A Gap Analysis for Subsea Control and Safety Philosophies on the Norwegian Continental Shelf

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The realisation of hydrocarbons from subsea oil and gas fields are exposed to different risks, different operating conditions, and different environment than topside operation. In spite of these differences, topside design principles and philosophies are often modified for subsea use, and insufficiently designed subsea systems may cause serious accidents. Tailor-made solutions for subsea control and safety systems therefore need to be developed, and the first step is to investigate current states and identify gaps.

The main objective of this study is to analyse gaps of safety and control philosophies in subsea production and processing. For this purpose, this paper first explores background knowledge that is required for the gap analysis. Subsea hazards, hazardous events, consequences, safety systems, and their connections are explored. Secondly, gaps in subsea control and safety philosophies are identified through investigating subsea regulations and standards. Finally, the results indicate that most subsea control and safety requirements are based on topside requirements or refer to topside only requirements. While there are a few subsea-specific standards, they cover subsea production systems only. This study therefore emphasises that subsea-specific control and safety philosophy need to be developed.

I. INTRODUCTION

Subsea systems are associated with different risks, different operating conditions, and different environment than topside systems. However, topside design principles and philosophies are often modified for subsea use to ensure well-proven design, and some regulations and key standards for subsea safety systems may not fit the needs and constrains in a subsea environment [1]. It is therefore required to develop tailor-made solutions for the realization of hydrocarbons from subsea oil and gas field. The first step of this development is to investigate current state and identify gaps.

The main objective of this study is to analyse gaps in subsea safety and control philosophies on the Norwegian Continental Shelf (NCS). For this purpose, five sub-objectives are established as below:

1) Identify subsea hazards, hazardous events, and consequences
2) Investigate subsea safety systems that prevent hazardous events and/or mitigate the consequences
3) Investigate Norwegian and international standards for subsea safety and control systems
4) Identify gaps in subsea safety and control philosophies

The focus of this study is on major consequences during subsea oil/gas production and processing, like acute release of hydrocarbons, topside blowout, damage to expensive subsea processing equipment, etc. Small regular oil spills, minor hydrocarbon release, leakage of injected chemicals, and other events with low consequences are not covered or only briefly touched in this study. Drilling and well intervention are also out of the scope of this study.

The rest of this paper is organised as follows: background knowledge for this gap analysis is explored in Section II. Section III identifies gaps in subsea control and safety philosophies, and finally, discussion and concluding remarks are presented in Section IV.

II. BACKGROUND KNOWLEDGE

II.A. Subsea System Overview

Subsea systems can be classified into two large categories: subsea production systems and subsea processing systems. Subsea production systems recover hydrocarbons from subsea wells and transfer the fluid to an offshore or onshore facility [2]. Subsea production systems consist of subsea Christmas trees and well head systems, the umbilical and riser systems, subsea manifolds and jumper systems, tie-in and flowline systems, and control systems [2]. An area extending 500 m from any part of an offshore oil and gas installation is designated as a safety zone [3].

Subsea processing can be defined as any treatment of the produced hydrocarbons prior to reaching the receiving facility [2, 4]. A subsea processing system is an additional facility to a subsea production system. The main type of subsea processing technologies investigated in this study are subsea separation, boosting, and gas compression.

A simplified hydrocarbon flow from well to receiving facility including a subsea processing system is shown in Figure 1.

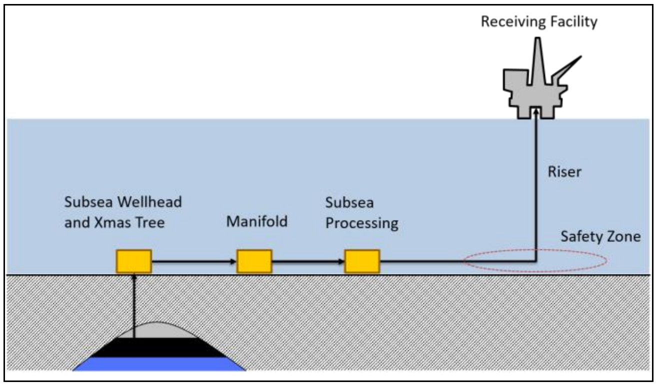

Figure 1. Simplified hydrocarbon flow in a subsea production and processing system.

