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A comparative analysis of process safety management (PSM) systems in the process industry

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Abstract

The root cause of most accidents in the process industry has been attributed to process safety issues ranging from poor safety culture, lack of communication, asset integrity issues, lack of management leadership and human factors. These accidents could have been prevented with adequate implementation of a robust process safety management (PSM) system. Therefore, the aim of this research is to develop a comparative framework which could aid in selecting an appropriate and suitable PSM system for specific industry sectors within the process industry. A total of 21 PSM systems are selected for this study and their theoretical frameworks, industry of application and deficiencies are explored. Next, a comparative framework is developed using eleven key factors that are applicable to the process industry such as framework and room for continuous improvement, design specification, industry adaptability and applicability, human factors, scope of application, usability in complex systems, safety culture, primary or secondary mode of application, regulatory enforcement, competency level, as well as inductive or deductive approach. After conducting the comparative analysis using these factors, the Integrated Process Safety Management System (IPSMS) model seems to be the most robust PSM system as it addressed almost every key area regarding process safety. However, inferences drawn from study findings suggest that there is still no one-size-fits-all PSM system for all sectors of the process industry.

Keywords: Process Safety Management (PSM); Accidents; Process Industry; Comparative analysis

1.0 Introduction

The continuous increase in worldwide energy demand has seen proliferating rates in the complexity of process facilities and operations in the process industry. These industry advancements have led to more exposure to higher risk levels which require urgent attention. Research findings by the International Association of Oil and Gas Producers (IOGP) as illustrated in Figure 1 show that the fatal accident rate (FAR) in the oil and gas industry has been on the steady increase over the last three years (IOGP, 2017). Despite the average reduction in fatal accidents over the last decade, there has been an upsurge of FAR from 1.1 in 2014, to 1.4 in 2015 and 1.7 in 2016. While there was reduction in fatalities from 54 in 2015 to 50 in 2016, more fatalities were witnessed in fewer incidents in 2016.

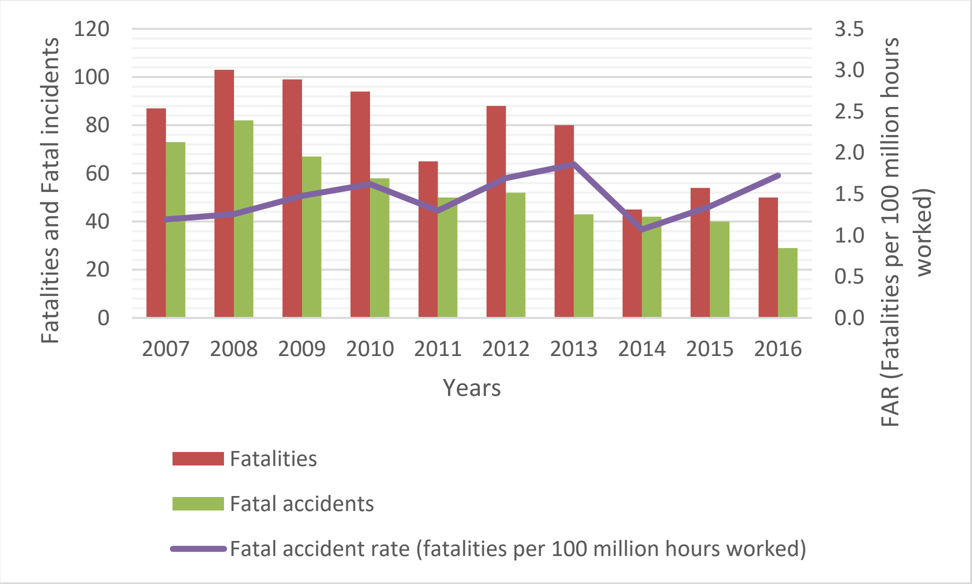

Figure 1. Number of fatalities, fatal accidents and fatal accident rates in the oil and gas industry from 2007 to 2016 adapted from IOGP, (2017)

There seems to be an unpredictability in the nature of accident occurrence, which reiterates the urgent need to address them using a preventive approach rather than reactive technique (Theophilus et al., 2018). Process safety is a field which is based on the prevention of explosions, accidental chemical releases, fires, and structural collapses in the process industry (AIChE, 2011). There is a huge debate regarding the distinguishing factor between process safety and occupational safety. However, it should be noted that occupational safety, unlike process safety, focuses solely on workplace hazards such as slips, trips and falls (Cheng et al., 2013).

There are dire consequences associated with process safety failings, most of which could lead to multiple fatalities, environmental damage, property loss, criminal charges, damage to company reputation and huge financial implications (Ismail et al., 2014). A typical example is the Deepwater Horizon blowout in 2010 which claimed 11 lives, spilled over 4 million barrels of crude oil into the Gulf of Mexico, led to death of diverse aquatic species, displaced businesses, tourists and indigenous inhabitants, and incurred criminal charges and financial implications to British Petroleum (BP) of up to $60 billion till date (Norazahar et al., 2014). Other case studies include the Piper Alpha disaster in 1988 which caused 167 fatalities, the Alexander Kielland collapse in 1980 which caused 123 fatalities and the BP Texas refinery explosion in 2005 which led to 15 fatalities and 180 injuries (Ismail et al., 2014). The root causes of these accidents have been attributed to process safety failings ranging from poor safety culture, lack of communication, asset integrity issues, lack of management leadership and human factors (Hsu et al., 2015). These could have been prevented with the adequate implementation of a process safety management (PSM) system across these process facilities (Bridges and Tew, 2010). This paper was not geared towards selecting the best PSM system for various industries, but it was rather aimed at developing a comparative framework which could aid in selecting the appropriate and suitable PSM system for specific industry sectors within the process industry. The key objectives of this research were to: -

a) Select the various PSM systems that have been developed across various fields and industries since the inception of process safety in the 1970’s.

b) Develop a framework based on different features that could be used in analysing the functionalities of the various PSM systems.
c) Compare the various PSM systems based on the developed framework and map them according to their levels of flexibility and robustness.
d) Recommend areas for future improvement in each of the PSM systems

This section provided a general overview of process safety and creates a rationale for this study using process accident statistics. The next section outlines the characteristics of various PSM systems and regulations, as well as their strengths and drawbacks. Furthermore, the development of the framework used for comparing the various PSM systems is discussed, after which the systems are compared using the developed framework. Suitable inferences are drawn from the study and appropriate recommendations are made accordingly for the PSM systems and the process industry going forward.

