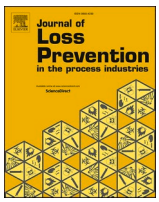
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Process safety education of future employee 4.0 in Industry 4.0

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ABSTRACT

The term "Industry 4.0″, which refers to a fourth industrial revolution, is a recent neologism. The rise of digital technology including, artificial intelligence, the Internet of things and networks, "smart" and responsive devices, etc … is more and more omnipresent. In solving the related challenges of Industry 4.0, it is necessary to improve the involvement and training of employers and employees. This is particularly true for their education in process safety. Two surveys were submitted to the relevant stakeholders. Their results showed absence of Industry 4.0 topics in the current courses on process safety. On the other hand, a review of the master's degree programs available in Europe revealed the recent emergence of new highly specialized courses in some of the topics of Industry 4.0. The definition of "Safety 4.0″ leads to recommend two potential global training pathways, with one corresponding to the requirements of Industry 4.0 & Safety 4.0 intersections, recommended within the framework of pedagogical taxonomy models.

1. Introduction

Industry 4.0 expresses the unification of the physical world of production machines (including Operation Technology, OT) with the digital world of the Internet and Information Technology (IT). Machines and information technology (IT) systems automatically exchange information in the course of production - within the factory and within the various IT systems operating in other parts of the company. But Industry 4.0 is not only about technology and processes including cyber-physical systems, the industrial internet of things (IIoT), internet of services (IoS), but also about new ways of working and roles of employees in industry (Alcacer and Cruz-Machado, 2019). This means new expectations for both employer and employee – who can be called employer 4.0 and employee 4.0. Employee 4.0 means the kind of person that has adapted to a digitalized work environment. The employer 4.0 will understandably have specific expectations about competences of employee 4.0, who will have to prove he/she has the appropriate skills. Additionally, given the increasing use of digital and information technologies in the plant of the future, process safety improvements are strictly connected to an effective system thinking and system engineering approach (Lee et al., 2019). This means that, when analysing the needs in process safety education, one must take into account not only of the people involved in the education process, i.e. the teacher and the student, but also of the employer and their expectations, when the student becomes employee 4.0.

The main goal of education in the field of process safety - or any other field - is to equip the student with knowledge to work in industrial companies or government institutions. That is to provide theoretical knowledge and practical skills which the student will be able to use as an employee. During the education, academic students must develop adequate integrated competences in terms of knowledge, skills and attitudes that can be applied in an industrial context of possible employment. The question related to process safety education, which needs to be addressed in the view of the industry moving towards Industry 4.0 is what changes does this impose on process safety education?

Fabiano (2017) indicated that special attention is on new challenges and related safety and security elements, as plant complexity and economic pressures are increasing, and technological innovations and societal changes are emerging. In this last regard, education is an impediment affecting process safety performance, recalling the importance of a joint effort among academia, industry and authorities. In the same way, Meyer et al. (2019) emphasized that process safety education should undergo a paradigm change to include the complex subject of digitalization.

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Gobbo et al. (2018) affirmed that there is a gap between the main concepts related to industry 4.0 and process safety in the literature, as well as a potential lag of integration between these two subjects. They argued that industry 4.0 will present new challenges and opportunity for process safety. Using the ISI Web of Science database, the authors analysed 789 and 1873 articles with related keywords Industry 4.0 and process safety respectively. Gobbo et al. (2018) identified the similarities and differences of the topics identified by article keywords. Table 1 shows on which topics there are similarities or differences among topics covered in respectively the Industry 4.0 and the process safety literature.

Table 1 shows significant differences in the presence of keywords between the Industry 4.0 literature and the process safety literature, as just 6 keyword topics occur in both. For example, it is surprising that the topics security and data mining don't appear in the process safety group of documents, even though the corresponding topics already appear in some teaching syllabuses. A limitation of this method of analysis may be the average annual number of articles examined and the limits of the fields of engineering, computer sciences and automation control systems alone.

Laciok et al. (2021) proposed a series of paradigm shifts in the newly defined Safety 4.0 concept. The authors present findings of surveys in the Czech Republic. Table 2 gives a list of Industry 4.0 technologies with a perceived importance with impact within the next 10 years.

The obtained results may probably reflect similar situations in other European countries currently experiencing the Industry 4.0 revolution. The main conclusion is that it is important to ensure Safety 4.0 incorporation into chemical engineering education by a significant redesign of academic process safety programs.