II.B. Subsea Hazard, Hazardous Event, and Consequence

Subsea systems are exposed to various kinds of hazards. Some representative hazards are trawling, ship anchors, dropped objects, subsea land slides, well pressure, water/sand in the fluid, hydrocarbon flow under pressure, etc. [4-11]. This study categorises subsea hazards into three types:

1) External hazards: Hazards that arise or are introduced due to external events, like critical loads from trawling, ship anchors, dropped objects, subsea landslides, etc.
2) Long-term hazards: Hazards that cause long-term failure mechanisms, such as material defects, structural stress, water and/or sand in the fluid causing erosion and/or corrosion, etc.
3) Inherent hazards: Hazards that are inherent in subsea oil/gas production and processing, like well pressure, hydrocarbon fluids under pressure, artificial pressurization by compressor/pump, multiphase fluids, etc.

These subsea hazards can lead to three hazardous events: topside blowout, unintended hydrocarbon release, and operations outside normal conditions to processing facilities. External hazards can develop into unintended hydrocarbon release and operations outside normal conditions to subsea processing equipment. Long-term and inherent hazards may result in topside blowout, unintended hydrocarbon release, and operations outside normal conditions to subsea processing facilities. Depending on the location of the release, hydrocarbon release may result in several different consequences and be associated with different subsea safety systems. Some representative release points are wellheads, pipelines, manifolds, subsea processing facilities, and risers [4-10]. Different safety systems associated with the location of hydrocarbon release are further explored in Section II.C.

Four types of consequences in subsea accidents, caused by subsea hazardous events, are provided by DNV-RP-H101 [12]: personnel, environment, assets, and reputation. This study follows this classification, but consequence to reputation is not included because of its ambiguity. In this study, the term “asset” is limited to expensive subsea equipment, like subsea gas compressors, boosting pumps, subsea power distribution systems, etc. Damage to minor subsea equipment (e.g., valves and pipes) is not considered as asset damage in this paper, even if a failed valve may result in downtime of the subsea facility. These damages can, however, be included in other categories, if they may cause harm to personnel or the environment.

Topside blowout and unintended hydrocarbon release can lead to injury and/or fatality at the receiving facility when they are not properly controlled. Unintended hydrocarbon release may also develop into large oil and gas spills to the environment. Subsea processing equipment can be damaged when outside normal operational conditions. Subsea hazards, hazardous events, and their consequences are illustrated in Figure 2. Three different colours in this figure refer to different types of consequences; purple to personnel consequences, green to environmental consequences, and blue to asset consequences.

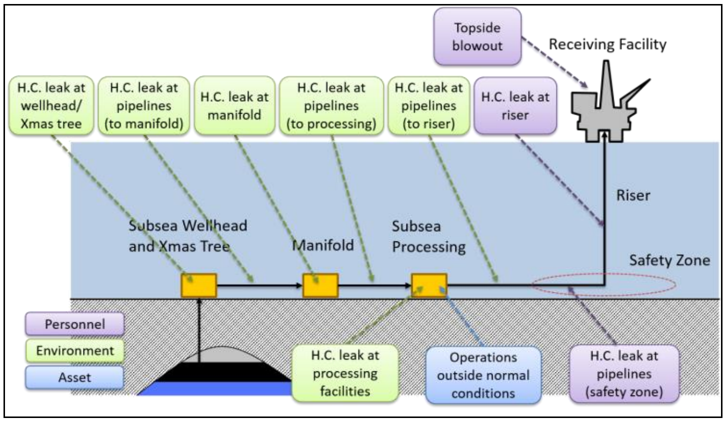

Figure 2. Subsea hazards, hazardous events, and consequences.