2.0 Overview of Process Safety Management Systems

PSM was first introduced in 1971 by experts in the European Federation of Chemical Engineering, which later evolved into the creation of systems and frameworks in the 1980's (EPSC, 2018). Various PSM systems have been developed over the years, with each having its strengths and drawbacks (Theophilus et al., 2018). The PSM systems that were selected to be examined in this paper were chosen based on their applicability in various sectors of the process industry. A summary of these PSM systems that have been selected for this study is presented in Table 1. This analysis shows the trend in development of PSM systems over the years, the theories behind their design, their framework for implementation, their industries of application and their drawbacks.

Table 1. Process safety management systems in the process industry adapted from Theophilus et al., (2018)

Model	Framework	Year of design	Theory Behind Model Design	Industry for the Model	Deficiency of Model	References
Responsible Care ® Process Safety Code (RCPSC)	It is built on a simple Plan-Do-Check-Act framework that elevates the standard for performance in industries, as well as being flexible in meeting needs of various companies	1984	It was designed to prevent the unintended release of hazardous substances by using technical improvements	Petrochemical	- It does not consider several human factors - There is no road-map for implementation of the elements within its framework	Howard et al. (2000) Lenox and Nash (2003)
CIMAH regulations	It applies a goal-setting framework to identify, evaluate and mitigate any dangerous consequences that may arise from industrial activities.	1984	It was designed to curb the consequences of major accidents on people and the environment	All industrial sectors except nuclear and armed-forces installations	- No safety reports - Changes to safety management systems not addressed - Emergency planning issues	Cassidy (2013) HSE (2015) Process Engineering (2000) HSE (2017a)
API RP 750	It is organized similarly to the OSHA and CCPS framework such that it embodies 11 elements and implements them using the PDCA framework	1990	It was designed as the first framework for managing process hazards in the oil and gas industry	Oil and Gas Petrochemical Refining	- It did not set out indicators for measuring process safety performance - Human factors are not well addressed	Patel (2005) API (2017) WorkSafe (2011)
US OSHA PSM Program	It is a performance-based framework hinged on management commitment which increases the workforce influence in managing process safety	1992	It was designed to mitigate the accidental release of hazardous chemicals	Manufacturing Chemical Transport	- It has remained unchanged and has few human factor elements in its framework	Belke (2000) Kaszniak (2010) Summers (2000)
Safety Case	Its regulatory framework was made to meet the recommendations in the Lord Cullen's report after the Piper Alpha disaster.	1992	It requires companies in offshore installations to produce a safety document to show that there is an efficient safety management system in place	Offshore	- It focuses only on paper safety and not real safety in practice. - They are compliance-driven - They reduce the level to which risks are being considered within organizations as they feel they already have a safety case	Cassidy (2013) HSE (2017a) HSE (2017b) Israni et al. (2015) Hopkins (2015) NOPSEMA (2017) CAPP (2014)
ExxonMobil OIMS	It is built on the ISO 14001 standard, as well as the Responsible Care	1992	It was designed to improve personnel,	Petroleum	- It is quite complex to be understood by people that are	ExxonMobil (2017a) ExxonMobil (2017b)

	initiative to manage health, security, safety and environmental risks		health, security and process safety performance		not part of the company - It does not certify employee compliance to standards.	Theriot (2002)
ILO PSM Framework	It is built on a similar framework with the OSHA PSM program	1993	It was designed to prevent major industrial accidents in the hazardous industries	All major hazard installations except nuclear, military and transport other than pipeline	- It does not incorporate key human factors like safety culture into its framework - It does not focus on performance measurement and management review	CAPP (2014) ILO (2017)
API RP 75	It is also organized similarly to the OSHA and CCPS framework such that it embodies 11 elements and implements them using the PDCA framework	1993	It was developed as a safety and environmental program for offshore operations and facilities	Oil and gas	- It does not incorporate human factors fully into its framework	API (2004) BSEE (2017) WorkSafe (2011)
EPA RMP	Its framework is centered around hazard assessment, a prevention program and an emergency response program which must be included in the RMP to be submitted to the EPA	1994	It was designed to monitor companies involved in the use of regulated toxic or flammable substances for prevention of accident release	Chemical Petroleum	- Human factors are not adequately addressed No certified method of implementation	US EPA (2013) Ufner and Igleheart (2017) US EPA (2017a) US EPA (2017b)
COMAH regulations	Its framework is extended from the CIMAH regulations and is designed to meet the requirements of the Seveso II Directive	1999	It allows competent authorities to assess the safety of designated sites using safety reports.	All hazardous industries	- Cost of compliance - Public information may affect commercial confidentiality and site security - Consent for hazardous substances - Different attitudes to implementing the Seveso II Directive across Europe	HSE (2015) Process Engineering (2000) HSE (2017a) HSE (2017b) CAPP (2014) Beale (2001)
AIChE/CCPS Risk Based Process Safety (RBPS)	Risk-Based Process Safety (RBPS) Framework builds the ideas of the earlier CCPS model to organize the	2007	It was designed after the Bhopal tragedy in 1984 to offer improved	Chemical Process Industries	- It does not address all human factors. - There is no road-map for	Pitblado (2011) Rigas and Sklavounos (2004)

Model	management system principles of the Plan-Do-Check-Act in order to be used across various organizations		results with less funds and as a benchmark for the industry		implementation of the elements within its framework	Frank (2007)
BP OMS	Its framework integrates BP's requirements on operational reliability, social responsibility, environment, security, safety and health into a common management system	2007	It was designed after the Deepwater Horizon blowout to ensure compliance of BP's industry standards with legislative requirements	Oil and gas	- It does not incorporate all safety management system elements in it framework	BP (2014) Dumon (2014) Whitford et al. (2011)
SEMS Regulation	Its framework is a performance-focused tool for managing and integrating offshore activities based on the API RP 75 third edition in 2004.	2010	It was enacted to make mandatory the API RP 75 rule in order to enhance environmental protection and safety of offshore oil and gas activities	Offshore oil and gas	- It does not fully incorporate all human factors into its framework	API (2004) BSEE (2017) WorkSafe (2011)
Energy Institute High-Level PSM Framework	Its framework is built with the Reason's Swiss Cheese model as a template, however, using the Health and Safety Management System developed by ILO and OSHA as a benchmark for its implementation	2010	It was designed to provide a basic and organized approach for small and large organizations across all energy sectors	Energy industry	- Human factors are not fully integrated into the framework - There is no adequate route map for implementation	Hooi et al. (2014) Murray (2015) Yew et al. (2014)
DuPont Operational Risk Management (ORM) Model	Its framework is built on high levels safety culture, with management commitment and operational discipline by workforce being the central point of focus in successful implementation of its plan	2010	It was initially designed to ensure safety of their facilities, but later was used as benchmark for other companies within and across various industries	Conglomerate comprising of various industrial sectors	- Its basic wheel-like structure shows no line of action or implementation of elements within its framework	Kalthoff (2005) Fernández-Muñiz et al. (2007) Hart and Milstein (2003)
CSChE PSM Guide 4th edition	It was built on a similar framework with the 1989 AICHE/CCPS Technical Management of Chemical Process Safety.	2012	It was created as a more efficient framework for the prevention of accidents	Chemical	-It does not consider involvement of the workforce and stakeholders -It does not also take into	CAPP (2014) Amyotte (2011)

