conditions on the feasible paths.
- The expectations of customers to address unarticulated potential for flexible design, where change propagation usually comes after considering changes sources.
- The available resources and time constraints for building the *FDO* database when applying the model during tenders.

Overall, the *FDO-EM* is designed to scale flexibly to accommodate a variety of real-world conditions and contexts such as these. The four paths represent a set of alternative levels as recommendations.

3.3.2 | Tracing and scenario building

The *FDO-EM* suggests a forward-oriented model for identifying FDOs that starts with the identification of *CDs* (M_1) and ends with the embedding of *CEs* into relevant *Change Objects* (eg, M_4 and M_5 with *Prerequisite CEs* in the Light path). When addressing a change scenario, this idealized workflow will often have to be adjusted to actual circumstances.

The articulated customer needs can cause various elements to instigate changes, thus altering the starting point for tracing in the *FDO-EM*. Here, we distinguish forward and backward tracing:

- (*Forward-*) *Tracing* is the forward-oriented identification of FDOs based on an instigating element. It concerns the identification of relevant downstream elements in the direction of causality and addresses both DMMs (interdomain tracing) and DSMs (intradomain tracing).
- *Back-tracing* is the backward-oriented identification of FDOs based on an instigating element. It reverses the tracing direction by going against causality, which facilitates the identification of upstream elements and the underlying reasons for changes that, in turn, might affect other elements that would not have been identified by downstream analysis of a predefined causal chain. It also applies to both DMMs and DSMs.

Despite the identified, articulated needs, and as Ross and Rhodes[3] emphasized, the goal of the system designer must be to identify as many of the unarticulated needs as possible, or at least make the system able to meet them when they are revealed or discovered. Based upon these tracing techniques, we suggest a process for building scenarios systematically in order to attain near-comprehensiveness in relevant change sources.

A scenario describes a possible future state stemming from a complex network of influencing factors.[50(p.82)] By defining particular, articulated, instigating elements, and tracing through the network, designers can build various partial scenarios and integrate them into a final, core scenario representing relevant elements and their attributes. Those scenarios must account not only for the *CDs* but also for the direction and magnitude of changes those elements will face, as shown by the anticipated future characteristics (eg, increase of drilling depth to 30 000 ft). In contrast to accounting for alternative developments of *CDs* (eg, 10 000 f. versus 30 000 ft drilling depth), it targets "focused planning"[19(p.101)] with only one future development (eg, drilling depth up to 30 000 ft) per scenario. Hence, multiple scenarios are considered, not because of alternative developments of *CDs*, but to account for independent, causal networks of FDO elements. Hence, scenario building targets a comprehensive representation of consistent or independent future scenarios for which the customer has interest to prepare. Ultimately, each scenario should have *CDs* that can be directly related to the *SR* domain, which is the basis for performing interdomain tracing.

The FDO methodology considers this assessment and decision-making in two ways: On the one hand, they are already addressed in stages I and II by assessing their relevancy on an element-by-element basis, as some potential relationships might not be applicable or relevant in a particular context and hence require no further consideration. The identification of *Change Objects* (Stage I) depends on certain criteria that have already been highlighted by various authors—eg, Refs. 12, 24, and 33. In general, they concern both the probability and (switching) cost of changes. Through *Tracing* in M_1, the poten-

tial relationships among *CDs* are checked by considering their probability of occurrence (P_{CD}). The probability of the instigating element (eg, P_{CD_a} with "a" indicating the instigating *CD*)—ie, the presumed root cause—is put on the element itself. The other probabilities in matrix *CD-CD* (M_1)—eg, P_{CD_ab} with "b" being the *CD* affected by *CD* "a"—concern the relationships among *CDs*—ie, the likelihood of impact between *CDs* once a change occurs in the instigating *CD*. Next, the probability of this *CD* having an impact on *SRs* (*CD-SR*, M_2), or the probability of one *SR* impacting another (*SR-SR*, M_6), determines if this *SR* will be considered further in the scenario. Besides the probability of change for *Change Objects* (P_{CO}), where the probability alone is sufficient to identify relevant *CDs* in M_1 or *SRs* in *CD-SR* (M_2) or *SR-SR* (M_6), the transition cost of *Objects* (TC_{CO}) must also be considered when addressing the risk of change in *SR-OB* (eg, M_3) and *OB-OB* (eg, M_{10})—ie, $P_{CO} \times TC_{CO}$. They play an important role "since decision-makers may not want to pay more in the initial design phase to enable flexibility if the system with standard design components can change easily in the future."[33] Note that diverse, customer-specific acceptability thresholds for probabilities and transition costs may lead to accounting for FDO elements in some cases, whereas in other cases, they may be ignored (eg, a probability of impact P_{CD_ab} = .6 might prompt accounting for affected *CD* "b" but might be ignored in other cases).

On the other hand, next to the continuous assessment and decision-making when running the *FDO-EM*, an intermediate or final assessment can occur. In general, to identify the best-performing *FDCs*, designers must perform a four-step, qualitative assessment to gradually contain the solutions. First, based on the experience of domain experts, designers discard irrelevant solutions. Second, designers make an absolute assessment of the remaining *FDCs* based on criteria related to technical risk and the system supplier's perspective (eg, technology readiness levels, feasibility for the project, etc.). Third, designers perform a relative assessment of the remaining *FDCs* according to criteria comparing the performance of each *Change Object* to each other and against the *Baseline Object*. This assessment relies upon an export of the *FDO-EM* to a separate report, from which *Flexible Design Solutions* may be deduced. The relative assessment criteria belong to three categories: (a) upgrade effort, the costs of exercising an upgrade; (b) upfront effort, the present costs of incorporating flexibility, such as greater design and manufacturing efforts, implicit opportunity costs such as by attributing additional space for future changes, etc.;[45] and (c) operational effort and losses, which emphasizes changes in the performance during operation. Although in this case, neither a positive nor a negative impact can be predefined across the board, flexible design may lead to significant performance changes that require consideration (eg, operating expenses and overall equipment effectiveness such as availability losses, performance losses, quality losses, etc.). Fourth, influencing criteria may impact the decision, as *CEs* vary in their usage frequency across the life cycle, which indirectly affects their performance when considering two main types of changes (frequencies of upgrades and of maintenance, repair, and overhaul activities).

4 | AN EXAMPLE APPLICATION OF THE FDO METHODOLOGY

In this section, we demonstrate an application of the Advanced path of the FDO methodology to the design of an offshore drilling platform—a real project that helped develop and implement the FDO methodology on the side. (Further details are available elsewhere.[15]) The Advanced path deals with both direct and indirect relationships. In this context, the iterative development of the FDO methodology, the population of the *FDO-DM*, and retrospective reflections drew mainly from semistructured interviews with project experts. This *FDO-DM* included both densely and sparsely populated matrices, which fed into the *FDO-EM*.