There is plenty of available literature on process safety education, ranging from general guidelines (OECD, 2010; EFCE, 2020), accreditation requirements (IChemE; ABET; CEAB; AEAC), through the analysis of teaching in different countries (Zhang et al., 2018; Muñoz et al., 2020), curriculum proposals, action strategies (Amaya-Gomez et al., 2019; Perrin et al., 2018; Boogaerts et al., 2017; Meyer 2017; Krause 2016; Cheah 2016; Dee et al., 2015; Amyotte 2013; PROCESSNET, 2013), teaching individual components of process safety (Perrin and Laurent., 2020; Pfluger et al., 2020; Gunasekera et al., 2020; Noakes et al., 2011) and finally literature review (Mkpat et al., 2018).

Other relevant literatures include "Teaching Safety in Chemical Engineering: What, How and Who?" (Pitt, 2012) and "Did we learn about risk control since Seveso? Yes, we surely did, but is it enough? A historical brief and problem analysis", (Jain et al., 2017), as well as books, which are compendia of knowledge in this area (Meyer et al., 2019; Mannan and Less, 2012).

Table 1
Similarities and differences between keywords occurrence in Industry 4.0 and process safety articles (Gobbo et al., 2018).

Keywords	found in Industry 4.0	found in process safety
Automation	x	X
Cloud computing	x	not existing
Data mining	x	not existing
Genetic algorithm	x	not existing
Human factors	x	X
Information technology (IT)	x	not existing
Innovation	x	not existing
Integration	x	X
Internet of things (IoT)	X	not existing
Logistics	X	not existing
Maintenance	X	X
Manufacturing	X	not existing
Optimization	X	X
Radio frequency identification (RFID)	X	not existing
Security	X	not existing
Simulation	X	X
Smart grid	X	not existing
Supply chain	X	not existing
Supply chain management	X	not existing
Sustainability	X	not existing

Table 2
List of selected Industry 4.0 technologies (Laciok et al., 2021).

Industry 4.0 Technologies	
Artificial Intelligence (AI)	Cloud Computing
Block chain	Smart electrical grid
Internet of Things (IoT)	Communication between machines
Augmented reality	Advanced production
Virtual reality	Interface human-machine
Robotics	Advanced storage energy
3D printing	Nano-materials
Drones	Nano-technologies
Big data	Autonomous automobiles
Cybersecurity	Advanced production

All authors emphasize the important role of process safety education. The contribution of process safety education to prevent major accidents in the chemical industry is significant (Swuste and Reniers, 2016; Mkpat et al., 2018). But the arising question is: Does the process safety education work? and is it effective?

Mkpat et al. (2018) present model of process safety education in their literature review: *"Process safety education is possible through three routes:*

(i) **a university-based route**, consisting of a bachelor's degree, a master's degree and PhD research;
(ii) **a professional route**, consisting of internships, so-called "On the Job Training" (OJT), Continuous Professional Development (CPD) or industry-based research;
(iii) **training in Governmental regulatory agencies** (competent for the review of safety reports and for inspections, e.g. in the framework of the application of European Directives addressing the control of major accident hazards)".

After M.J. Pitt: "*There is a need to distinguish between training and education and to appreciate the background of the learner with respect to language and prior knowledge. Some matters can only be properly understood when the individual has some industrial experience, and the traditional university method is not well suited to deal with the complex interactions on which safety depends.*" (Pitt, 2012).

Mkpat et al. (2018) in their literature review summarize "*Despite stakeholders' participation in curriculum development, the implementation of such curriculums amongst universities is seen as ineffective*". At present, generally-accepted curricula for process safety education do not seem to exist in university or industry (Krause, 2016; Rae, 2016). Currently, the courses offered in most universities - especially to chemical engineering students - include asset integrity and reliability, chemistry, hazard and risk assessment, fire and explosion modelling, and process safety management. Whilst a curriculum can be revised in the event of a process incident, as it was for example in case of the so-called 'T2 laboratory reactive incident' in the USA (CSB, 2009; Spicer et al., 2013), an overcrowded curriculum poses a threat to any revision (Saleh and Pendley, 2012; Dixon and Kohlbrand, 2015).

As amply acknowledged, there is the need of collecting qualitative and quantitative information for the purpose of evaluating programs in public health, education and safety research (Needleman et al., 1996), for example by observations, interviews, questionnaires and relevant documents. Some of the questions on curriculum development still unresolved and addressed, at least to some extent, by the surveys presented in this paper are:

- Is enough being done to provide Chemical and Process Engineers with a sound foundation on Process Safety for future employment?
- What is the optimum process safety knowledge to be included in Chemical and Process Engineering academic degrees?