			in the Canadian chemical industries		account the manner in which operations are conducted.	
IOGP/IPIECA OMS Framework	The framework uses a Plan-Do-Check-Act approach to address security, process safety, quality, environment and social responsibility risks.	2014	It was designed to improve the development and application of health, safety and environmental management systems.	Oil and Gas	- It does not fully address human factors within its framework - It totally relies on human compliance and does not provide enforcement actions	IOGP (2014) CAPP (2014)
Process Safety Information Management System (PSI4MS)	The PSM system is developed based on Process Safety Information (PSI) element of PSM 29 CFR 1910.119 (d)	2014	It was designed as an OSHA PSM compliance system for managing process chemicals, technology and equipment information in pilot plant.	Chemical	- The PSM system focuses solely on process safety information which is one of many elements in a PSM system	Aziz et al., (2014)
Contractor Management System (CoMS)	This PSM system was developed based on OSHA PSM 29 CFR 1910.119 (h)	2015	It was designed to provide a structured and easy technique to plan and implement a practical and comprehensive contractors' management system	All hazardous industries	- The PSM system focuses solely on contractor management which is one of many elements in a PSM system	Abdul Majid et al., (2015)
Emergency Planning and Response (EPR) model	The framework was created based on OSHA CFR 1910.119 (n) and a model was developed to reflect this framework	2016	It was designed to provide a structured and easy technique for organisations to plan and implement emergency planning and response based on PSM requirements	All hazardous industries	- This PSM model is solely based on emergency planning and response, which is one of many elements in a PSM system	Abdul Majid et al., (2016)
IPSMS model	The Integrated Process Safety Management System (IPSMS) model	2017	It was designed as a robust and holistic	Oil and Gas	- This model was only validated using literature,	Theophilus et al. (2018)

	was designed using the PDCA framework, while its implementation strategy adopted the DuPont tripartite operational discipline model of three main aspects: personnel, technology and facilities		alternative to the previous PSM models by integrating their elements into one PSM system and including the human factors missing from them		without any input from industry professionals - It failed to consider factors such as impact of climate change on oil and gas operations in its design	

2.1 Process safety functional pillars

Process safety is fundamentally built on functional pillars (CAPP, 2014; ISC, 2018). The Canadian Association of Petroleum Producers (CAPP) proposed four functional pillars and had previously compared the elements of only four processes safety management systems (PS-MS) using these four functional pillars listed below (CAPP, 2014, p. 18).

Pillar 1: Commit to Process Safety
Pillar 2: Understand Hazards and Risk
Pillar 3: Manage Risk
Pillar 4: Learn from Experience

Similarly, the Energy Institute proposed four functional pillars which closely match those proposed by CAPP and are depicted in the Figure 2 (Energy Institute, 2016). Both the CAPP and the Energy Institute identified leadership commitment to be top and the need to learn from experience (review and improvement) as key to processes that must follow all risk control management processes.

Figure 2. Four functional pillars proposed by the Energy Institute (Energy Institute, 2016)

However, IChemE Safety Centre (ISC) proposed six functional pillars depicted in the Figure 3 (ISC, 2018). These pillars identify that effective management of process safety requires leadership commitment as central to process safety management in an organisation. It also reflects on the four pillars proposed by CAPP and Energy Institute. However, these six pillars created some overlap and was also acknowledged by the ISC For instance, safety culture could be considered the under the human factors pillar or the culture pillar.

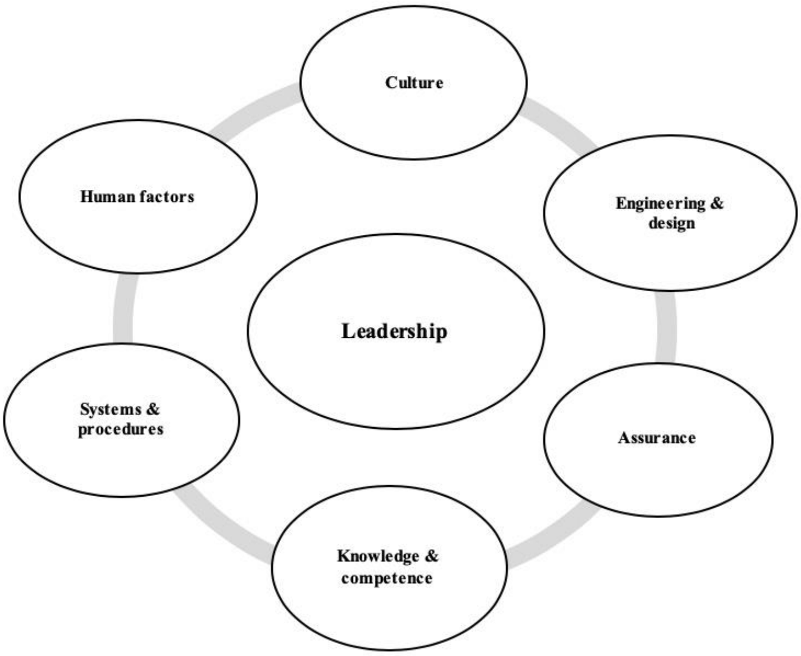

Figure 3. Six functional pillars proposed by the IChemE Safety Centre (ISC, 2018)

While the Canadian Association of Petroleum Producers (CAPP) had previously compared the elements of only four processes safety management systems (PS-MS) (CAPP, 2014, p. 18) using the four pillars listed above, this paper will compare the elements of all the known PS-MS (seventeen in total) using the same four functional pillars.

2.2 Key Elements of a Process Safety Management System

Regulators and process industry managers alike are recognising that there are key process safety elements that must be part of any process safety management system (PS-MS) and must address process safety functional pillars. As illustrated in Figure 4, the ISC prosed seven process safety functional pillars as: 1) Process Safety Leadership (PSL); 2) Knowledge and Competence (KC); 3) Engineering and Design (ED) 4) Systems and Procedures (SP); 5) Learn from Experience (LE); 6) Human Factors (HF) and 7) Safety Culture (SC). Therefore, any process safety management system (PS-MS) elements should address these key functional pillars. For example, there is an increased acknowledgement that “strong Process Safety Leadership is vital, because it drives the “safety culture” of an organisation, and safety culture in turn influences employees’ behaviour and participation in safety. Similar to occupational safety, tasks may also be delegated in process safety. However, the responsibility and accountability to ensure that safety will always remain with the leadership of the organisation (IChemE, 2015). Therefore, Process Safety Leadership is a vital element in any PSM system to encourage an atmosphere which inspires safe behaviour.