II.C. Subsea Safety Systems

Subsea hazardous events and consequences are controlled by several subsea safety systems. The main objective of this section is to identify which safety system prevents which hazardous event and mitigate which consequence.

II.C.1. Downhole Safety Valve

Downhole safety valve (DHSV) is the first and most important well barrier element that closes automatically when the hydraulic pressure is lost. The loss of hydraulic pressure can be initiated by a command from the topside emergency shut down (ESD) system, or an abnormal situation such as rupture of the umbilical cable which may also cause loss of hydraulic pressure. [2, 13, 14]. DHSV is applied to prevent unintended hydrocarbon release in the event of ESD or loss of wellhead integrity [13]. The main purpose is to stop the flow of hydrocarbons below X-mas tree, and by closing the DHSV it is also possible to mitigate the effects of hydrocarbon leakages downstream, such as at wellhead/Xmas tree, in pipelines/flowlines, at the manifold, and other downstream subsea and topside facilities.

II.C.2. X-mas Tree PMV & PWV

A subsea X-mas tree is installed to control the flow of hydrocarbons from reservoir through several valves and fittings [13]. The production master valve (PMV) and production wing valve (PWV) form the second pressure barrier that are installed inside the subsea Xmas tree [2]. The PMV and the PWV are closed mainly by the command of the topside ESD and production shutdown (PSD) system and in some cases, also by the subsea PSD system. These valves can prevent or mitigate hydrocarbon release except in the case of destruction of the wellhead/Xmas tree.

II.C.3. Manifold Valves

A subsea manifold is an arrangement of pipes and valves that are designed to combine, distribute, control and monitor the fluid flow. Subsea manifolds can simplify the subsea system, minimize pipelines and risers, and optimize the flow of hydrocarbons by tying several wells together [2]. Subsea manifold valves are installed to gather the production fluids or to distribute injection fluids [2]. While subsea manifold valves are not designated as safety systems, closing these valves can prevent or mitigate hydrocarbon release at pipelines (between the manifold and a receiving facility), the processing facility, risers and topside.

II.C.4. Trip and Isolate Processing Facility

A subsea processing facility can be equipped with a PSD system that trips processing equipment, such as compressors and/or boosting pump, and isolates the process facility, when abnormal levels, pressures and temperatures at certain points are detected. [15]. An example of the PSD system can be found in the Åsgard gas compression system. The PSD system aims to stop any development that could result in hydrocarbon leakage, however, the PSD system is not necessarily suited to detected leakages after they have occurred. The PSD system closes isolation valves and trips compressors and/or condensate pumps to minimise the consequences of process upsets. The leakage of hydrocarbons can be detected through a leakage detection system and/or low pressure from several points of the facility. On the other hand, if the compressor/pump outlet pressure is higher than the design pressure, it can result in the pipeline bursting, damage to risers, and/or topside blowout. Thus, the PSD system detects downstream pressure and also trips pumps and compressors when the pressure is too high [15].

Some trip functions (often implemented as part of PSD) are added to protect equipment like compressors and pumps from damage and not primarily to avoid leakage. If the level in the scrubber is too high, the gas compressor will be automatically stopped to prevent liquid from entering the compressor. When the level is too low, the condensate pump will be stopped automatically to prevent gas from entering. Too high temperatures downstream of the pump/compressor can also trip the pump/compressor to protect the processing facility and to prevent hydrocarbon leakage [15].

The isolation function in the PSD system can thereby prevent or mitigate topside blowout and hydrocarbon release at the processing facility, pipelines, and risers. Additional trip functions can prevent subsea equipment from being damaged by outside normal operation conditions.

II.C.5. Subsea Isolation Valve

A subsea isolation valve (SSIV) is sometimes installed to prevent or reduce unintended release of hydrocarbons in or close to the riser being connected to the topside facility [10]. A SSIV is designed fail safe, and will automatically be closed when an active signal from the ESD system is lost [16]. Closing the SSIV can prevent or mitigate the consequences of rupture of the riser and topside blowout.

II.C.6. Summary

A simplified layout of subsea safety systems, associated hazardous events, and their connections are shown in Figure 3.