- Is a foundation being provided that will be of value in whichever Country in Europe the student starts work?

W. Keller (2018) has shown the importance of the rapid temporal evolution of Industry 4.0 technologies. He highlighted the relevance of digital technologies and their development in the German chemical industry. Using the responses to a survey of 10,693 active employees in the industry, Keller showed the importance and the significant development of the respective relevance 2018 and 2025 according to the respective business perspectives innovation, training, industrial engineering, purchasing, production and quality, maintenance and repair, sales and marketing. The main future competences required for the initial training of chemists and chemical engineers in relation to chemical Industry 4.0 technologies are digital competences, soft competences (with culture, leadership, communication and organization) and the business or management competences, such as decision-making, complexity, process and strategy competences. In summary, the first group of digital competence includes the understanding of basic data, information, process software and system safety and the ability to handle IT security and safety. This forward projection explains our choice of a context limited to process safety. training in process safety.

The reminder of this paper is organized into four sections. Section 2 introduces the goal and methodologies of investigation based on two survey questionnaires. Section 3 presents the results from questionnaires. Section 4 discusses observations of established knowledge from graduate and postgraduate education. Summary of the results and conclusions remarks on required further efforts are provided in section 5.

2. The goal and methodology

The aim of this paper is to provide some answers about what technical and scientific skills of the safety domains new graduates in chemical and process engineering have and should have. As input to an answer to the first part of the aim the results of a survey on the knowledge about process safety graduates working mainly in European industry is presented.

The focus of the survey was to understand what process safety knowledge was acquired during an engineering degree program and what was acquired later. The level of knowledge about process safety divided into three areas:

- general aspects: ethics, process terminology, risk and perception, environmental protection, PPE, SMS, inherently safer processes, hazard identification, reliability, fires and explosions, toxicology, protective systems, cost benefit analysis, human factors, safety culture, learning from accidents, safety in design;
- process safety tools: HAZOP, FMEA, FTA & ETA and release calculations;
- regulations and procedures: legislation, design standards, electrical areas, permits to work, emergency planning.

The employee questionnaire was developed by the EFCE Working Party on Loss Prevention and Safety Promotion following the 9 step guidelines on marketing research and information system ("Marketing Research and Information Systems" (1997) UN FAO, Rome, ISBN 92-851-1005-3) using the open source tool LimeSurvey available at https://community.limesurvey.org/and in our case hosted on a computer in Germany. Potential respondents were identified as engineers with less than 10 years of experience in the European chemical industry, and this group was targeted through EFCE - the European Federation of Chemical Engineering. The members of the EFCE Working Party reviewed the wording, grouping and order of questions and tested the final questionnaire.

The detailed questionnaire, promoted through the Member organizations of EFCE, is shared in appendix as supplementary data. The questionnaire was sent to active employees in the European industry, members of professional associations, college and university teachers, regulators and others. The analysis of the results was based on 355 returned questionnaires of which 165 were complete responses and 190 were partial responses, mainly due to privacy reasons. Among the respondents to the peculiar considered item, 38% held postgraduate degree and 70.5% were member of a national engineering professional Society.

A further survey focusing on establishing the importance of different topics in process safety education was created and distributed to professional experts and academics of the EFCE Working Party on Loss Prevention in the area of loss prevention and process safety and health worldwide. The survey rated topics on a 5-point Likert scale from very low (0) to very high (5). This survey was distributed via email. The survey results are limited by the number of collected responses (15), but provide an answer to the second part of the aim of this paper 'should have'.

The result of the survey is presented in the next section, which is in part based on Jensen's "European map of the universities teaching the process and plant safety" (Jensen, 2012).

3. Results of surveys of knowledge level on process safety topics

The survey of process safety knowledge is presented first followed by the survey on the importance of process safety topics.

3.1. Employees survey

3.1.1. Process safety knowledge of graduates

Assessment of graduates' process safety knowledge was done by asking employees about their level of knowledge of a number of process safety topics: Did they have practical knowledge? Did they recognize the topic? or was it not in the course syllabus? The topics of process safety were: ethics, process terminology, risk and perception, environmental protection, personal protective equipment, SMS, inherent safety, hazard identification, reliability, fires and explosions, toxicology, protective systems, cost-benefit analysis, human factors, safety culture, learning from accidents, safety in design and mechanical design. The distribution of the answers for each process safety topic is presented in Fig. 1.