Figure 4. Six functional pillars of process safety (IChemE, 2015)

2.2.1 Essential Elements of Corporate Governance for Process Safety

According to OECD, (2017), there are five categories which represent the essential elements of corporate governance for process safety. These are illustrated in Figure 5 using a process of risk awareness, information, competence and action; while leadership and culture form the central focus. Leadership and culture create an open environment for process safety (Frank, 2007). CEO and leaders ought to provide policy on corporate governance for process safety which describes the management expectations, required commitment, and corporate activities in relation to process safety (Webb, 2008). With regards to risk awareness, there should be a clear understanding of vulnerabilities and risks (Hendershot et al., 2011). It is also essential that management has knowledge of the importance of process safety throughout life cycle, identifies various layers of protection within process systems, ensures consistent management systems, assesses risks of budget reductions on process safety, and takes responsibility for emergency planning (OECD, 2017). Similarly, CEO and leaders ought to ensure that process safety programmes are driven by essential data that proactively seek out information relating to process safety (audits, performance indicators, inherent hazards and risks, dangerous trends, effective control of risks, contractor management, etc). Also, management should ensure that process safety programmes are robust enough to guarantee organisational competence to manage the hazards of its operations (Elangovan et al., 2005). Process safety programmes ensure that organisational leaders engage in articulating and driving active monitoring and plans.

Figure 5. Essential elements of corporate governance for process safety (OECD, 2017).

2.2.2 Essential features of a process safety management system

Every PSM system has various features that aid the implementation of process safety in an organisation. The robustness of a PSM system is hugely dependent on the elements contained within its framework and the existence of a clear implementation strategy for each of these elements. Theophilus et al., (2018) developed an integrated process safety management system (IPSMS) model which was geared towards addressing human factors that were missing from existing PSM systems. This IPSMS model was developed by pooling elements across various PSM systems to develop its theoretical framework. As illustrated in Table 2, every essential feature of a PSM system that was present in any PSM system was highlighted using a tick mark, while those that were absent were left blank. The table shows that the IPSMS model contains all essential elements of a PSM system. However, this is because it integrated elements from all existing PSM systems; thereby improving on the weaknesses of individual PSM systems.

Table 2. Essential features of a process safety management system

Process Safety Management (PSM) System Elements	**Energy Institute High-Level PSM Framework**	**DuPont ORM/PSM Model**	**OSHA PSM Program**	**AIChE/CCPS RBPS Standard**	**Responsible Care Process Safety Code**	**CSChE PSM Guide 4th edition**	**API RP 75/SEMS**	**API RP 750**	**COMAH Regulations**	**CIMAH Regulations**	**Safety Case**	**BP OMS**	**ExxonMobil OIMS**	**IOGP/IPIECA OMS**	**PSI4MS**	**CoMS**	**EPR model**	**ILO PSM Framework**	**EPA RMP**	**IPSMS Model**
1. Management commitment, responsibility and accountability to process safety	√			√	√	√	√	√	√		√	√	√	√	√	√			√	√
2. Compliance with legal and industry standards	√			√	√	√	√	√	√	√	√			√	√	√	√	√	√	√
3. Worker consultation	√		√	√					√	√	√			√				√		√
4. Objectives, targets and safety programs				√	√	√	√	√						√		√				√
5. Employee, contractor and supplier selection and management	√	√	√	√			√	√	√	√	√	√	√	√		√	√	√		√
6. Stakeholder involvement	√			√			√	√				√	√	√			√		√	√
7. Process hazard analysis	√	√	√	√	√	√	√	√	√	√	√	√	√	√	√	√	√	√	√	√
8. Health evaluation and fitness for duty				√												√				√
9. Document and record control, and process knowledge management	√		√	√	√	√	√	√	√	√	√	√	√	√	√				√	√
10. Operating manuals and procedures	√	√	√	√		√	√	√	√	√	√	√	√	√	√			√	√	√
11. Process safety information	√	√	√	√		√	√	√	√	√	√	√	√		√			√	√	√
12. Standards and safe work practices	√	√		√		√			√	√	√	√	√	√	√	√	√	√	√	√
13. Management of change	√	√	√	√		√	√	√	√	√	√	√	√	√	√			√		√
14. Operational readiness and pre-startup reviews	√	√	√	√		√	√	√	√	√	√	√	√	√	√	√	√	√		√
15. Emergency planning and response	√	√	√	√	√	√	√	√	√	√	√	√	√			√	√	√	√	√
16. Inspection and maintenance	√			√	√	√	√	√	√	√	√	√	√	√		√		√	√	√
17. Performance and quality assurance		√		√		√			√	√	√	√	√	√	√	√		√	√	√
18. Asset integrity and management of safety critical devices	√	√	√	√		√	√	√	√	√	√	√	√	√	√	√	√	√	√	√
19. Operational control, permit to work and risk management	√		√	√	√	√	√	√	√	√	√	√	√	√	√	√	√	√	√	√
20. Communication amongst workers				√	√		√	√						√						√
21. Training, competency and performance		√	√	√	√	√	√	√	√	√	√	√	√	√		√	√	√	√	√

22. Incident reporting	√			√			√	√	√	√	√			√		√			√	√
23. Benchmarking				√			√	√				√	√	√		√				√
24. Audits	√	√	√	√	√	√	√	√	√		√			√				√	√	√
25. Incident investigation	√	√	√	√		√	√	√	√	√	√	√	√	√		√		√	√	√
26. Management review and intervention for continuous improvement	√			√	√	√	√	√	√	√	√	√	√	√	√	√	√			√

3.0 Research methodology

This research paper adopted a qualitative methodology, with primary and secondary data collected for qualitative data analysis. Merriam and Tisdell, (2015) highlight qualitative research as an inductive process where data is analysed for the purpose of formulating hypothesis. Similarly, Creswell, (2013) suggests that qualitative research helps in investigating and providing solutions to gaps in knowledge in several disciplines. Although, Flick, (2009) opines that this method is time-consuming and less accurate with cognitive interpretations to study findings. However, the argument of Creswell et al., (2007) that qualitative research deals with richer information and provides deeper insight into the phenomenon being studied makes it a preferred method of choice for this study. Hence, this research adopted the qualitative approach as the preferred method of choice to develop a comparative framework for process safety management systems in the process industry.