4.1 | Use case basis

In conventional offshore drilling, performed under atmospheric pressure, drilling fluid and gas exit the top of the wellbore through a diverter and flowline to a mud gas separator (MGS), which separates the gas from the liquid. Solid control equipment such as a shale shaker separates the fluid from solid rocks, and after treatment, the purified mud can be reinjected into the wellbore. In a stable state of drilling with circulating mud, the bottom-hole pressure P_{BH} in the wellbore equals the hydraulic pressure (P_{Hyd}) plus the dynamic pressure due to annular friction (P_{AF}). When the circulation ceases, due to, eg, making up drill pipes on the rig, P_{BH} exceeds P_{Hyd}, which can cause an influx that must be circulated out of the well. Such well control incidents come in addition to the repeating "kick-stuck-kick-stuck" scenarios triggered by lost circulation, stuck pipe, and wellbore instability. All of these contribute to nonproductive time (NPT) on the rig.[51]

In contrast, *MPD* utilizes a closed vessel, where fluids exiting the borehole are not exposed to the atmosphere. In addition to the static, hydraulic pressure (P_{Hyd}) and the dynamic pressure (P_{AF}), a back pressure (P_{Back}) can be applied flexibly to the closed system, whereby drillers can better control the annular pressure profile with instant reactions to pressure changes. Especially in complex formations with narrow pressure margins, MPD can significantly reduce NPT by better controlling P_{BH}. Most of the equipment for MPD operations is the same as for conventional drilling (eg, hoisting, rotating, tubular handling), requiring minor modifications (if any) to upgrade a conventional rig to a MPD rig. Nevertheless, integrating a new MPD capability requires installing some specialized equipment for well control and mud circulation.

As shown in Figure 5, in order to ensure a pressurized circulation of drilling fluid, the riser gas handling device (RGHD) is attached to the riser string below the telescopic joint of the riser. The RGHD consists of two main components in the upper riser package: the riser drilling device (RDD) and the flowspool. The RDD consists of highly resistant and lubricated rubber sealing elements and provides an active seal on the drillstring to contain annulus pressure while allowing the drillstring to rotate. To protect the RDD from excessive wear, a seal integrity circuit (SIC) on the topside of the rig circulates synthetic fluid from tanks to the rubber seal via hoses and back. The mud returns are prevented from bypassing the RDD and are run through a flowspool and the attached hoses (return lines) back to the rig. The mud return then enters the buffer manifold, which merges the flows, and then the coriolis meter, which measures the mass flow rate. Next, the flow enters the pressure control manifold, which consists of chokes that can be flexibly closed to increase the backpressure (P_{Back}) if the mud flow decreases. In case of a sudden backpressure loss (eg, a late response of closing the chokes), the loss remains until flow resumption of the well or additional pressure from another source.[52] One such source could be a backpressure pump (not shown in Figure 5)—an automated, on-demand pump that ensures sufficient fluid supply and thereby prevents unwanted backpressure losses in the first place, or reestablishes backpressure once lost. The pressure control manifold then diverts the mud return to the drill floor, going through a MGS, from which large portions of gas are removed and released (gas vent). The mud return then runs through shale shakers to remove large cuttings and continues to be cleaned and treated with additives before being reinjected into the mud circuit.

4.2 | Initial situation and preparation

The use case is based upon a long-term tender, in an operator-dominated system development, for a drillship that is run collaboratively between a drilling contractor and an oil company. The project addresses the need for drilling operations in increasingly tougher conditions as fields mature and more challenging operating environments are selected. Those environments are usually in deep water (up to 10 000 ft) and drilling depth (up to 40 000 ft), with the rig and drilling systems being exposed to extreme reservoir pressures and temperatures. The deep water also increases the seawater overburden, leading to narrow pressure windows that complicate conventional drilling (due to frequent "kick-stuck-kick-stuck" scenarios) and cause a negative impact on NPT. The objective of the rig is to foster efficient and safe drilling operations, including well completion and intervention.

In this use case, (a) the main technical specifications of the hull design are already set, and system suppliers are now competing in a tender to provide suitable drilling systems to meet those specifications. (b) The price of oil has recently dropped, with a prolonged negative outlook, causing deep-water drilling operations to be less attractive in the near future. (c) The customer still plans to build the drillship anyway, but it considers a change of scope that was not embodied in the initial, technical specifications. The customer expresses the following need: "In the long-run, this rig is still very likely to drill wells at extreme temperatures and pressures. That was the initial intention and the hull is ready for it. Therefore, we would consider having MPD on board once the market picks up again." Hence, the customer now considers postponing the investment in MPD capability but preparing the drillship to acquire this capability in the future. The customer would like to know
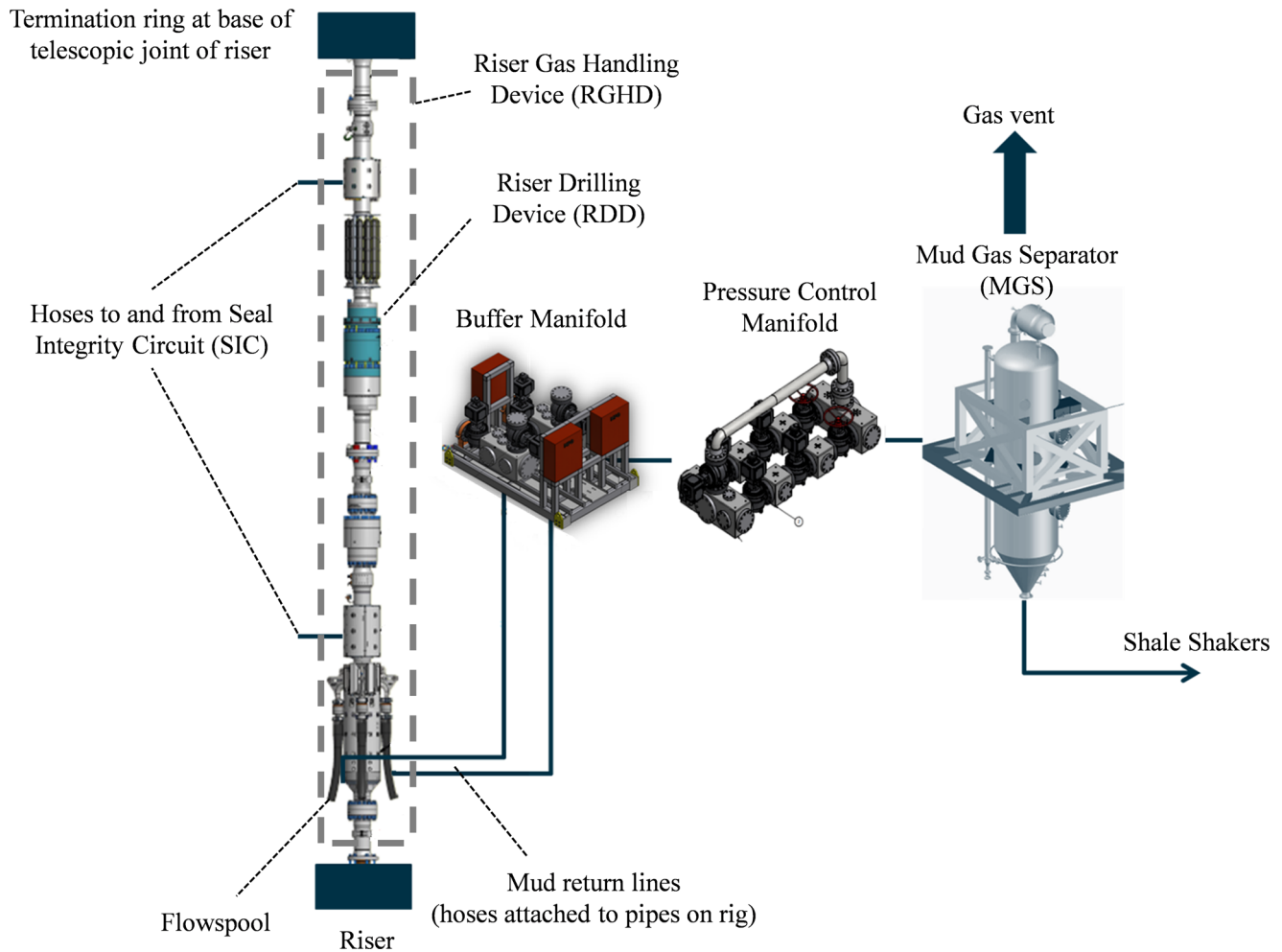
FIGURE 5 Build-up of typical MPD system (adapted from MHWirth AS[55])