More than 25% of graduates have demonstrated practical knowledge of process safety terminology, risk and perception, environmental protection, PPE, hazard identification, fires and explosions, learning from accidents and safety in design. However, more than 25% of graduates have not learned about ethics, SMS, reliability, protective systems and human factors.

Graduates were also asked about their knowledge of process safety tools using the same levels of knowledge, and with the relevant process safety tools being: HAZOP (Hazard and Operability Study), FMEA (Failure Mode and Effect Analysis), FTA (Fault Tree Analysis) and ETA (Event Tree Analysis) and release calculations. The distribution of the answers for each process safety tool is presented in Fig. 2.

More than 20% of graduates have a working knowledge of HAZOP and release calculations, while a somewhat smaller group have the same level of knowledge about FTA & ETA, and only about 10% of graduates have a working knowledge of FMEA. However, almost 25% of graduates have an appreciation of all four process safety tools.

The last surveyed area was graduates' knowledge about safety regulations and industrial procedures. Again, the same levels of knowledge were used as in the previous two questions. The topics considered were legislation, design standards, electrical areas, permits to work and emergency planning. The distribution of knowledge among the survey participants is presented in Fig. 3.

Less than 10% of graduates have a working knowledge of electrical areas, permits to work and emergency planning. For legislation (Seveso and similar regulations) and design standards up to 25% of graduates have working knowledge. However, more than 50% of survey

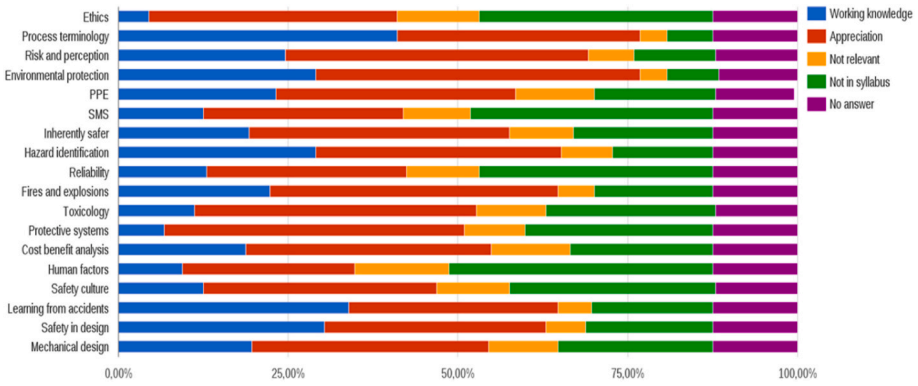


Fig. 1. Graduates knowledge about process safety topics.

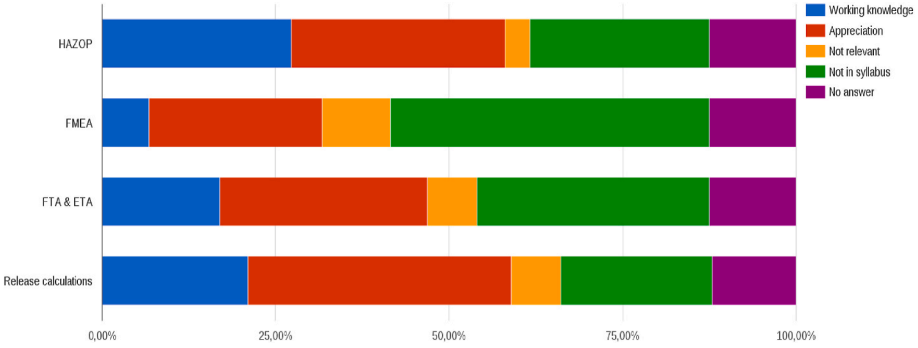


Fig. 2. Graduates knowledge about process safety tools.