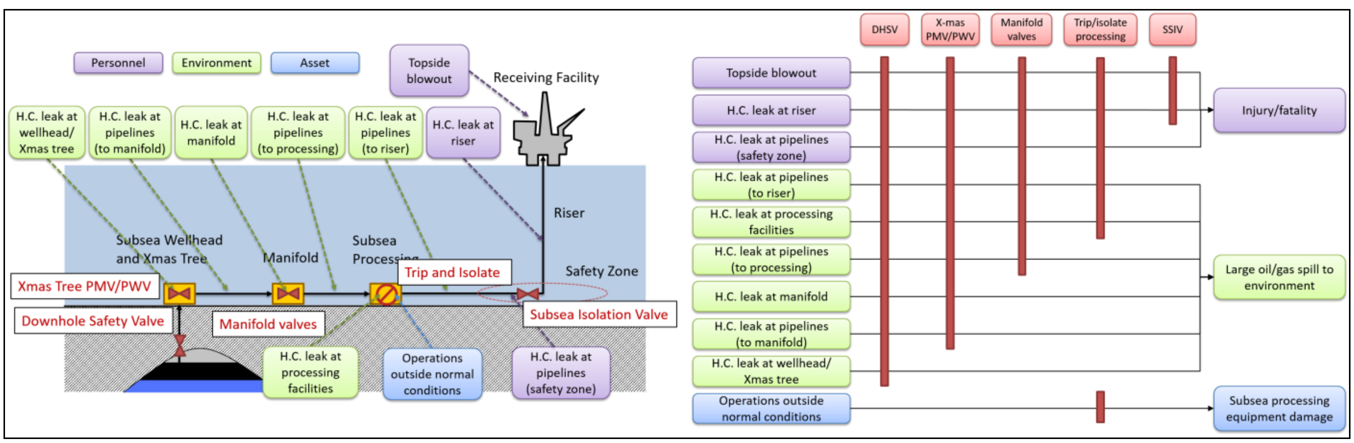

Figure 3. Subsea hazardous events, consequences, and safety systems.

III. GAP ANALYSIS

Subsea safety and control systems, identified in Section II.C, should be designed in accordance with several regulations and standards, and the gaps in subsea safety and control philosophies can be identified through investigating these regulations and standards. This section investigates several key subsea requirements to explore current state and identify gaps in subsea safety and control philosophies. The following regulations and standards are identified as being particular relevance to the subsea safety and control system on the Norwegian Continental Shelf:

- Facilities Regulations of The Petroleum Safety Authority Norway (PSA)
- OLF GL 070 of the Norwegian Oil and Gas Association, Guidelines for the application of IEC 61508 and IEC 61511 in the petroleum activities on the continental shelf
- NORSOK S-001, Technical Safety
- NORSOK I-002, Safety and automation system (SAS)
- NORSOK P-002, Process system design
- NORSOK U-001, Subsea Production Systems
- ISO 10418, Petroleum and natural gas industries - Offshore production installations - Analysis, design, installation and testing of basic surface process safety systems
- ISO 13628-1, Petroleum and natural gas industries - Design and operation of subsea production systems - Part 1: General requirements and recommendations
- ISO 13628-6, Petroleum and natural gas industries - Design and operation of subsea production systems - Part 6: Subsea production control systems

III.A. Current State

III.A.1. Facilities Regulations – PSA

The Petroleum Safety Authority Norway (PSA) is the regulatory authority for safety in the petroleum sector on the Norwegian Continental Shelf. The PSA issued several regulations and guidelines to govern petroleum activities [17]. While there is no specific subsea regulation in PSA, *the Facilities Regulations* [18] and *Guidelines Regarding the Facilities Regulations* [19] can be applied to subsea safety and control systems. These two documents provide functional requirements for safety functions and process safety systems referring to other international and national standards for a detailed specification.