the implications of such a decision—ie, what is the cheapest way to buy this real option?

Applying the FDO methodology to this use case requires the eight steps of the *FDO-PM*. Initially, designers compare the technical specifications to existing drilling systems placed on similar hulls. Despite limited data on other projects meeting those extreme technical specifications, they select the closest possible reference design (Step 1 in the *FDO-PM*). The boundary conditions—especially the customers also being the system users and the long-time horizon of the tender project—allow the selection of a more comprehensive set of *Baseline Objects*. Only the least upgrade-critical *Objects* are filtered out from the reference design. The rest of the drilling equipment and all bulk items represent the imported *Baseline Objects* considered in the *FDO-EM* (Step 2 in the *FDO-PM*). As the main uncertainty addresses "adding a new capability," which usually requires additional dedicated *Objects*, designers must check if any MPD-dedicated *Objects* are already part of the reference design (and thus already imported as *Baseline Objects;* iteration "B" in the *FDO-PM*). In this case, the reference design already includes the customer-articulated MPD capability, so no further *Baseline Objects* are needed.

Although we performed extensive data elicitation and validation to build the *FDO-DM* with all MPD-relevant elements, our presentation here will consider only a subset of the data, represented by M* matrices, and focus on the Advanced path, followed by an intermediate assessment for one of the *Change Objects*. In stage I, the reduced matrix *CD-CD** (M_1^*) is verified in its entirety and represents a densely populated and MPD-relevant section of the sparse matrix *CD-CD* (M_1). *CD-SR* (M_2), *SR-SR* (M_6), and *SR-OB* (M_3) are reduced to *CD-SR** (M_2^*), *SR-SR** (M_6^*), and *SR-OB** (eg, M_3^*), with only seven relevant *SR*s in this application context. They still represent sparsely populated matrices in the *FDO-EM*—ie, further influences on *SR*s or *Objects* are possible than the ones mapped. The same applies to the *OB-OB* matrix (eg, M_{10}), which is reduced to *OB-OB** (M_{10}^*) with only 11 *Objects*. Stage II, the generation of *FDC*s, employs densely populated matrices, with the exception of *CE-CE** (eg, M_5^*). *OB-CE* (eg, M_4), and hence, *OB-CE** (eg, M_4^*) are densely populated. Finally, *OB-TR* and *CE-TR* are also dense and entirely verified models, which, as noted above, are superimposed, with the *SR-OB* and *OB-CE* matrices not being represented explicitly in the *FDO-EM*. In the following, we refer to those matrices by singular identifiers (eg, M_3^* and M_7^* for *SR-OB**).

4.3 | Building change scenarios

Designers can deduce *CDs*, *SRs*, or even *Change Objects* directly from articulated customer needs that refer to potential change requests in the future. Hence, these represent the instigating elements in the causal network. An initial scenario—a causal network of relevant *CDs*—can be built by *Back-tracing* and *Tracing* from those instigating elements. The Advanced path builds upon the Light path, which requires first identifying the *CDs* (M_1) and first-degree *SRs* (M_2). As part of "Recognition of change sources" (Step 3 in the *FDO-PM*), designers do this by building a scenario. First, the core statements of the need articulated by the customer are assigned to the corresponding FDO domains and elements. "Extreme temperatures and pressures" can be assigned in the database (ie, the *FDO-DM*) to the *CD* "Change of Well Pressure & Temperature." "MPD" refers to the *SR* "Managed Pressure Drilling [Capability]," which can also be found in the database.

Next, the causal network in the *FDO-EM* is traced by using the articulated need on future change, highlighting use-case-relevant FDO elements and corresponding relationships in Figure 6. Based on *SR* 5 (MPD [Capability]), the causal network is backtraced (Step 1 in *FDO-EM*). The *CDs* are selected based on high P_{CD} and customer-specific acceptability thresholds. *CD* "h" (Demand for Dynamic Well Pressure Control) is identified as the underlying reason for a change in *SR* 5. Further *Back-tracing* (Step 2 in the *FDO-EM*) leads to the identification of two other relevant *CDs* in this context: "Demand for Increased Uptime" (k) and "Change of Well Pressure & Temperature" (c). The latter also represents the other articulated, corresponding FDO element, and thus belongs to the same initial scenario, as it appears in the same causal chain as the other articulated, corresponding FDO element, namely, the *SR* "MPD" or "Managed Pressure Drilling [Capability]."

Here, we refrain from further *Back-tracing*, as the results so far provide sufficient starting points for further *Tracing*. Based on the two indirectly identified *CDs* "c" and "k" in M_1^*, we select the new *CDs* "j" and "m" (Step 3 in the *FDO-EM*). As both connect directly to M_2^*, and further *Tracing* in M_1^* (Step 4 in the *FDO-EM*) does not add further results, we complete the process of building the initial scenario.

Based on the two new *CDs* "j" and "m," we perform interdomain *Tracing* to identify further, as-yet-unarticulated *SRs* (Step 5 in the *FDO-EM*). The confirmation of potential relationships is based on a high P_{SR} and customer-specific acceptability thresholds. In this reduced matrix M_2^*, *CD* "j" has no impact on other *SRs*, whereas *CD* "m" affects *SR* 1. Consequently, the core scenario consists of the governing *CDs* "h," "j," and "m."