3.1 Population Sample and Data Collection Method

3.1.1 Collection of documentary data

The study utilised documentary data which contained relevant information about process safety management systems. These documentary data were sourced from peer-reviewed literature in academic databases such as Science Direct, Scopus, Research Gate, Wiley Online Library and Google Scholar. found peer-reviewed journals to be very reliable sources of information for academic research. Process safety data were also sourced from websites of reputable organisations such as Institution of Chemical Engineers (IChemE), UK HSE, OECD, DuPont, Energy Institute American Institute of Chemical Engineers (AIChE) and Canadian Association of Petroleum Producers (CAPP). The Zotero research assistant was used to collate all documentary data used for analysis in this study and also served as the primary reference tool for this research. After searching each of these databases, a total of 21 PSM systems were selected for comparison in this study.

3.1.2 Collection of interview data

Qualitative interviews were conducted to understand the perception of process safety experts regarding the comparative framework for PSM systems in the process industry. The interviews helped in buttressing and validating the documentary data collected from academic literature. A total of 9 process safety experts were contacted to participate in the interview; however, only 4 of them responded and agreed to be part of the study. The interviewees were selected using simple random sampling based on their job affiliation and level of experience in the process industry. The interview participants included two Process Engineers and two Process Safety Management Lecturers. The interviewees were engaged through telephone calls and face-to-face meetings. Upon seeking permission of each interview participant, the location and time of the interview were scheduled. Each interview lasted for about 15 to 20 minutes and some probing questions were asked after specific questions to gain more detailed information about the comparative framework being developed. Interviews were recorded and later transcribed to ensure that every conversation was appropriately documented.

3.2 Qualitative Data Analysis

3.2.1 Documentary analysis

After analysing documentary data from journal papers and company websites, the factors that were selected for the comparative framework of PSM systems include: -

- **Framework and room for continuous improvement: -** Every PSM system is required to have continuous improvement strategies which could help organisations cope better with management of change (AIChE, 2014). Ideally, after conducting risk assessments or incident investigations, some flaws may be identified within an organisation's PSM system that need to be addressed (AlKazimi, 2015). Therefore, framework and room for continuous improvement was selected as a key factor for the comparative framework. All PSM systems which had continuous improvement strategies in their framework were marked as "Yes", while those without one were marked as "No".
- **Design specification: -** IChemE Safety Centre (ISC) prosed seven process safety functional pillars as: 1) Process safety leadership (PSL); 2) Knowledge and competence (KC); 3) Engineering and design (ED) 4) Systems and procedures (SP); 5) Learn from experience (LE); 6) Human factors (HF) and 7) Safety culture (SC) (ISC, 2018). The Canadian Association of Petroleum Producers (CAPP) proposed four functional pillars and had previously compared the elements of only four processes safety management systems (PS-MS) using these four functional pillars including: Commit to process safety, understand hazards and risk, manage risk and learn from experience (CAPP, 2014, p. 18). Similarly, the Energy Institute proposed four functional pillars which closely match those proposed by CAPP comprising of: Process safety leadership, Risk identification and assessment, Risk management, as well as review and improvement (Energy Institute, 2016). Also, OECD, (2017) highlights five categories which represent the essential elements of corporate governance for process safety including: risk awareness, information, competence and action, as well as leadership and culture. The design specification of the IPSMS model by Theophilus et al., (2018) was developed by incorporating all 26 essential features of existing process safety management systems as seen in Table 2. Therefore, this study included design specification into its comparative framework to account for essential features of PSM systems. Since the PSM systems have a total of 26 elements in their framework collectively, each PSM system was given a score out of 26 to account for the essential elements of a PSM system contained in their framework.
- **Industry adaptability and applicability: -** Industry adaptability and applicability were selected as one of the comparative criteria as the process industry comprises of various sectors. It is imperative that any PSM system which is developed for the process industry should at least be applicable across a number of sectors within the process industry (McGuinness and Utne, 2014). The various PSM systems were assessed from a scale of 1 to 5, with 1 denoting low industry adaptability and 5 representing a very high industry adaptability. This means that PSM systems that are used within just one sector are given a score of 1 while those applicable to multiple sectors have scores increasing up to 5, depending on the number of sectors they could be used in.
- **Human factors: -** Human factors were also selected as key factors that could be paramount in ascertaining the robustness of PSM systems, since the safety and integrity of activities that take place in the process industry are functions of the interaction among man, equipment and process (Rodríguez and Díaz, 2016). In this regard, the PSM elements were evaluated using the Human Factors Analysis and Classification System (HFACS) by (Shappell and Wiegmann, 2013). The HFACS system comprises of 19 human factors which were all juxtaposed with the various

PSM systems to see which of the systems addressed key human factor categories. Any PSM element that addressed all 19 human factor components sufficiently was allotted a score of 19, and corresponding scores were given to any PSM system depending on the number of human factors they adequately addressed.

- **Scope of application: -** The scope of application was another factor that was taken into consideration, with Theophilus et al., (2016) suggesting that PSM systems could be affected based on the hierarchical level within the organisation which it applies to. These various levels ranged from 1 for employees and staff, 2 for line managers and supervisors, 3 for senior management of company and organisation, 4 for safety regulators and 5 for national and international agencies and institutions. Depending on the level of hierarchy that a PSM system was applicable to, they were designated a range of scores. For example, a PSM system that was applicable from personnel to national and international agencies was given a range of 1-5, implying that its scope of application was extensive.
- **Usability in complex systems: -** The usability of the PSM systems in very complex systems was also taken into context. The process industry is made up of several complex systems and the levels of complexity within these systems have tremendously increased over the years, which goes to suggest that PSM systems ought to also evolve to cater for these complexities that could pose new hazards (Qureshi, 2008). Ideally, PSM systems should accommodate tier 1 (greater consequence) and tier 2 (lesser consequence) process incidents (AIChE, 2011). The scores allotted to each PSM system under this category were either “Yes” for those that can be used in complex systems and “No” for those that cannot.
- **Safety culture: -** It is satisfactory for every organisation in the process industry to have a PSM system in place. However, it is also vital to note that safety culture is pivotal in ensuring the success of any of these systems (Shirali et al., 2016). Without a good safety culture in any organisation, all safety policies, procedures and measures could be in serious jeopardy (Morrow et al., 2014). Consequently, safety culture was added as one of the criteria for examining the PSM systems and it was also designated using the “Yes” or “No” classification.
- **Primary or secondary mode of application: -** Some PSM systems are designed to be applied as stand-alone components of a PSM system, while others require the incorporation of one or more PSM systems to function successfully (Moore et al., 2015). Consequently, the PSM systems were grouped in this category under P for primary and S for secondary systems, with primary systems being those that can function alone while secondary systems require integration with other PSM systems to be successfully implemented. Some systems which could function solely, and could also be integrated with other systems were assigned as PS.
- **Regulatory framework and enforcement: -** Similar to the analogy of safety culture being pivotal in ensuring the success of PSM implementation, it is noteworthy to include regulatory enforcements as prerequisites in PSM systems as national and international agencies, as well as regulatory bodies could better execute PSM elements to the latter (Kwon et al., 2016). A typical example is the Safety Case Regulations which places an onus on all operators of offshore oil and gas facilities to produce a safety case document to ensure that they have mitigated all possible hazards as far as reasonably practicable (UKHSE, 2006). This is key in not just ensuring that there is a safety policy but goes as far as confirming that every requirement in the policy is met. Hence, PSM systems that did not place emphasis on regulatory enforcement were designated as “No, while those which did were marked “Yes”.