While this regulation can be used for both topside systems and subsea systems, most requirements are based on topside systems, and there are few subsea-specific requirements in the regulations. In addition, there are obviously requirements that are not relevant for subsea. For instance, clauses like fire divisions, fixed fire-fighting systems, ballast systems, means of evacuation, living quarters, etc. are irrelevant to subsea systems. The PSA regulations refer to a number of standards in relation to process safety and other (emergency) safety functions: Clause 8. Safety functions in the regulation refers to NORSOK S-001, NORSOK I-002, GL 070, IEC 61508, ISO 13702, and ISO 13849. Clause 33. Emergency shutdown system requires the use of ISO 13702 and NORSOK S-001. Clause 34. Process safety system refers to ISO 10418, NORSOK P-002, ISO 4126 (API RP 520), and ISO 23251 (API RP 521). None of these standards is a subsea-specific standard. Three of these standards are only for topside; namely NORSOK P-002, ISO 10418, and ISO 13702.

III.A.2. GL 070

The Norwegian Oil Industry Association (OLF) Guideline 070 [20] is a national guideline that applies to the Norwegian Continental Shelf. This guideline specifies a process to adopt and simplify the application of IEC 61508 and IEC 61511, and suggests the use of minimum safety integrity level (SIL) requirements for commonly used safety instrumented functions, as an alternative to the full risk-based approach described in IEC 61508 [17].

Similarly to *the Facilities Regulations* of PSA, this guideline can be used for both topside and subsea systems, but most requirements are based on topside systems. The appendix of the guideline provides minimum SIL requirement for 13 safety instrumented functions: PSD functions, segregation through ESD, blowdown, isolation of topside well, isolation of riser, fire detection, gas detection, electrical isolation, firewater supply, ballasting safety functions, isolation of subsea well, drilling and well intervention, and manual initiators. Four out of the 13 requirements are relevant to subsea production and processing: PSD function, segregation through ESD, blowdown, and isolation of subsea well. Among these four requirements, “isolation of subsea well” is the only subsea-specific requirement. The others are common requirements for both topside and subsea systems, which are mainly considering topside systems. For instance, the requirement of PSD function includes flare KO drum that are not necessary for subsea processing. The current version of GL 070 also provides reliability data for use in reliability assessments that are primarily based on topside field experience.

The main purpose of the guideline is to specify a process for the application of IEC 61508 and IEC 61511, and therefore, the guideline can be applied to subsea production and processing systems, regardless of the fact that there is only one minimum subsea-specific SIL requirement in the guideline. However, it might be necessary to include more subsea-specific minimum SIL, regarding the increasing trend of applying subsea processing solutions. It may be remarked that GL070 is now under revision and the new version will most likely be available in late 2016 or in 2017.

III.A.3. NORSOK S-001

The NORSOK standard *S-001 Technical Safety* [21] describes the principles and requirements for the development of the safety design of offshore installations for production of oil and gas. This standard states the required standard for implementation of technologies and emergency preparedness to establish and maintain an adequate level of safety for personnel, environment and material assets, together with ISO 13702.

Similarly to *the Facilities Regulations* and GL 070, this standard can be used for both topside and subsea systems, but most requirements are based on topside systems. The standard consists of 21 clauses, excluding introduction clauses, like scope, definitions, etc. Only two out of the 21 clauses seem directly relevant to subsea control and safety systems: 9. Process safety and 10. Emergency shut down (ESD). Even the two clauses mainly focus on topside systems. The process safety clause, for instance, refers to NORSOK P-002 and ISO 10418, which are standards for topside processing. The ESD clause states ESD actions for both topside and subsea systems, including DHSV and SSIV. However, this clause does not include any requirements for subsea processing.

III.A.4. NORSOK I-002

The NORSOK standard *I-002 Safety and automation system (SAS)* [22] covers functional and technical requirements and establishes a basis for engineering related to safety and automation system design.

Similarly to the above standards, NORSOK I-002 also describes a common requirement for both topside and subsea systems. Clause 4.2. SAS functions in the standard states required features for ESD, PSD, and PCS, which can be applied to subsea production and processing. However, this clause is mainly focused on topside systems. The PSD requirements in this clause, for instance, refer to ISO 10418, a topside requirement as mentioned in Section III.A.7.

