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Skills and expertise required by chemical engineers to adopt new technologies

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Abstract

As technology is changing at a rapid rate and the chemical industry's uptake of new technology is also picking up pace, we highlight the need to review the Skills and Expertise required by chemical engineers to adopt new technologies.

The paper argues that there is increased complexity when using new technology which has an impact on identifying hazards & risks. Increasing complexity needs to be understood by practitioners in order to identify all hazards and risks. Limited research exists regarding the uptake of evolving technology in industry and the effectiveness of current tools being used to identify the associated hazards and risks. [1], [2].

This paper brings to the attention of industry practitioners the difficulties in identifying and understanding hazards and risks associated with new technology where decision-making cannot be seen. We also recognise the role of people in understanding hazards and risks with process designs using new advanced control systems/techniques such as neural networks, machine learning, and artificial intelligence.

Given that there is some evidence that subject matter experts (SMEs) are currently leaving the chemical industry, we place a spotlight on this issue to recognise its impact on understanding hazards and risks. We provide a demonstration of a chemical engineer's career pipeline, which shows how long it takes to create an SME to fully appreciate the impact of losing critical knowledge and being replaced with lacking skill sets.

The research aims to highlight that there can be negative impacts when trying to understand the hazards and risks of processes using advanced control systems with inadequate skills and expertise. We acknowledge that the chemical industry may not realise the extent of the problem of lack of skills, and therefore, it does not know that a step change is required in skills and expertise. Rather than waiting for an incident, we propose that there is a need for industry to acknowledge the pre-requisites in skills and expertise when adopting new advanced control systems/techniques to avoid future major accident hazards.

1 Introduction

This paper argues the need for industry to acknowledge the pre-requisites in skills and expertise when adopting new Advanced Control Systems (ACS).

The Chemical Industry is increasingly adopting new technology due to globalisation-related demands. New technology types create a different complexity that is not well understood. In addition, a lack of skilled engineers could exacerbate the situation and impact process safety.

The demands of globalisation, which have caused increased competition in the chemical industry, have created constant pressure to reduce costs and are a major driving force in how the process industry must be constantly responsive. Using digitalisation and automation as the route to stay competitive is being made easier with the rapid development of technology.[3], [4] There is a consistent gap found in research regarding the lack of understanding and knowledge surrounding the unintended effects of rapid transformations in technology types and their exponential uptake in industry.

This paper first discusses the changing landscape of the chemical engineering workforce in the UK in section 2. Section 3 restates our previous paper regarding the technology types being focused on, provides a simple taxonomy for advanced control systems, and defines ACS from previous research.

The other two major drivers are the complexity created by the adoption of new technology, which is discussed in section 4, and the second driver is people-related. As subject matter experts leave the chemical industry (discussed further in section 2), it creates gaps in competence and qualifications. Which is directly linked to the ability to understand, identify and risk assess hazards.

When we couple the adoption of new technology with a lack of skilled, competent, and experienced engineers required to understand, identify and risk-assess hazards these situations can impact process safety.

This paper highlights the importance of the competence and qualifications required to identify hazards and risks associated with adopting new and not fully understood technology on chemical sites. Section 5 describes the journey of a chemical engineer from student to subject matter expert (SME), highlighting how long it takes to create an SME.

2 The impact of a changing chemical engineering workforce

Here, we discuss the changing landscape of the chemical engineering workforce in the UK. We bring attention to the loss of skilled and knowledgeable engineers and note that the replacement may not have the correct skill set. This is more of an issue when dealing with new technologies, which is discussed further in section 4.

The adoption of new technology is a normal component of process industry development; however, a lack of skilled, knowledgeable and experienced engineers is creating a situation that is forcing companies to adopt new technologies sooner rather than later. The Chemical Industry Association (CIA) recognises there is a shortage of skilled engineers, and this concern is now being felt by the wider process industry. The CIA along with trade associations such as the Hydrogen Energy Association, Environmental Services Association, the Manufacturer's Organisation, Offshore Energies UK, Engineering Construction Industry Association etc have combined forces in a cross-industry letter to the current UK Prime Minister Addressing skilled labour workforce shortages in the UK [5].