4.4 | Running the Advanced path in the *FDO-EM*

Building upon the Light path, the Advanced path identifies indirectly affected *SRs* (Step 3 in the *FDO-PM*). *SR* 1, "Active Heave Compensation [Capability]," was not directly articulated but rather identified by *Back-tracing* and *Tracing*. It and *SR* 5, the customer-articulated "Managed Pressure Drilling [Capability]," provide the starting point for further *Tracing*, as noted by Step 6 in Figure 7. The confirmation of potential relationships depends on high P_{SR} and customer-specific acceptability thresholds. While *SR* 5 has potential impacts on five other *SRs*, *SR* 1 does not affect any others. Embedding the "MPD capability" will certainly affect *SRs* 2 and 3, as new equipment must be installed and powered. *SRs* 6 and 7 may be affected as well, as increased capacity is required for the additional gas that is returning from the formation due to operations close to pore pressure, while increasing the mud flow and trapped gas compared to conventional drilling. *SR* 3, in turn, itself requires increased electric power capacity (*SR* 2): This allocation requires intradomain *Back-tracing* (step 7 in Figure 7). Due to the previous allocation by *Tracing*, however, *SR* 2 has already been selected. Hence, in this case, intradomain *Back-tracing* leads to a double allocation of *SR* 2.

Based on the indirectly affected *SRs*, designers can now trace *Objects* (*OBs*) in M_7^* (Step 4 in the *FDO-PM*). *Change Object* identification should account for both the probability of occurrence (P_{CO}) and the transition costs (TC_{CO}). As shown in step 8 in Figure 7, *OBs* B, C, and D are affected. *OB* D and its underlying *SR* "Electric Power [Constraint]," however, lie outside of the solution space, beyond the scope of the main system supplier. Hence, no specific *Transition* (Step 5 in the *FDO-PM*) is selected for it, although information about its impact may be forwarded to other suppliers, who will have to agree on a flexible solution. In M_7^*, designers can specify it together with the *Change Object* selection (*Transition*-driven approach) by allowing the selection of the allowed types of *Transitions* (in this case, *TRs* 1, 2, 3, 4, 5, and 7 are available for the *Change Object* as drop-down selections for the hydraulic power unit [HPU]). In line with customer preferences, *Change Object* C is to be designed robustly to prevent future changes; hence, "TR 1" (Passive) is selected. In contrast, in case of the MGS, designers must consider the *Transition* as a yet-undefined design variable following the *Enabler*-driven approach. Therefore, in this case, the MGS is only selected as a *Change Object*, and the selection of the *Transition* is performed later, together with the *CE* in M_8^* (Step 6 in the *FDO-PM*).

We use M_8^* to select suitable *CEs* (step 9 in Figure 8) based on customer preferences. Given the locked *Transition* selected in M_7^*, *OB* C allows only the selection of *CE* 20, oversizing the power unit; *CE* 4, instead, is incompatible to the already-selected *TR* 1, and thus, cannot be selected as a solution. In the *Enabler*-driven approach chosen, designers select the *Transition* and *CEs* for *OB* B (MGS) simultaneously. Two alternative *Transitions* are reasonable: *TR* 1 ("Passive"), which requires no physical changes because it includes an extracapacity MGS at the beginning, and *TR* 5 ("Adding"), which adds a second MGS later. However, designers should further evaluate the suitable *Object-Transition* (*OB-TR*) and *CE-Transition* (*CE-TR*) combinations before making a selection. The following *CEs* are available for *OB* B with an indication of where the *CE* is to be embedded (*CE* Reference Object):

- *CE* 3, a design-detachable bolted hatch in room (structure) for removal/integration of *Object*
- *CE* 4, *Change Object*, use bolts instead of welding for *Object* fixation
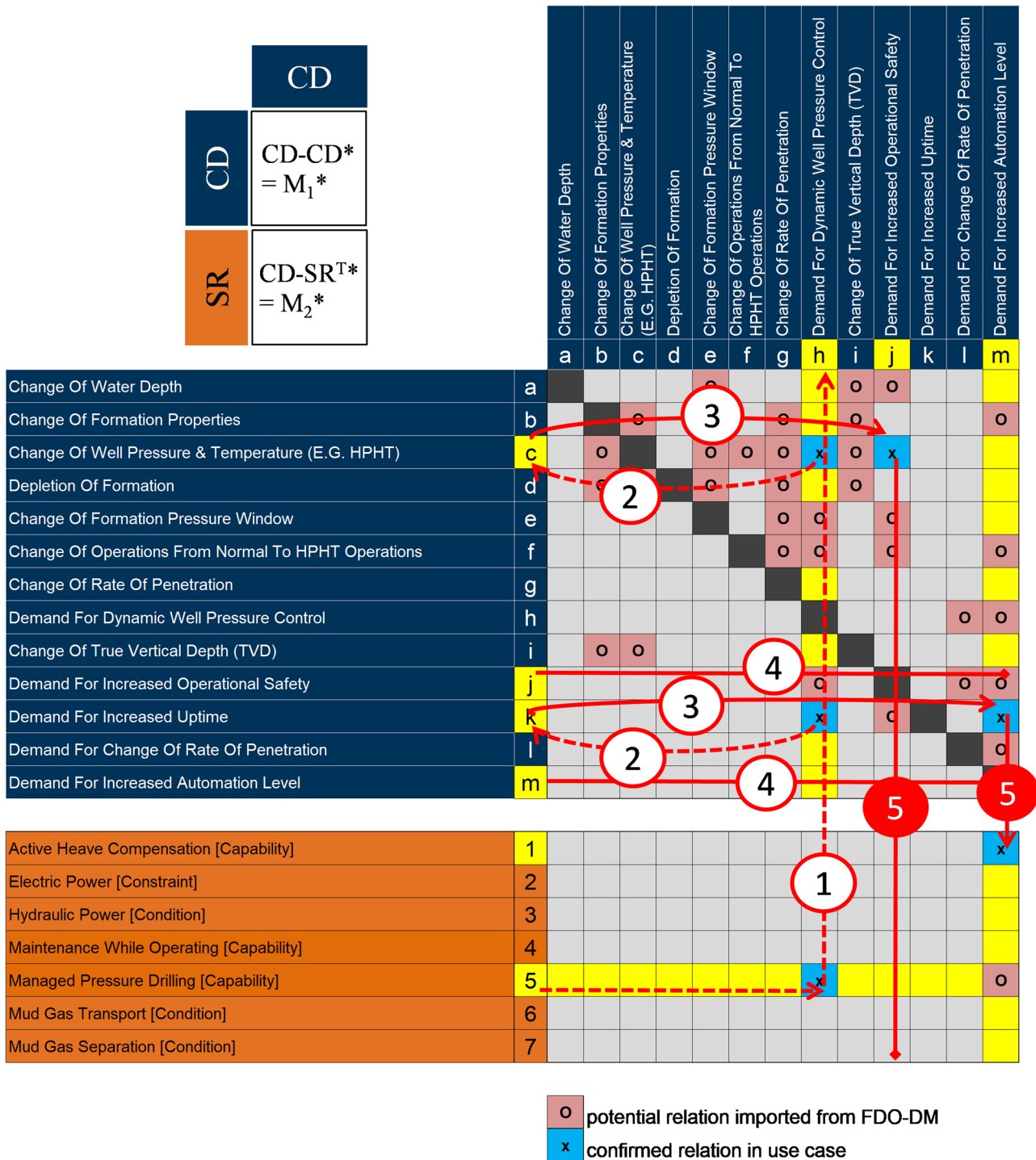
FIGURE 6 Building scenarios and identifying *SRs* in the *FDO-EM* (detail from upper left of Figure 4)