Appendix B in the standard suggests time response of several commands and updates: operator command, closed loop control, alarm display text, ESD initiation from fire and gas (F&G), etc. Required time responses of these commands are between 2 and 4 s. However, there is no specific time response requirement for subsea processing systems. Some subsea processing equipment requires very fast response time to prevent equipment damage, while for some subsea facilities longer response time may be allowed due to processing equipment being distributed with long inter-distances. The criticality of internal leakage of valves may also be different subsea compared to topside. Today, many of the associated requirements for response time and internal leakage are based on assumptions that have not been fully checked towards subsea conditions. Specification of criteria for response time and internal leakages for subsea processing equipment need to be included in this standard as an expansion or in a separate NORSOK standard.

III.A.5. NORSOK P-002

The NORSOK standard *P-002 Process system design* [23] provides requirements for topside process piping and equipment design on offshore production facilities. NORSOK standard *P-001 Process design* and *P-100 Process Systems* have been combined into NORSOK P-002 to improve accessibility and remove duplication.

This NORSOK standard covers topside processing systems only. It might be possible to use some of the features of NORSOK P-002 for subsea systems, but it is clearly defined that this standard is prepared for topside systems in Clause 1.

III.A.6. NORSOK U-001

The NORSOK standard *U-001 Subsea Production Systems* [24] is applicable to the design, fabrication, and testing of subsea production multiplexed electro-hydraulic control systems. This standard is based on ISO 13628 and provides specific requirements and recommendations that are not covered by the ISO 13628 series of standards.

Unlike the regulations and standards in Sections III.A.1-III.A.5, NORSOK U-001 consists of subsea-specific requirements. Most requirements are about structural loads of subsea production systems. The only clause relevant to subsea safety and control systems is Clause 5.9. Subsea system design. This clause, however, provides brief and high-level specifications for subsea production systems, e.g., "During production activities at least two independent and tested barriers shall be available between reservoir and environment…" Today, some of these barriers are operated through the same subsea control module as the functions being used for normal operation. It does not seem to be any specific philosophy for achieving physical and/or functional independence between safety and control system, to ensure that a negative impact from non-safety can affect safety-critical functions

III.A.7. ISO 10418

The international standard ISO 10418 *Basic surface process safety systems* [25] provides objectives, functional requirements and guidelines for techniques for the analysis, design and testing of surface process safety systems for offshore installations for the recovery of hydrocarbon resources. In this standard, the basic concepts associated with the analysis and design of a process safety system for an offshore oil and gas production facility are described, together with examples of the application of typical process components. This standard refers to ISO 10417 for the design and installation of subsurface safety valves.

Similarly to NORSOK P-002, this international standard is prepared for topside systems. In Clause 1, it is defined that the scope of this standard is surface process safety systems for offshore installations.

III.A.8. ISO 13628-1

The international standard ISO 13628-1 [11] provides general requirements and overall recommendations for the development of complete subsea production systems, from the design phase to decommissioning and abandonment.

Similarly to NORSOK U-001, in this standard contains subsea-specific requirements, but covers only subsea production systems. Subsea processing is not the scope of this standard. Clause 5.10. Production controls in the standard sets high-level requirements for subsea production control, referring to ISO 13628-6.

III.A.9. ISO 13628-6

The international standard ISO 13628-6 [26] is applicable to the design, fabrication, testing, installation, and operation of subsea production systems. This standard covers surface control system equipment, subsea-installed control system equipment and control fluids.

Similarly to NORSOK U-001, this standard contains subsea-specific requirements but covers only subsea production systems. A suitable design practice for control and safety systems for subsea production (well isolation and manifold) may not necessarily be adopted for subsea processing, in light of higher complexity and need for instrumentation. Similarly to what was mentioned in relation to U-001, it would have been of interest to expand the scope of ISO 13628 to also address requirements for subsea processing. One specific need is to formulate requirements that do not result in overly complex implementation of functions for process shutdown and asset protection, and which do not compromise with requirements in IEC 61508 and IEC 61511.