- **Competence level: -** The various ways and methods through which PSM systems can be applied are most times detailed in their implementation strategy. This provides the end-users which could be staff, regulators, government or even the general public on how they could implement this system. However, a major factor to be considered is the level of competence (knowledge, ability, training and experience) required to implement a PSM system in any organisation (Dekra, 2017). Most PSM systems may require advanced competence in order to be applied, while some require basic competence. Depending on the level of competence required to use any of these systems, "A" was assigned to those systems that needed advanced competence level to gain knowledge of their application, while "B" was allotted to those which needed basic competence to use.
- **Inductive or deductive approach: -** Finally, the principle of operation for each PSM system was considered. PSM systems were analysed for how they execute the various elements provided within their framework. PSM systems adopt either an inductive or a deductive approach in their method of application. Inductive PSM systems stipulate various key areas, elements, factors and measures that should be present within an organisation to ensure safety, while the deductive systems verify the levels of functionality, compliance and adequacy of the measures being suggested (Sklet, 2004). Any system found to be inductive was marked as "I" while those that were deductive were marked as "D". The systems that applied both inductive and deductive approaches were marked as "ID".

3.2.2 Content analysis of interview responses

The interview data for this study was analysed using content analysis due to its ability to identify paragraphs, themes and keywords in an interview. Content analysis involves the process of identifying perceptions, collecting samples of these perceptions and analysing them in order to find any correlations (Elo et al., 2014). The analysis of interview data highlighted some notable factors which are to be considered when comparing PSM systems. The interview questions were structured to first seek expert opinion about the factors which should be included in the comparative framework, before suggesting some other factors obtained from literature. In this section, key findings from the transcribed interview responses are extracted, trimmed and presented as quotes.

Process safety experts were first quizzed about the factors that they believed were important when comparing process safety management (PSM) systems. Their responses are presented below: -

> *'...I believe that an ideal process safety management system should be compared based on their ability to prevent loss of containment. They should have elements that specifically tackle risks associated with fires, explosion, collapses, and structural damage.' – Process Engineer, oil and gas company in Aberdeen*
>
> *'...Well, I think any system for process safety should be able to manage process hazards and risks. Things like facility or equipment damage, operational procedures, and regulatory compliance are important factors to be considered.' – Process Engineer, chemical manufacturing plant in Nigeria*
>
> *'...It is one thing to have a process safety management system, but it is another thing for that system to be easily understood and implemented in industry. I would say factors such as complexity of the system, the various features contained within the management system, and*

> *adequate knowledge and training for the implementation are all vital.' – Process Safety Management Lecturer, United Kingdom*

> *'…The factors in question will depend on the particular industry within the process sector because each industry comes with its own unique risks' – Process Safety Management Lecturer, United Kingdom*

Afterwards, interviewees were probed further using the comparative factors obtained from literature. After listing all 11 factors used for the comparative framework, participants were asked if there were any other factors that were missing from the framework. Their responses were thus: -

> *'…The factors you just mentioned are good enough to compare process safety systems' – Process Engineer, oil and gas company in Aberdeen*

> *'…Not exactly. I believe these are well detailed' – Process Engineer, chemical manufacturing plant in Nigeria*

> *'…Like I said earlier, training is important. So, it is good that competence has been added because it covers training, knowledge, experience and ability' – Process Safety Management Lecturer, United Kingdom*

> *'…PSM system should be compared depending on the industry which is using them. So yes, I believe industry adaptability and applicability are important factors to consider' – Process Safety Management Lecturer, United Kingdom*

Participants were also asked whether they believed that PSM systems should be flexible in their scope of application and the criteria which flexibility of PSM systems should be based on. They responded by saying: -

> *'…To say a process system is flexible, they should be applied across any industry and in any situation that arises' – Process Engineer, oil and gas company in Aberdeen*

> *'…For flexibility, I will say anyone with limited knowledge or experience should be able to use it' – Process Engineer, chemical manufacturing plant in Nigeria*

> *'…Such a PSM system should be able to cater for any kind of process safety risks before you can deem it to be flexible' – Process Safety Management Lecturer, United Kingdom*

> *'…This means that the PSM system can be applied in any situation and in various ways' – Process Safety Management Lecturer, United Kingdom*

Lastly, participants were also asked whether they believed that PSM systems should be compared based on their levels of robustness and the criteria which robustness of PSM systems should be based on. Their responses were: -

> *'…That has to do more with the amount of process risks that are addressed by the management system' – Process Engineer, oil and gas company in Aberdeen*

> *'…A process system is robust if it can manage if it addresses all the comparative factors listed here' – Process Engineer, chemical manufacturing plant in Nigeria*

> *'…A robust process safety management system must not be lacking any essential features of a standard process safety management system – Process Safety Management Lecturer, United Kingdom*

> *'…Again, I think this might depend on the industry of application because what might be robust for one industry might not be the same for another' – Process Safety Management Lecturer, United Kingdom*

The last two questions on flexibility and robustness of PSM systems were used to compare PSM systems in the study using a quadrant matrix similar to the study of Hollnagel and Speziali, (2008). In their study, accident investigation tools were compared according to their levels of coupling and tractability. As seen in Figure 6, this quadrant matrix helped in understanding the accident investigation tools that were either loosely coupled and tractable, tightly coupled and tractable, loosely coupled and intractable, as well as tightly coupled and intractable. Similarly, in this study, the quadrant matrix was used to show PSM systems that were flexible and robust, inflexible and robust, flexible and not robust, as well as inflexible and not robust.