- *CE* 6, *Change Object*, equip with lifting lugs or pad-eyes for *Object* handling
- *CE* 15, preinstall structure base to ease subsequent integration of *Objects*
- *CE* 20, *Change Object*, oversize with regard to power/energy/capacity
- *CE* 25, extra room to provide space around *Object* for better accessibility

While *CE* 20 is suitable for *TR* 1 ("Passive"), all other *CEs* go with *TR* 5 ("Adding"). *CEs* 15 and 25 are also prerequisites for the exercise of specific *Transitions* in the first place (here: "Adding"). Designers will select among the *CEs* for the MGS as they are suitable. In this particular case, due to the system layout, the *Enabler Reference Object* "room" of the selectable *CEs* 3 and 25 refers to an enclosed structure that can be opened from above when the MGS is lifted into it.
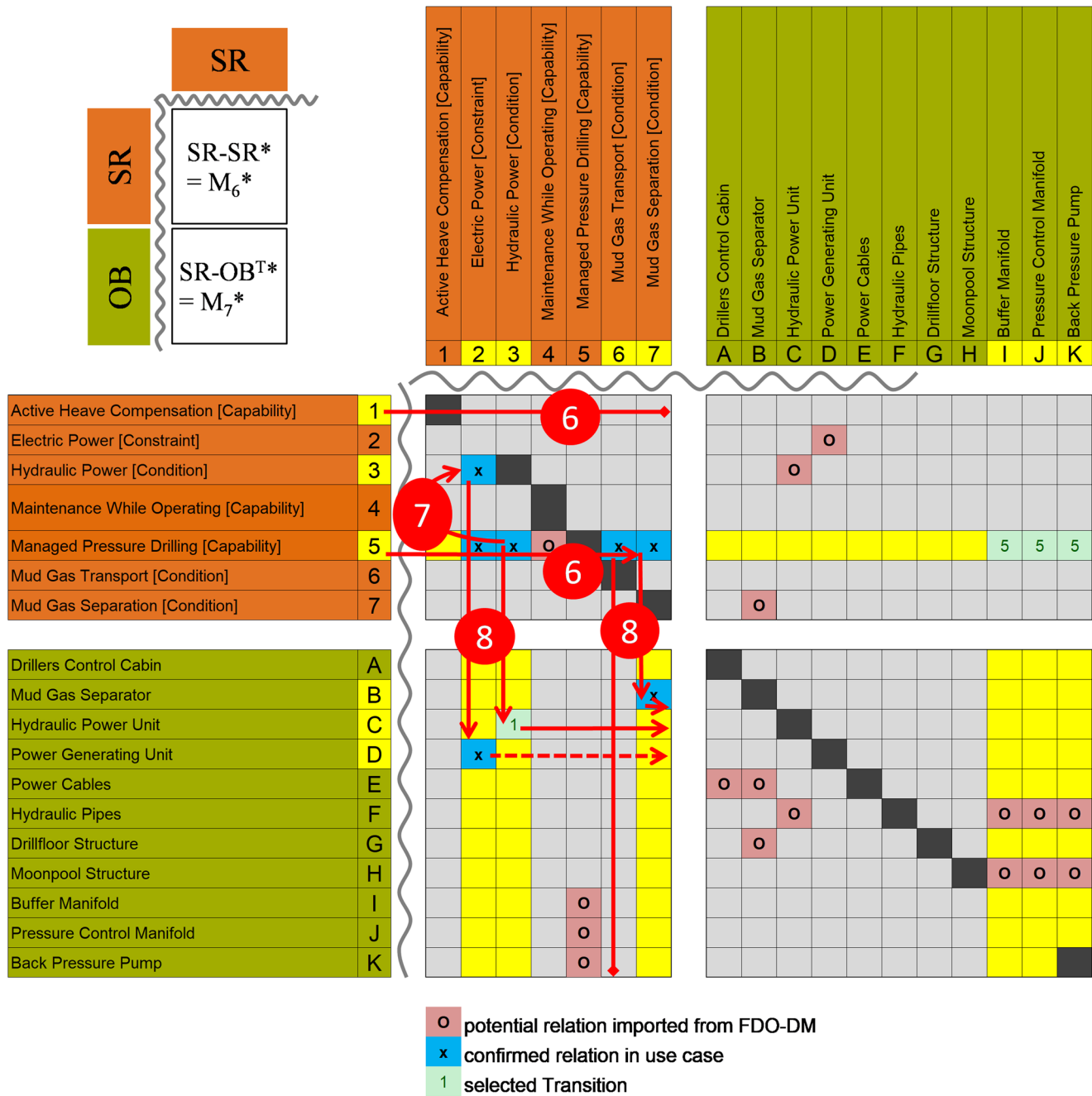
FIGURE 7 Identifying *Change Objects* in the *FDO-EM*

Considering both types of *Transitions* for the same *Change Object* B suggests a *FDC* that is not yet internally consistent. A subsequent homogenization (agreement on only one *Transition* for the MGS) is needed both to identify other *Objects* via change propagation (*OB-OB*) and to determine a final, high-performing *Flexible Design Solution*. Hence, the *FDC*s are exported to *FDO-EM Reports* and an intermediate assessment is performed (Step 7 in the *FDO-PM*) to homogenize *Transitions* for the MGS and return to stage II of the *FDO-PM* to identify the *Change Objects* affected by any change propagation. However, in the next subsection, we focus solely on the intermediate assessment (Step 7 in the *FDO-PM*), and, based on that, the selection of a *Flexible*

Design Solution for the MGS (Step 8 in the *FDO-PM*) without considering change propagation.