III.A.10. Summary

Nine national and international standards, which are used for the design and operation of the control and safety systems for subsea production and processing, were investigated in Sections III.A.1-III.A.9. Most standards are intricately connected with each other, as shown in Figure 4. In this figure, three different colours refer to different applications of the standard; purple standards apply to both subsea and topside, orange to subsea only, and blue to topside only.

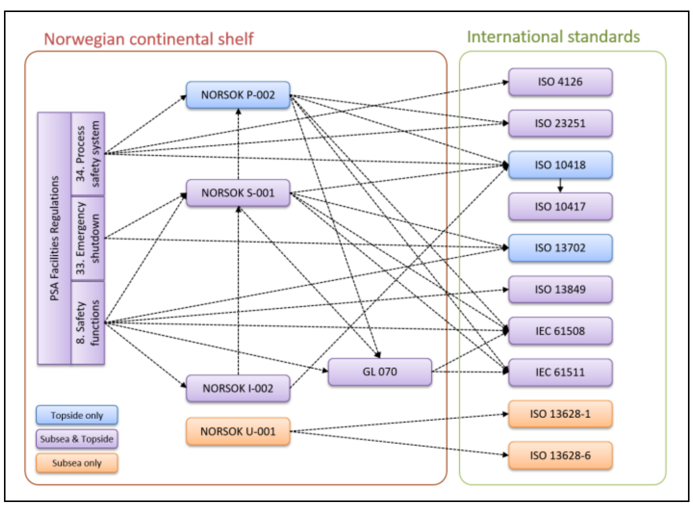

Figure 4. Regulations and standards for subsea safety and control systems in subsea production and processing.

Figure 4 shows that there are only a few subsea-specific standards. Regulations/standards and their application are also summarised in Table 1. The other standards contain general requirements that are applied for subsea control and safety systems as well as for topside. The general impression is that when the standards are applied subsea, it sometimes lead to complex configurations. The few subsea-specific standards cover subsea production only, and currently there are not many other options than to adapt topside philosophies to subsea.

Table 1. Regulations/standards and their application

No.	Regulation/Standard	Topside only		Common/General		Subsea only	
		Production	Processing	Production	Processing	Production	Processing
1	PSA Facilities Regulations			X	X		
2	OLF GL 070			X	X		
3	NORSOK S-001			X	X		
4	NORSOK I-002			X	X		
5	NORSOK P-002		X				
6	NORSOK U-001					X	
7	ISO 10418		X				
8	ISO 13628-1					X	
9	ISO 13628-6					X	
10	ISO 4126			X	X		
11	ISO 23251			X	X		
12	ISO 10417			X			
13	ISO 13702			X			
14	ISO 13849			X	X		
15	IEC 61508			X	X		
16	IEC 61511			X	X		

III.B. Identification of Gaps

III.B.1. Gaps in Control and Safety Philosophies in Subsea Production

As previously mentioned, three standards cover control and safety systems for subsea production: NORSOK U-001, ISO 13628-1, and ISO 13628-6. The other standards cover requirements for control and safety systems that are (seemingly) joint for both topside and subsea production. As far as we understand, the joint requirements are mainly based on design philosophies developed major accident prevention on topside facilities. The facilities Regulations of PSA, for instance, refer to ISO 10418 and NORSOK S-001 that mainly address topside, and to ISO 13702 that applies to fire and explosion prevention of topside facilities. In some cases, for example for process safety systems, there may be significant differences in the needs for subsea compared to topside. Such distinctions may be expressed in the recommendations to the regulatory regulations, or by referring to standards that are more tailor-made to address subsea conditions.