From experience, we have witnessed organisations trying to recruit competent chemical engineers for nine months without success, ultimately leading to the organisation turning to technology developers for help. For example, hiring third-party companies to scan and build a 3D model of the site, which is then passed onto another third party to design new processes, all while the site is operational and dynamic.

There are many reasons for the shortage of skilled, knowledgeable, and experienced engineers. One such reason is retirement. Carone et al. [6] propose that an aged population will create a direct impact on labour supply by stating "Ageing not only leads to an increase of the average age of the population but also leads to a decline in the size of the working-age population as older generations are replaced by less numerous younger cohorts."

Whilst the fact that people are living longer is not the centre of this research it is more so related to the demographic hitting a retirement age which creates an impact on industry. Caronne et al [6] show the mean population age was circa 37 years in 2004 and in 2022 this mean age has now reached nearly 60 years. This is a large portion of the population who will be retiring very soon in the UK. We simply acknowledge that people with thirty years of experience in the industry develop a highly specialised knowledge base (see section 5.1). The loss of a large proportion of the skilled workforce will have an impact on process safety.

Losing expertise and knowledge has a direct impact on process safety. Results from a five-year longitudinal study carried out by Rex 2018 [7] identified that "organisational knowledge loss by employee exit has a negative impact on safety. The generation of a capability gap creates a decline in the capacity to manage risk due to a significant deficiency in knowledge". Having an incorrect or lacking knowledge base has a direct impact on an organisation's ability to understand and identify hazards and risks.

Further to this point Schinner et al 2011 [8] discuss that the generational change in the workforce will have an impact on the organisation's effectiveness at hazard identification and risk assessment. They state, "With the retirement of clever aged workers, important knowledge for maintaining industrial competitiveness will leave the companies. Therefore, companies increasingly depend on the knowledge, skills, and experience of their older workers". This situation could be inflamed further by the adoption of ACS whose unintended actions are not well understood.

Although this paper does not fully address the intricacies of an ageing workforce, it is recognised as a larger issue in itself. There is a need to cover this topic area as subject matter experts leaving the chemical industry create gaps in competence and qualifications, which are directly linked to the ability to understand, identify, and risk assess hazards (see section 5).

Expert knowledge loss leads to a gap in the ability to perceive risk in the same way. The change in perception of risk could be due to their interpretation of identified risks or their ability to know risk exists. The study by Rex 2018 [7] found that new or remaining employees found difficulty comprehending the knowledge associated with dealing with risk events. The knowledge was considered more complex and less accessible. The remaining employees were found to be learning, whereas the employees who left were able to utilise their skill sets to re-use knowledge. The most revealing aspect of the study was that the organisation did not understand that the replaced employee would not be performing at the same level as the expert who left. [7]. This is a cause for concern especially as industry will continue to adopt new technology at an exponential rate versus the time it takes to create experts and build knowledge bases (see section 5.1).

Associations such as The CIA are placing a spotlight on the shortage of skills and expertise in the workforce at the highest level [5]. However, the issue from an academic perspective deserves a mention. We also recognise that attracting engineering students is important [9] [10]. For example, previously, industries like petroleum were thought of as the prestigious route for graduates however the new generation observes such industry sectors as unattractive due to the environmental impacts.

Babadagli et al [11] speak of concerns regarding the uptake and attractiveness of engineering education. They describe their research on international students as showing a systematic decline in the uptake of engineering studies with a year-on-year decline of 3%. This has a knock-on effect which is observed in industries with a shortage of skilled engineers.

With experts leaving industry, we review how long it takes to create a subject matter expert in section 5.1. This is done with the intention of placing a spotlight on how long it takes to acquire critical knowledge, competence, and skill sets.