4.5 | Assessing FDOs with the FDO-EM report

Once specified, *FDC*s may be assessed (stage III in the *FDO-PM*). However, selections performed within the *FDO-EM* are not especially amenable to assessment in that format. Thus, we export the *FDC*s into a formatted table called the *FDO-EM Report*, exemplified in Table 4 for a derived *FDC* of the MGS (with the "Adding" *Transition* and *CE* 4).
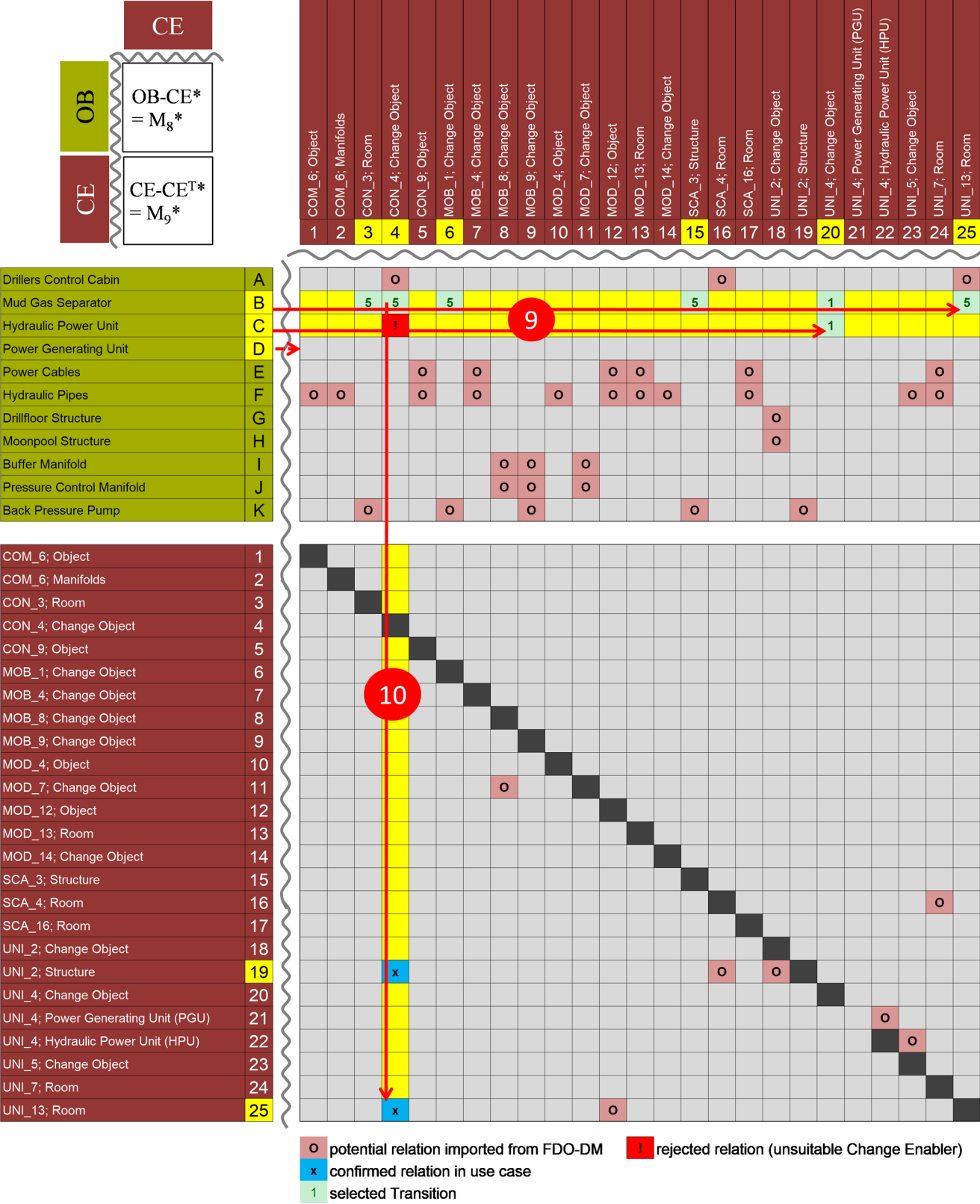
FIGURE 8 Generating *Flexible Design Concepts* (*FDCs*) in the *FDO-EM*

TABLE 4 Example *FDO-EM Report* for a *FDC* ("mud gas separator")

FDC ID#	Object Class	Change Object	Change Object	Matrix ID (SR-OB)	Change Object (f^a)	Change Object (n^b) (OB-OB)	Matrix ID	Transition	Change Enabler (selected) (OB-CE)	Matrix ID	Prerequisite Change Enabler #1 (CE-CE)	Prerequisite Change Enabler #n	Matrix ID	System Requirement (CD-SR)	System Requirement (f^a) (SR-SR)	System Requirement (n^b)	Change Driver (CD-CD)
1																	
2																	
3																	
4				Assessment & decision-making													
5																	
6	a	b	c	d	e	f	g	h	i	j	k	l	m	n	o	p	q
n																	

FDC example

	Mud Gas Separator (MGS) with CE "CON_4; Change Object"
a	Pressure Vessels
b	Mud Gas Separator (MGS)
c	Mud Gas Separator (MGS)
d	M_7
e	not applicable
f	not applicable
g	not applicable
h	(5) Adding
i	CON_4; Change Object
j	M_8
k	UNI_2; Structure
l	UNI_13; Room
m	M_9
n	Managed Pressure Drilling [Capability]
o	Mud Gas Separation [Condition]
p	not applicable
q	Demand For Dynamic Well Pressure Control

Flexible Design Concept example

Each *FDC* represents a unique *Change Object-TR-CE* combination. Designers must assess each *FDC* individually, because each *Change Object* can be subject to different *Transitions* and *CEs*. Consequently, the initial table usually consists of various *FDCs* for each *Change Object*. After assessment and decision-making, each *Change Object* should have only identical *Transitions* and best-performing *CEs*. The final *Flexible Design Solution* for each *Change Object* might be a combination of various *FDCs* (rows) with different, best-performing *CEs*. *FDCs*, however, should be internally consistent. For instance, *CEs* with different *Transition* types (eg, *TRs* 1 and 5) cannot be combined into one *FDC*, nor can conflicting *CEs* (eg, "reducing weight of *Object* for better mobility" vs. "oversize *Object* with regard to stress/load cases").

The assessment process refers to the four steps introduced in Section 3.3.2 for an intermediate or final assessment of *FDCs*. The intermediate assessment is performed identically to the final assessment (Step 7 in the *FDO-PM*), but the use of the results differs: In contrast to the final assessment, which is the basis for generating *Flexible Design Solutions* (Step 8 in the *FDO-PM*), the intermediate assessment uses the decision made on *FDCs* in addition in stage II (*FDO-PM*) to homogenize *Transitions*, and then again in stage I (*FDO-PM*) to identify *Objects* affected by change propagation (iteration "F" in the *FDO-PM*). Our present example focuses on just the intermediate assessment and, based on that, the selection of *Flexible Design Solutions* for the MGS.

Based on the intermediate *FDO-EM Report* (Table 4), designers should draw upon expert knowledge to homogenize the *Transitions*. In this example, we skip the first step of the assessment process (ie, discarding irrelevant solutions based on the experience of designers) and proceed to the second by performing an absolute assessment, where the remaining *FDCs* are assessed based on exclusion/bypass criteria related to technical risk and the system supplier's perspective. As all six *CE* solutions have already been in place in previous projects (long track record), they all perform positively concerning the "technology readiness level." The long feasibility phase of the considered tender project

further ensures the successful incorporation of these *CEs*. As shown in step 10 of Figure 8, two *Prerequisite CEs*—ie, those *CEs* that are not explicitly selected in M_9^* (*CEs* required for other *CEs*) but are required for the selected *CEs* in M_8^*—are relevant to consider for *CE* 4, accounting for the system context:

- *CE* 19: Structure, oversize with regard to stress/load cases—ie, sufficient structural enforcement of the deck to allow for bolting
- *CE* 25: Room, provide space around *Object* for better accessibility, to ensure that bolting can be performed

According to the experts, *Prerequisite CE* 25 also represents a "*Must Change Enabler*," as it must be in place before another MGS can be added. Prior installation of a base structure is required to allow the subsequent addition of a MGS. *CEs* 19 and 25 are both obligatory only if "Adding" (*TR* 5) is finalized as the selected *Transition*. Both *CEs* must be considered for a performance rating, as this could affect the ultimate decision about the preferred *Transition*.