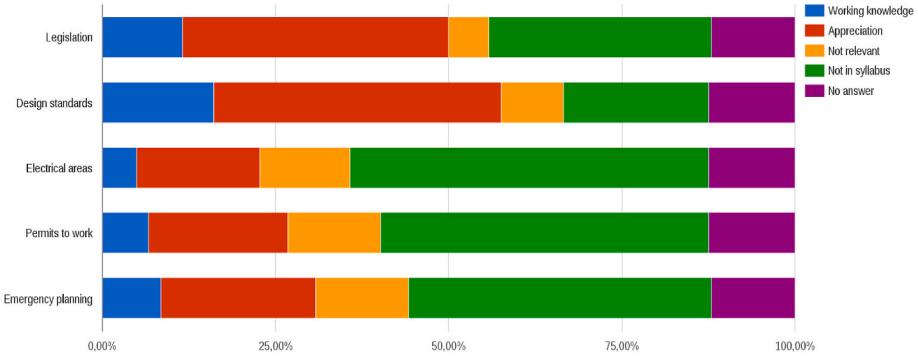


Fig. 3. Graduates knowledge about regulations and industrial procedures.

participants indicate they have not encountered emergency planning, permits to work and electrical area classification in the course syllabus.

3.1.2. *Post-graduated education*

As the graduates become employees after being offered a job, their education continues even though at this stage successful learning is critically dependent on the prior skill and knowledge of the learner and is helped by their motivation and effort (Pitt, 2012). In this context, their education continues. In this regard, survey participants were asked in which process safety areas they received further education. Fig. 4 shows how many survey participants received further training and in which areas.

More than 50% of survey participants received further training in all the areas mentioned in this question, and most of this education is by their employer, and not professional institutions, colleges, universities or other external providers.

A similar picture is seen with respect to post-graduate training in process safety tools, as shown in Fig. 5. Globally, the need for additional workplace preparation seems not connected to the level of safety education received in graduate courses. These figures emphasize the importance of higher industry involvement into the safety educational process, also accounting for the evidence that better prepared new employers translate into shorter learning curves and enhanced productivity.

3.2. *Industry and academic experts survey*

The respondents to this survey were industrial process safety practitioners, process safety researchers and process safety educators. Fig. 6 shows how the respondents rated the importance of fifteen process safety topics from least important (score 1) over moderately important (score 3) to mandatory items (score 5), grouping them into three coloured bands.

The respondents considered all subject areas at least moderately

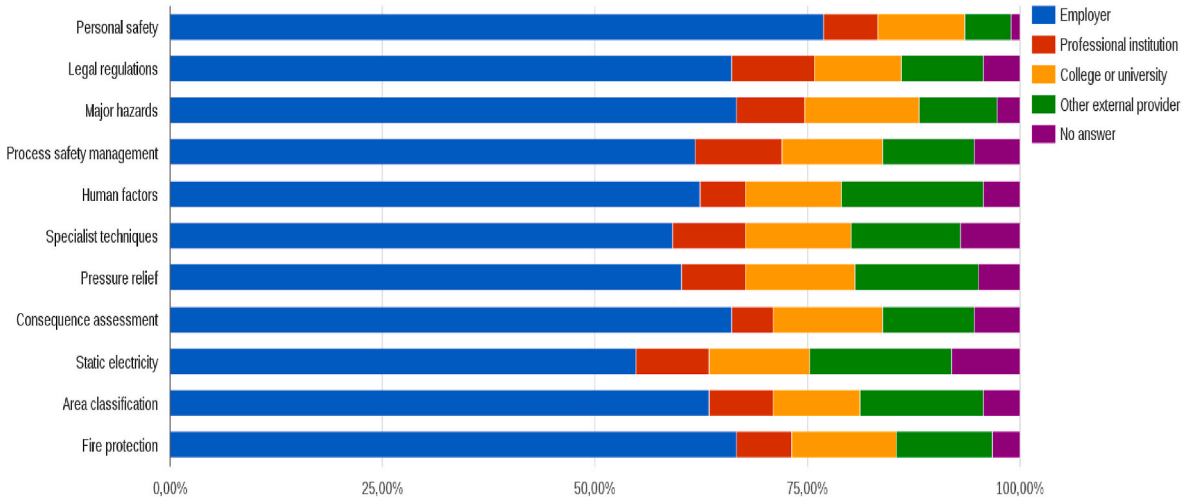


Fig. 4. Post-graduation education.