We go on to narrow down the research in the following sections by defining the specific types of new technology and their functions as well as the impact on process safety. Firstly, we define advanced control systems (ACS) and then look at the complexity caused by adopting ACS coupled with lacking industry experts.

3 Definition of ACS

We have defined ACS in a previous paper [12], "The term "advanced control system" is defined as a process design which is automated to a point where a human does not have the final say and cannot see the decisions being made." Below we restate the main points we made whilst deriving the definition of ACS.

Defining ACS

Phrases such as ACS and Automation and Digitalisation are widely used and do not provide clear information regarding the type of technology being referred to. This causes confusion as technology has developed over the decades. We have also realised that the confusion in terminology can impact the perception of risk which directly impacts process safety. Especially activities which allow us to identify hazards and risks. Therefore, we provide an interim solution with the following definition of the term "advanced control system"

The term "advanced control system" is defined *as a process design which is automated to a point where a human doesn't have the final say and cannot see the decisions being made*.

Where modern or new technology is used to control the process for example real-time flowsheet optimization and control under uncertainty, or dynamic predictive control systems. Technology which is difficult to predict and understand such as an ACS is a good reason to better understand and clarify the complexities associated with it.

The definition is based on a simple taxonomy which can be used as a tool to guide practitioners' perception of risk by correctly categorising technology, its functions and the expertise level required to handle it safely.

1. **Hardware** - These are typically mechanical devices such as a pressure relief valve (PRV). A PRV's function is to open at a predetermined pressure and release excess pressure in order to avoid an overpressure scenario

2. **Conventional Software** - This is split into two parts firstly well-understood piping and instrumentation control loops. Typical chemical sites use a Closed control loop. The function of this is to measure a process variable via an instrument and provide feedback against a desired outcome. If the desired outcome is breached the control loop takes action via an actuator (normally closing a valve). The second type of conventional software most commonly in use within the chemical industry is well-understood complex software used to aid design decisions. These typically have the function of predictive modelling to aid design decisions. Software modelling to predict scenarios such as flooding in a distillation column, models to predict process efficiency or feasibility.

3. **Advanced Software** - A simple statement that this type of software is not well-understood with complex layers of algorithms which may also be combined with machine learning. The first example is a neural network which is an artificial intelligence used to process data and learn from it similar to a human brain. The second example is predictive control. This is different to predictive modelling which is discussed in conventional software. Predictive control is software to pre-empt a negative situation. By controlling the process via artificial intelligence which processes data and determines the best course of action and carries out that action.

4 Adopting ACS Coupled with Incorrect or Lacking Skills & Expertise Impacts Process Safety

In this section, we explore how the adoption of ACS could increase risk in the process industries; however, we also note the positive aspects of new technology. Vaidya et al. (2018) [13] describe how automating processes is advantageous in many aspects, such as better processing efficiencies, reduction in waste, and the ability to adapt the manufacturing process to suit market demands. Whereas Khan et al. 2021 [2] argue that the scale and complexity of the process increase as more and more process parameters are integrated into the process. This is a worry as the adoption of technology has largely been driven by a business requirement. There is a realisation that technology uptake has yet to be fully validated from a safety perspective. This is a real gap in both practical and theoretical knowledge.

Therefore, a brief look at how adopting ACS potentially causes added and not understood complexity. Firstly, we contemplate the meaning of complexity and its relevance for this paper in this section. However, complexity theory is a large topic area, and this paper won't cover the theory in its entirety. The purpose is to understand what complexity is and aid in realising how advanced control systems could impact process safety.

We use the definition of complexity by McDermid et al. [14], who states that a system's "complexity is determined by the nature of the interactions between the parts and the relationship between the parts and their environment." This definition takes into consideration a process or system as a whole rather than the complexity of an individual or sub-sectional part of the process.