Requirements for more extensive and complex subsea production and processing facilities also need to be established. Most standards assume the existence of (and interface to) a topside facility and describe their requirements based on this assumption. For instance, NORSOK S-001 includes both topside and subsea shutdown. Without the topside facility, or the topside facility being more remote, it may be required to establish a different type of shutdown philosophy and implementation. Can we apply the same shutdown philosophy and simply exclude topside shutdown actions (e.g., shutdown of fans/heaters and bilge/ballast pumps)? Alternatively, do we need to formulate a new subsea-specific ESD and PSD philosophy for future subsea systems that are not connected to a topside platform? If a new philosophy is required, then should this be included in NORSOK S-001 as an extension or stated in a new NORSOK standard?

III.B.2. Gaps in Control and Safety Philosophies in Subsea Processing

As previously mentioned, no standards cover control and safety systems in subsea processing. Moreover, the Facilities Regulations of PSA specifies that all facilities outfitted with or attached to process facilities shall have a process safety system. This general requirement applies also to subsea facilities, however, only standards that relate to topside facilities are references in the guidelines (NORSOK P-002 and ISO 10418). One practical challenge is that some of the solutions for ensuring independence between safety and non-safety systems may be easier to realize topside than for subsea, when considering the resulting complexity.

IV. RESULTS AND DISCUSSION

In this study, the connections between subsea hazards and safety systems, and features of subsea regulations/standards were identified. Subsea hazards were classified into three categories: external hazards, long-term hazards, and inherent hazards. These hazards were linked to three types of subsea hazardous events, which were further developed into ten hazardous events. Each hazardous event was associated with three types of consequences: injury/fatality, large oil/gas spill to environment, and subsea processing equipment damage. It was found that subsea production systems can cause major harm to humans and the environment, while the main consequence in subsea processing systems is damage to assets. These subsea consequences can be prevented or mitigated by five subsea safety systems: DHSV, X-mas tree PMV/PWV, manifold valves, trip/isolate processing, and SSIV. These subsea safety systems should be designed in accordance with several regulations/standards, which have various applications, like subsea only, subsea & topside, topside only, processing only, and production only.

It was found that only a few standards suggest suitable implementations for control and safety of subsea systems, in particular for subsea processing facilities. High-level standards can be applied to both topside and subsea systems, but lack of more specific guidance on applicable solutions for subsea, when considering subsea conditions and constraints, may result in overly complex and costly design solutions.

The gaps in subsea control and safety systems emphasise the necessity of subsea-specific standards. Especially for current subsea processing, no standard covers subsea-specific control and safety requirements. While there are a few subsea-specific standards for current subsea production, the main regulations refer to topside-only or topside-based standards. Regarding the fact that operational conditions and the environment are completely different between topside and subsea, applying topside-based philosophy to subsea operations can cause serious adverse consequences to humans, the environment, and assets.

This paper investigated some implementations of safety systems for typical (i.e. known) subsea cases. Therefore, subsea control and safety systems identified in this study may not fit other specific subsea cases, especially extreme subsea cases. For instance, Section II.C.1 states that PMV and PWV can prevent or mitigate hydrocarbon leakage in pipelines. However, in a remote subsea filed with potentially long pipelines, it may be a very long distance from the leakage point to the wells. In this case, closing these valves may not be a sufficient mitigating measure.

Another example is subsea processing facilities. Section II.C.4 investigated subsea processing technologies currently in use, like Åsgard subsea gas compression or Tordis subsea separation, boosting, and injection. The dimensioning consideration for these is not harm to environment, but costs associated with potential damage in these subsea processing. Protection of subsea processing equipment against damage is expected to be of high importance also for new subsea processing units. However, new processing units may also introduce new hazards with potential to cause environmental leakages. One example may relate to subsea water treatment.

One hazardous event not covered in this paper is hydrate formation. Prevention and mitigation of hydrate formation is wholly different from the other hazardous events. The other hazardous events can be mitigated through activating safety system(s). For instance, the consequences of a hydrocarbon leak at a pipeline can be mitigated by closing several subsea valves. The consequences of hydrate formation cannot, however, be mitigated by subsea safety systems. Rather, continuous monitoring and control of the hydrocarbon flow can prevent the occurrence of hydrate formation. This hazardous event also needs to be further investigated.

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