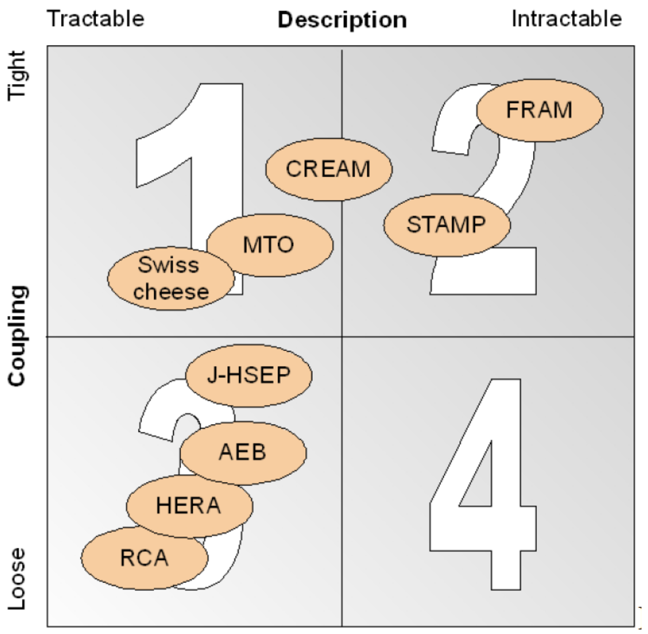

Figure 6. Quadrant matrix used to classify accident investigation tools (Hollnagel and Speziali, 2008)

4.0 Comparison of PSM Systems using Developed Framework

Table 3. Comparative Framework of PSM systems and regulations in the process industry

Criteria for comparison **PSM systems**	**Framework and room for continuous improvement**	**Design specification**	**Industry adaptability and applicability**	**Human factors (man, machine, process)**	**Scope of application**	**Usability in Complex systems**	**Safety culture**	**Primary or Secondary mode of application**	**Regulatory framework and enforcement**	**Competency level**	**Inductive/Deductive approach**
Responsible Care ® Process Safety Code (RCPSC)	Yes	12/26	1	15	1-3	Yes	Yes	S	No	B	I
CIMAH regulations	Yes	19/26	5	9	1-5	Yes	No	S	Yes	A	D

API RP 750	Yes	22/26	3	9	1-3	Yes	No	S	No	B	I
US OSHA PSM Program	No	14/26	5	9	1-5	Yes	Yes	PS	Yes	A	ID
Safety Case	Yes	21/26	1	9	1-5	Yes	No	S	Yes	A	D
ExxonMobil OIMS	Yes	19/26	1	9	1-3	Yes	Yes	P	No	A	ID
ILO PSM Framework	No	17/26	5	13	1-5	Yes	Yes	P	Yes	A	ID
API RP 75	Yes	22/26	1	10	1-3	Yes	No	S	No	B	I
EPA RMP	No	17/26	1	9	1-5	Yes	No	S	Yes	A	ID
COMAH regulations	Yes	21/26	5	13	1-5	Yes	No	S	Yes	A	D
AIChE/CCPS Risk Based Process Safety (RBPS) Model	Yes	26/26	5	13	1-4	Yes	Yes	PS	Yes	A	ID
BP OMS	Yes	22/26	1	9	1-3	Yes	Yes	P	No	A	ID
SEMS Regulation	Yes	22/26	1	10	1-5	Yes	No	S	Yes	A	D
Energy Institute High-Level PSM Framework	Yes	20/26	5	14	1-4	Yes	Yes	P	Yes	A	ID
DuPont Operational Risk Management (ORM) Model	No	13/26	5	9	1-3	Yes	Yes	PS	Yes	A	ID
CSChE PSM Guide 4th edition	Yes	19/26	1	9	1-4	Yes	Yes	P	No	A	ID
IOGP/IPIECA OMS Framework	Yes	23/26	1	13	1-3	Yes	Yes	P	Yes	A	ID
PSI4MS	Yes	13/26	1	9	1-4	Yes	Yes	PS	Yes	B	ID
CoMS	Yes	18/26	5	13	1-4	Yes	Yes	PS	Yes	B	ID
EPR model	Yes	11/26	5	9	1-4	Yes	Yes	PS	Yes	B	ID
IPSMS Model	Yes	26/26	5	19	1-5	Yes	Yes	PS	No	B	ID

As seen in Table 3, all PSM systems have framework and room for continuous improvement, with the exception of the US OSHA PSM Program, ILO PSM framework, EPA RMP, DuPont ORM model. The PSM systems with the highest level of industry adaptability “5” within the process industry include: CIMAH regulations, US OSHA PSM program, ILO PSM framework, COMAH regulations, Energy Institute High-Level PSM framework, DuPont ORM model, CoMS, EPR model and IPSMS model. Most of these PSM systems can be widely applied in the chemical, oil and gas, petrochemical and other major hazardous installations across the process industry. Based on the HFACS framework, the PSM systems that addressed at least 10 out of 19 human factors in the framework include the RCPSC, ILO PSM framework, API RP 75, COMAH regulations, AICHE/CCPS RBPS model, SEMS regulation, Energy Institute High-level PSM framework, IOGP/IPIECA OMS framework, CoMS and the IPSMS model. For the scope of application, the number of PSM systems that are applicable from national and international agencies down to the personnel include: CIMAH regulations, US OSHA PSM program, Safety Case, ILO PSM framework, EPA RMP, COMAH regulations, SEMS regulation and IPSMS model. Considering the complex nature of operations in various sectors of the process industry, it is evident that all current PSM systems can be applied in complex sociotechnical systems. However, some of these PSM systems as highlighted by other comparative factors may not be robust enough to adequately address key concerns in the process industry. The PSM systems that considered safety culture in their framework include RCPSC, US OSHA PSM program, ExxonMobil OIMS, ILO PSM framework, AIChE/CCPS RBPS model, BP OMS, Energy Institute High-Level PSM framework, DuPont ORM model, CSChE PSM Guide 4th edition, IOGP/IPIECA OMS framework, PSI4MS, CoMS, EPR model and IPSMS model. Some PSM systems could also be easily incorporated with other PSM systems during process safety implementation such as US OSHA PSM program, AIChE/CCPS RBPS model, DuPont ORM model, PSI4MS, CoMS, EPR model and IPSMS model. There are certain PSM systems that also ensure regulatory enforcement if not adhered to such as CIMAH regulations, US OSHA PSM program, Safety case, ILO PSM framework, EPA RMP, COMAH regulations, AIChE/CCPS RBPS model, SEMS regulation, Energy Institute High-Level PSM framework, DuPont ORM model and IOGP/IPIECA OMS framework. With regards to training needs for the various PSM systems, there are few that require basic competence for employees in implementing them such as RCPSC, API RP 750, API RP 75, PSI4MS, CoMS, EPR model and IPSMS. The other PSM systems are quite complex in implementation and could be cumbersome to implement without adequate and intensive training. The RCPSC, API RP 750 and API RP 75 adopt an inductive approach in their implementation strategy while CIMAH regulations, Safety case, COMAH regulation and SEMS regulation adopt a deductive approach. Other PSM systems adopt a mixed approach of inductive and deductive methods in implementing their PSM strategy.