Wall 2009 [15] states that "In practice, given that the process, the control system and the plant are each systems in their own right, and given that there are obvious interactions between them, then this gives rise to additional complexities that eventually will need to be accounted for." This is especially relevant when considering the adoption of ACS as there is limited knowledge of the unintended interactions from using ACS. This is a gap in research. For example, the competent authority in the UK (HSE) expects the chemical industry to be good at analysing unintended interactions, especially through process hazard analysis (PHA). However, this is all well and good if all the components are well understood. This is not the case with our definition of ACS.

The possibility that organisations are adding more complexity by adopting ACS is important as it affects the way complexity is seen and dealt with. More importantly, considering the full environment in which the process belongs is central to ensuring all impacts on process safety are identified. Hence, the reason for the chemical industry to understand the idea of complexity and complex systems.

The chemical industry will have to deal with the complex issues created by advances in control systems and create a more collaborative intelligent plant [2]. The concept of a complex system is important as it impacts process safety. Adopting ACS on high-hazard chemical sites where all hazards and risks associated have not been fully understood can have serious repercussions. High-consequence incidents could result in incidents that cause fires, explosions, toxic releases, major injury, loss of life and damage to the environment. From a process safety perspective, as yet there is little research [16], [17] regarding the safety impact of ACS on the wider environment of a system. Also, there is limited knowledge of complexity increasing the potential for unintended consequences from using advanced control systems. The chemical industry is in a new era of technology use, and appropriate consideration needs to be given to the safety aspects of using new technology.

Understanding the intricacies of a complex system is best explained by Wall 2009 [15], who states, "For a given system and any given degree of scrutiny, there are at least three common contexts, and hence dimensions, that may be applied to complexity – structural complexity (how the system is connected together – its topology), dynamic complexity (how the system behaves) and operational complexity (who the system interacts with the surrounding systems)." Recognising the characteristics of complex systems can aid in knowledge generation of the complex system, which will aid in hazard and risk identification efforts.

Professor Kletz's concept of an inherently safe design is significant to the complexity of systems. An Inherently Safer Design incorporates four pillars (i) minimise, (ii) substitute, (iii) moderate (iv) simplify [18]. If an inherently safe design aims to minimise and simplify therefore are we (chemical engineers) going against the grain by adding more complexity to engineering design where the aim has been Inherently Safer Design [19]–[21]?

There is limited literature on how to incorporate an inherently safer design whilst adopting ACS [19], [22]). We relate to our earlier point about how there is little research which is the same for ASC as another area of research that is only really just getting started. This is a concern as inherent safety is a part of process design and there is no evidence to show that inherent safety is incorporated into the process design which uses advanced control systems. To take this one step further, this could be due to a gap in knowledge on how to incorporate inherent safety into a process design that uses ACS. However, we acknowledge that the use of new technology to simplify design and operations can potentially remove human error, and assuming that we can create a safe ACS, it can lead to a more stable plant operation. It is uncertain if the positives outweigh the unknowns.

Khan et al 2021 [2] state, "Process system complexity continues to evolve in a manner demanding more sophisticated methods to assess and manage process safety." The importance of managing process safety is to help organisations prevent and mitigate major process accidents such as fires, explosions, and toxic releases. Therefore, the priority of this research is to focus on the identification of the hazards and risks which lead to these major incidents.

We focus on the identification of hazards and risks for the simple reason that you cannot protect against things you do not know about. Among the community of process safety practitioners, it is considered a truism that understanding your hazards and risks is a vital component of reducing risk and providing assurance to all stakeholders. It is a fundamental building block upon which a safety case can be made.

Khan et al 2015 [1] state, "Many accidents in process industries have occurred because employees did not recognize the hazards and risk associated with the activities they were undertaking such as when operating, changing, or maintaining processes, plants, and equipment." It is a fundamental part of the PSM system to be able to identify hazards and risks, and increased complexity makes it harder to recognise hazards.