Progressing to the third step of the assessment, designers benchmark the *FDCs* relatively using performance criteria. We weight each criterion in the three main performance categories individually and progressively. We then rate each *CE* for the applicable *Change Object* (here: MGS) and *Transition* (here: "Adding" or "Passive") by comparing it to the *Baseline Object*, multiplying by the weighting, and then normalizing. We add these results to the performance profile shown in Figure 9. Hence, if different *FDCs* exist, each of them would usually have a different profile, performance rating, and ranking. The overall performance rating is derived by summing up the performance ratings in each category (eg, upgrade effort) for each *FDC*. Although the performance ratings and rankings support decision-making, a comparison of the full performance profiles of various *FDCs* should also be considered, as these
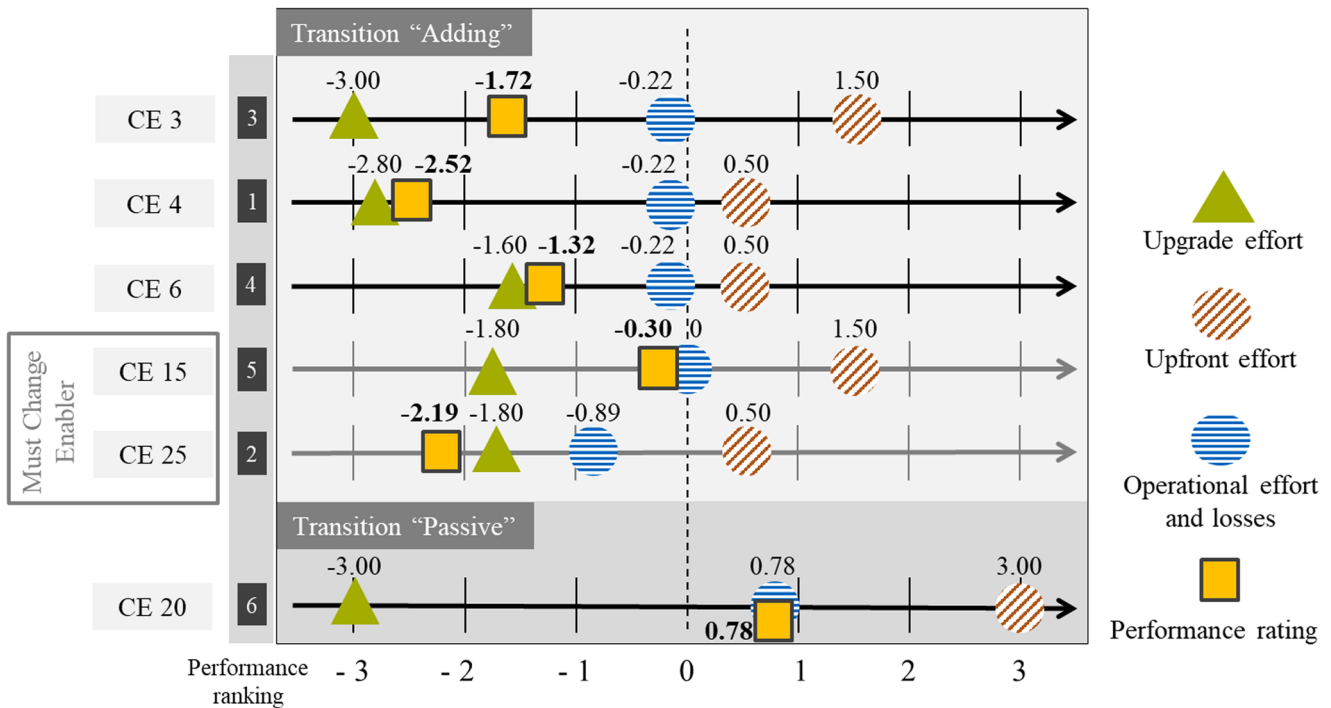
FIGURE 9 Performance profile of *FDC*s for "mud gas separator"

profiles may illuminate more nuances than the mere performance rankings.

In Figure 9, to determine the most suitable *Transition* for the *FDCs* of the MGS, we compare the five *CEs* for "Adding" to the one for "Passive" (*CE* 20), which is in both the left (upgrade effort) and right (upfront effort) sides of the chart. The overdimensioned MGS (*CE* 20) also has significant operational deficits compared to a fit-for-purpose, rigid design (the other *CEs*), especially due to the higher operational and maintenance costs. This observation is reflected in the only positive (bad) "operational effort and losses" rating (0.78), resulting in the weakest performance among *FDCs* and the sixth-place ranking for *CE* 20. Its rating also depends on the usage frequency of the overdimensioned MGS (influencing criteria considered in the fourth step of qualitative assessment), which will be "once" or "never" (a single anticipated upgrade across the life cycle). Here, the customers of that project also represent the system users who directly benefit from lower life cycle costs, so the *FDC* with *CE* 20 is deemed suboptimal to ones that consider "Adding" a MGS. Hence, we remove the solution with the "Passive" *Transition* and henceforth focus on the "Adding" *Transition* for the *Change Object* MGS. Next, we may further assess the other *FDCs* to generate the best-performing *Flexible Design Solution(s)* (Step 8 in the *FDO-PM*).

All remaining *CEs* for "Adding" a MGS have beneficial performance ratings and a high frequency of utilization, as they enable maintenance, repair, and overhaul activities. In particular, *CE* 3 has a very high utilization rate, as the hatch in the ceiling for removal/installation of the *Object* can also be used by other *Objects* for multiple purposes. Two *CEs* (15 and 25) are obligatory *Must Change Enablers*, and the other three *CEs* (3, 4, and 6) have advantageous performance profiles (<0) and are

mutually consistent, meaning that they can be combined. Hence, all *FDCs* besides *CE* 20 for the *Change Object* MGS are now integrated to provide a high-performing, *Flexible Design Solution* that can now be included in the reference design (iteration "L" in the *FDO-PM*).

We opened all *Change Objects* in the *FDO-EM* to unique *Transitions*, so their change propagations could then be determined. We focused on the "Adding" *Transition* with the Advanced path, but change propagations based on those results would have to be identified using the Complete path. The *FDO-EM* could be run for all four paths, leading to a range of *FDCs* that must be evaluated and integrated to determine the full set of *Flexible Design Solutions*.