4.1 Flexibility and robustness of PSM systems

According to findings from the comparative framework, it is pertinent to group these PSM systems according to their levels of flexibility and robustness. This could ease the decision of companies who wish to adopt a PSM system by providing them a summary of all PSM systems in the process industry at first glance (Lee et al., 2016). As illustrated in Figure 7, this categorisation of PSM systems was done in a matrix structure similar to the study of (Hollnagel and Speziali, 2008). Flexibility of PSM systems was decided based on 3 factors including industry adaptability, competence level and inductive/deductive approach; while robustness was decided based on all 11 comparative factors shown in Table 3. Therefore, the matrix was calibrated using a scale of 3 for flexibility and 9 for robustness. Firstly, any PSM with a high score in industry adaptability was deemed to be flexible and robust in its application, while those with low scores had less flexibility and robustness ratings. PSM systems with high scores under human factors were also classified as robust systems as they could address multiple flaws emanating from various accident causal factors. Also, PSM systems whose scope of application spanned from national agencies “5” to personnel “1” were also grouped as robust PSM systems. Since all PSM systems in the process industry are applicable to complex systems, they were all deemed to be robust in this regard. Similarly, PSM systems that included safety culture in their framework were considered to be robust. Some PSM systems can be used as primary standalone systems and also secondarily in conjunction with other PSM systems. Such PSM systems which had both primary and secondary applications were also believed to be robust since they can be used in almost every scenario (Energy Institute, 2016). It is one thing to have a PSM system and another thing to ensure that it is enforced (Moore et al., 2015). Without enforcement of these PSM systems, they could just be bureaucratic formalities which will not be adhered to by employees (Pitblado, 2011). Therefore, for a PSM system to be robust, it must also have regulatory enforcement at the heart of its implementation. The more robust a PSM system is, the more advanced the training needs for it will be (Fernández-Muñiz et al., 2007). Hence, PSM systems with advanced training needs were classified as robust. However, this could hamper their level of flexibility as they might not be flexible to be applied by novices in the process industry. Likewise, PSM systems which applied inductive and deductive approaches in their implementation strategy were thought to be flexible and robust.

As illustrated in Figure 7, the IPSMS model seems to be the most flexible and robust of all the PSM systems in this study. This is possibly because the IPSMS model was developed by incorporating the elements from all other PSM systems to form its theoretical framework; hence, making it a robust coalition of PSM systems for the process industry (Theophilus et al., 2018). One factor it was lacking, however, was the lack of regulatory enforcement offered by its implementation strategy. A possible reason for this could be because this model has not been adequately validated and tested in the process industry. Therefore, more research needs to be carried out to validate and test the IPSMS model in various sectors of the process industry. Other PSM systems that also showed high levels of flexibility and robustness include the AICHE/CCPS RBPS model, ILO PSM framework, US OSHA PSM program, DuPont ORM model and Energy Institute PSM framework. However, PSM systems such as the IOGP/IPIECA framework, COMAH regulations, SEMS regulation, CIMAH regulations, and EPA RMP are less flexible in terms of competency but more flexible in terms of industry adaptability. The API RP 750, API RP 75, BP OMS, Safety case and ExxonMobil OIMS are all highly specialised PSM systems restricted to use within the oil and gas industry; hence the reason for their low level of flexibility in industry adaptability. The PSI4MS, CoMS and EPR model have moderate levels of flexibility and robustness, possibly because they are highly specialised PSM systems solely for process safety information, contractor management, and emergency planning and response respectively. Evidence from these findings suggest that there is still more research to be done in terms of enhancing the flexibility and robustness of PSM systems in the process industry.

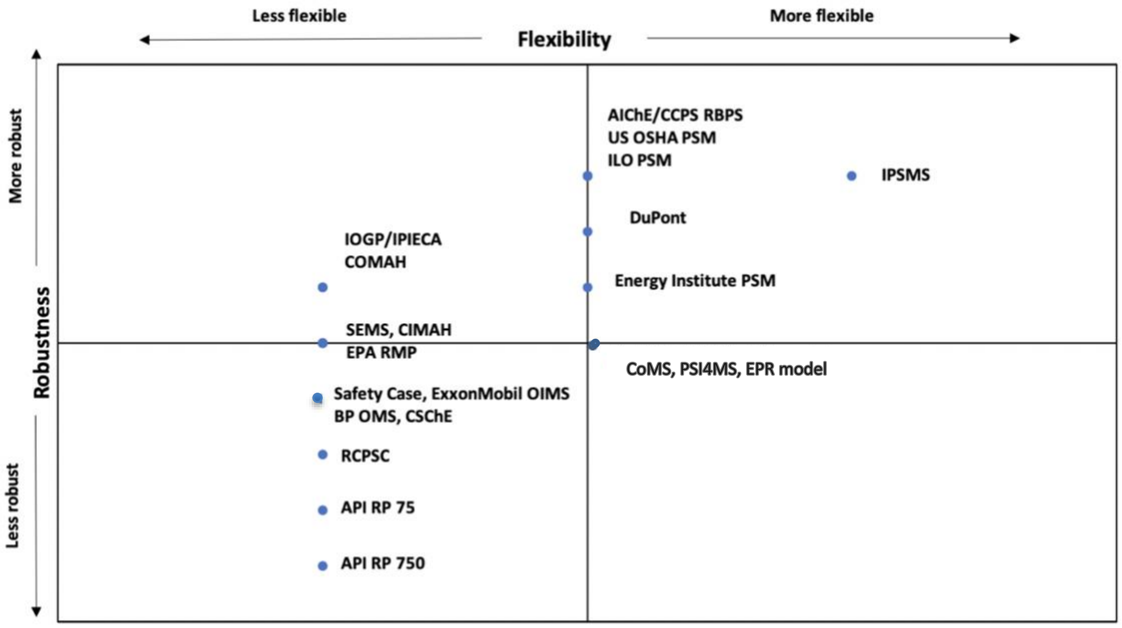

Figure 7. Quadrant matrix showing the flexibility and robustness of PSM systems in the process industry

5.0 Conclusion

This research was aimed at conducting a comparative analysis of PSM systems in the process industry. The study involved the development of a comparative framework to aid in the selection of appropriate PSM systems for specific industry sectors within the process industry. A total of 21 PSM systems were selected for this study and their theoretical frameworks, industry of application and deficiencies were all explored. This comparative framework was designed using 11 key factors which were applicable to the process industry including: industry adaptability, human factors, scope of application, use in complex systems, safety culture, primary or secondary mode of application, regulatory enforcement, training requirement, as well as inductive or deductive approach. After conducting the comparative analysis using these factors, the Integrated Process Safety Management System (IPSMS) model was deemed to be the most robust PSM system as it addressed almost every key area regarding process safety. However, the IPSMS model has not yet been tested or validated by any organisation within the process industry and this poses to be a major flaw of the system. A major inference drawn from this research is that there is no one-size-fits-all PSM system for all sectors of the process industry. Instead, process industry sectors should be extensive and thorough when selecting the right PSM system that will be most suited to the scope of their operations.

Conflict of interest

The authors have no conflict of interest to declare.

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