Identifying hazards in a complex system, even if the system has a small number of parts, is a challenge. When adding advanced control into the mix, there are many factors to consider. For example, is there enough knowledge regarding advanced control systems and their impacts on the entire system to enable employees to identify hazards and risks? This is a noted gap in literature.

We are highly reliant on people to recognise hazards and risks therefore need to look at the role of people.

5 The role of competence and qualifications to identify hazards and risks

This section will look into the impacts of what effects competence and qualifications have on the ability to understand, identify and assess hazards within the context of increased use of ACS. This section takes into consideration the role of people in understanding hazards and risks. We acknowledge the emergence of HazOp AI however this is not widespread, and the majority of the chemical industry still uses the traditional method of HazOp. Therefore, our focus remains on people and the impact ACS has on competence and qualification for the identification of hazards and risks associated with it.

Organisations have experts with critical knowledge, competence and skill sets. As industry adopts advanced control which creates complexity the correct knowledge base must exist in the chemical industry. We are proposing that the required knowledge base may be different. There is a requirement for experts who can understand the process safety impact of advanced control on the wider environment of a system. This requires organisations to have knowledge, skill and ability. Therefore, we looked at how knowledge is lost in section 2. In this section, we go on to explore how knowledge and competence levels are developed for effective hazard identification and risk assessment.

Another important issue is that the specialised knowledge that is developed over many years is being lost. Murray 2014 and Saleem et al 2018 [23], [24] state that an organisation such as NASA "was unable to return to the moon because they no longer had knowledge of how to build rockets and spacecraft due to the loss of knowledge of workers through retirements and deaths." This example is particularly useful as academic knowledge is available, yet large organisations such as NASA were unable to achieve their goals. NASA found that theoretical knowledge is not all that is needed and that there is probably some tacit knowledge (practical know-how etc) that is also needed, which isn't in a textbook.

Therefore, we conclude that a large amount of knowledge cannot be taught in an academic setting and must be experienced in order to create an in-depth competence level and skill set. This is also mentioned by Joe et al 2013 [25] who state there is a "distinction between base knowledge, which is established through education such as an academic qualification, and the experience that needs to be built on this foundation". This is also a relevant learning point for the chemical industry where theoretical knowledge is not enough and expertise needs to be gained in the field.

Joe et al 2013 go on to specify that, "knowledge-intensive organisations include engineering, architecture, surveying, legal, scientific research and management consulting firms." These types of organisations have subject matter experts (SMEs) with critical knowledge, competence and skill sets. As characterised by Joe et al 2013 [25] SMEs "have skills, knowledge and experience in technical or scientific knowledge as well as professional knowledge that complements their specialist knowledge". That said, we look at how a subject matter expert is generated.

5.1 Path to becoming a subject matter expert

An SME is developed over a period of time, and it is unrealistic for an organisation to expect less experienced employees to operate at the same level as an SME. From experience as a chemical engineer, academics, and mentors to young engineers, we propose a prospective chemical engineer's career pipeline, (see Figure 1). This depiction shows how a knowledge base is built over the lifecycle of a career. It also demonstrates that an organisation will create a subject matter expert that they utilise to remain competitive.

When a prospective engineer enters into a career it is under the proviso that relevant training and tools will be provided by the organisation. As well as a progression plan to ensure the career pipeline keeps going. The problem lies if the organisation has a loss of knowledge due to employee departure or new employees lacking knowledge and experience. This creates a loss of safety knowledge.