4.6 | Reflections on the example application

After the example application, to provide further insights on the utility and usability of the FDO methodology, the first author interviewed a dozen workers involved from the drilling system supplier. These 12 evaluators included relevant stakeholders such as users, senior engineers, senior advisors, and lower and middle managers. They agreed that the FDO methodology provided a valuable "decision-support tool" during the early phases of design, and they especially noted its value in providing greater transparency for decision-making. In general, they found that the matrix-based approach, embedded in a spreadsheet-based tool, enabled a systematic yet user-friendly means of FDO identification. It enabled retracing decisions, which is advantageous for reasons such as internal documentation and communication across internal and external stakeholders. The continuous consideration of change risk factors (eg, probability and transition costs) in stage I, and

the project context in stages I and II, helped to avoid irrelevant work, and thus, kept the efforts required for stage III within acceptable limits.

Nevertheless, the example application has several particular limitations. The number of evaluators (12) and the time frame for the expert evaluation was limited, and these evaluators observed but did not themselves apply the FDO methodology. The example application focused mostly on the matrix-based portions of the FDO methodology (*FDO-EM*). Due to the effort required to capture so much data, the matrices were only partially populated, without ensuring completeness of the relations among elements in the *FDO-DM* and *FDO-EM*. This limitation may be ameliorated by maintaining the database as an evolving, knowledge management tool, but assembling it the first time from scratch requires extensive effort for complex systems.

5 | CONCLUSION

The FDO methodology presented in this paper is divided into three strongly interdependent parts: a procedural model (*FDO-PM*), a data model (*FDO-DM*), and an execution model (*FDO-EM*). Running the *FDO-EM* generates *FDC* alternatives that we assess in terms of relevance and performance. It is a comprehensive methodology with the ability to embed empirical data and heuristics to guide designers interactively through identifying affected *Objects* and short-listing relevant concepts to generate *Flexible Design Solutions*. The FDO methodology is intended to add the most value during early, conceptual design stages. We applied the methodology to a real project in the offshore drilling industry that exhibits large usage uncertainty and high potential for embedding flexibility. We expect the FDO methodology to be useful for many other types of large-scale, enduring systems.

This research has several limitations and unresolved aspects that present opportunities for further investigation. These especially concern the more effective building and maintenance of the *FDO-DM*. For instance, future research should target the systematization of data in the *FDO-DM* to ease its use in the *FDO-EM*, such as further structuring the elements within domains into groups that may then be interrelated across domains, and facilitating the targeting of specific types of elements during execution. For instance, *SRs* might only affect *Objects* at certain hierarchical levels (eg, at the factory level, or the machine level), and this information may allow hiding the elements in irrelevant groups, which will enhance usability when running the *FDO-EM*. Although the methodology explicitly accounts for change propagation, it becomes more difficult to manage if higher degree change propagations are considered. However, this need can be relativized, especially as technical systems have a limited change propagation extent.[29,53]

The integration of further features discussed in literature, such as compound options (ie, an "option on an option," such as combining "Relocation" and "Partial Replacement"),[18,54] which had no applicable use case in this research, could be a subject of future work. The scenario-building process could be extended to allow one to shift from the current "focused strategy," with one possible future, to a "future robust" strategy, accounting for varied attribute values of *CDs*.

Concerning implementation in a software tool, a stepwise implementation of the *FDO-EM* workflow would greatly support application in an industrial context. Research could then address matching user-specific boundary conditions and preferences to alternative workflows. Further research should also seek to validate the generated *FDC*s and *Flexible Design Solutions*, their assessment metrics, and the ability of decision-makers to identify the best results. In this regard, a further detailing on identified *FDOs*, such as the suitable degree of flexibility (eg, degree of modularity as emphasized by Engel et al[36]), would allow *FDCs* to be defined in greater detail. In addition to extending aspects already incorporated into the FDO methodology, future studies could also consider the "process management" of Concept Generation (Figure 1), "a rich environment for novel research contributions."[13] Closing the gap between the changes envisioned during design and the ones exercised during system operation is also of great interest, as it can further increase the effectiveness of *Flexible Design Solutions*. In this regard, it may be advantageous to consider the selection of multiple, alternative *Transitions* for a *Flexible Design Solution*, as preferences for selected future *Transitions* may change, or new stakeholders who favor other *Transitions* may become involved. Hence, the *Flexible Design Solutions* considered initially may turn out to be suboptimal if preferences shift across the life cycle. If future research can successfully address these aspects, the value of the FDO methodology will increase, as will the ability to augment the conceptual design process with artificially intelligent design tools that account for many future uncertainties in a system's operational use.

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APPENDIX

List of Terms and Short Definitions

Back-tracing	Backward-oriented identification of FDOs based on an instigating element
Baseline Object	Relevant *Objects* of the reference design worth considering in terms of potential flexibility
Change Driver (CD)	Both the root and resulting causes that can lead to unfulfilled *SRs* and thus drive system change
Change Enabler (CE)	Inherent features or properties embedded in physical *Enabler Reference Objects* to facilitate *Transitions* of physical *Change Objects* in a time and cost-efficient manner
Change Object	An *Object* that is subject to a *Change Trigger*
Change Trigger	Result of a *Baseline Object* in the *Object* domain not fulfilling a *SR*
Enabler Reference Object	An *Object* that allocates flexibility, as it may not always correspond to the *Change Object* that is to be facilitated
FDO Data Model (*FDO-DM*)	A systematized, master database containing heuristics on relevant industry- and company-specific elements and relations evaluated by domain experts
FDO Execution Model (*FDO-EM*)	Builds upon the *FDO-PM* and the *FDO-DM*, consisting of multiple representations of the single represented matrices inheriting data from the *FDO-DM*, to allow a directed and traceable identification of FDOs
FDO-EM Report	The basis for evaluation of *FDCs* in a condensed and comparable format after having run the *FDO-EM* to generate *Flexible Design Solutions*
FDO Procedural Model (*FDO-PM*)	Application context-independent procedure for systematic identification of FDOs through stages and steps
Flexible Design Concept (FDC)	A combination of *Change Objects* and suitable design variables consisting of *Transitions* and *CEs*
Flexible Design Opportunities (FDOs)	The relevant physical components enabling flexibility in a system, and the reasons for embedding flexibility
Flexible Design Solution	The best-performing *FDCs* that already represent solutions or can be combined with existing ones
Must-change Enabler	*CEs* that must be in place as a prerequisite for enabling the exercise of specific *Transitions*
Object (OB)	Physical constituents of a system that can be influenced by a stakeholder (eg, a system supplier that can affect design of *Objects*)
Prerequisite Change Enabler	*CEs* that must be in place as a prerequisite for the exercise of other necessary *CEs*
System Requirement (SR)	A statement of system capability that is: qualified by measurable conditions, bounded by constraints, and can be validated
Tracing	Forward-oriented identification of FDOs based on an instigating element
Transition (TR)	Externally imposed change strategies for physical *Change Objects* to make them refulfill any violated *SRs*