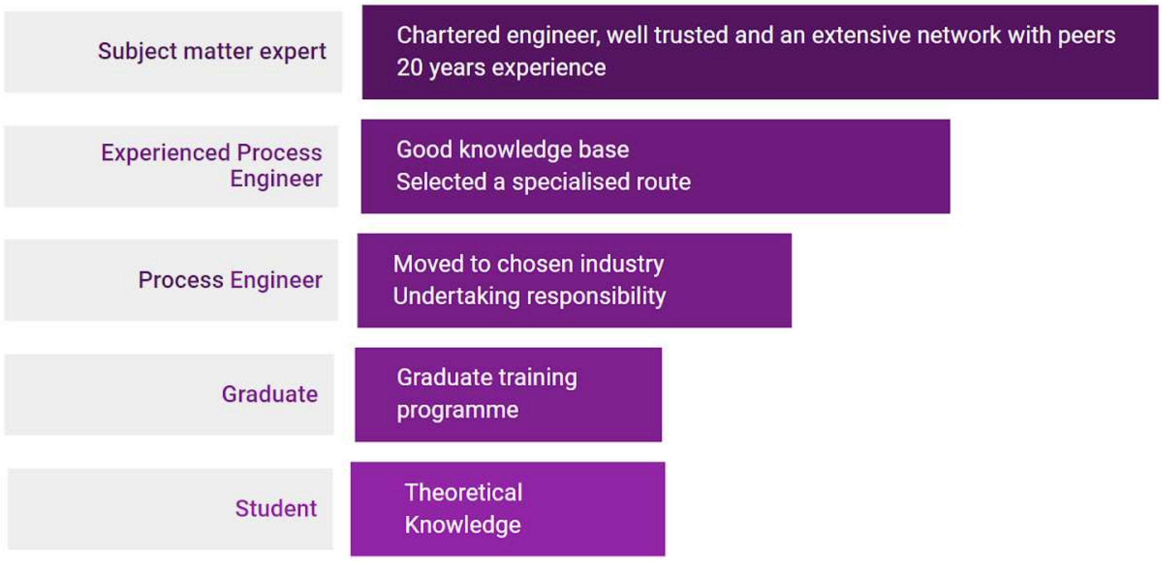

Figure 1 Career Pipeline of an Engineer

The impact of competence and qualifications on the ability to understand, identify, and assess hazards is impacted by the loss of knowledge due to an aged expert leaving the workforce and the adoption of new technology that is not fully understood. This creates a new complexity in an organisation's ability to incorporate technological advances safely. Employees are now being expected to adopt digitalisation which brings about more complex interactions [8]. This is especially relevant when considering the adoption of advanced control as there is limited knowledge of the unintended interactions from using advanced control techniques. The chemical industry can have serious consequences as a result of not fully understanding how an ACS operates both intentionally and unintentionally.

6 Conclusion

The global trend in the chemical industry is to move towards smart factory setups, which include intelligent, integrated, and fully automated factories. [2], [26]. However, there is a gap in research regarding the uptake of evolving technology in industry and the effectiveness of current tools for identifying the associated hazards and risks.

Khan et al 2021 [2] explains that the scale and complexity of the process increase as more and more process parameters are integrated into the process. The chemical industry will have to deal with the complex issues created by advances in control systems and create a more collaborative, intelligent plant.

As the adoption of technology has largely been driven by a business requirement there is a realisation that technology uptake has not been fully validated from a safety perspective. This is a real gap in both practical and theoretical knowledge.

In addition to the complexities created by adopting ACS, there is a problem of knowledge and skills leaving the chemical industry and being replaced by incorrect or lacking skills.

Based on arguments seen throughout the paper, we question whether the current SMEs are enough for the new, changing world. This is especially relevant when considering the adoption of advanced control as there is limited knowledge of the unintended interactions from using advanced control techniques. This leads to the question of whether or not the intended safety measures of ACS are adequate versus the conventional safety measures, which are well understood.

Further research should address the knowledge gap and identify the training and development needs to ensure we have the correct skill sets to deal with ACS. Consideration should be given to both theoretical and practical requirements. Future research should also aim to verify whether the current hazard identification methodologies are adequate for ACS. Lastly, future research activities should also look into how we evaluate the success of the training and what are the criteria to assess against.

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