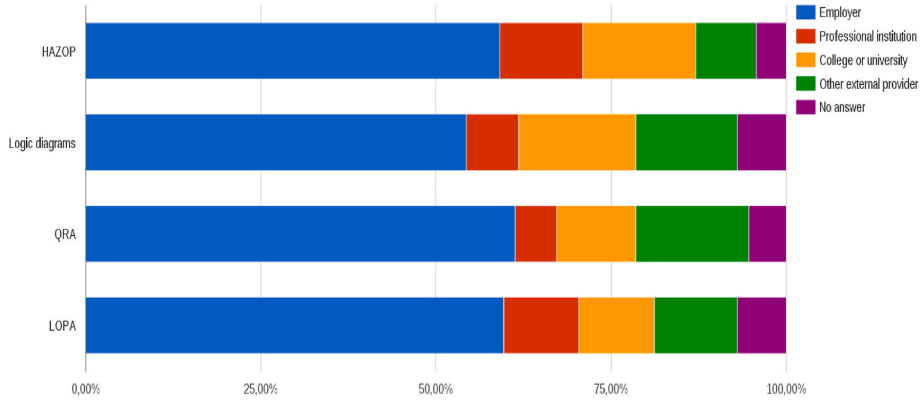


Fig. 5. Post-graduation education in relation to process safety tools.

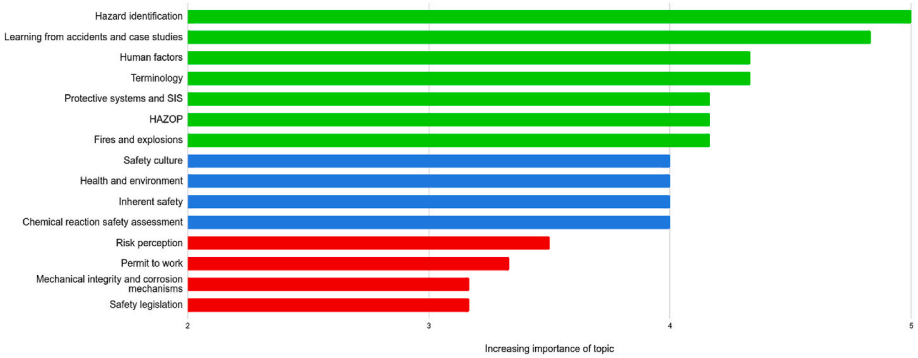


Fig. 6. Rating of importance of safety topics by educators and industry w.r.t. inclusion in Chemical and Process Engineering curricula.

important. Hazard identification, learning from case-study, human factors, protective systems were considered more important, while risk perception, permit to work, mechanical integrity and legislation were considered less important in process safety education. The comment section indicated that some chemical engineers in Europe finished their degree having heard little, or even nothing about process safety. This observation in some way confirms the previous results of the main survey about employees, for whom the main path to tackle process safety education are employer training on-the-job, or leaving process safety issues entirely to specialists, or external consultants. However, it is worth mentioning Pitt (2012) in distinguishing the different appropriate objectives of training and education: the former is about knowing and practicing what to do in predefined circumstances, while the latter relates to knowledge and understanding and should enable people to deal with new situations.

3.3. *Short review of the masters courses in process safety*

Jensen (2012) reported a number of rather different Master programs around Europe for process safety education. An updated selection of representative Master programs is presented in Table 3. Using the classification adopted by Meyer et al. (2019), the selected examples are

Table 3
Selected examples of representative Masters and PhD programs for process safety education.

Specialization area	Master - PhD program - University
Industrial risk management	Postmaster on Industrial Risk Management (IRM) (Paris, France) https://www.crc.mines-paristech.fr/en/education/post-masters-degree-in-industrial-risk-management/Master of Science on Risk management (Stavanger, Norway) https://www.masterstudies.com/Master-of-Science-in-Risk-Management/Norway/University-Of-Stavanger/Master on Risk Analysis (Stavanger, Norway) https://www.uis.no/en/master-risk-analysis Master on Risk and Safety Management (Aalborg, Denmark) https://www.en.aau.dk/education/master/risk-safety-management Master of Science - focus on Risk Management and Policy ETH (Zürich, Switzerland) https://mtec.ethz.ch/studies/special-programmes/riskmanagement.html Master on Safety Science University of Antwerp (Antwerp, Belgium) https://www.uantwerpen.be/en/study/programmes/all-programmes/master-of-safety-sciences/study-programme/Master on Safety Engineering for Transport, Logistics, and Production University of Genova (Genova, Italy) https://courses.unige.it/10377#chapter-3
Reliability and safety management	Master on Reliability, Availability, Maintainability and Safety (RAMS) (Trondheim, Norway) https://www.mastersportal.com/studies/309/reliability-availability-maintainability- and-safety.html Master Safety, Risk and Reliability Engineering Heriot Watt University (UK) https://www.hw.ac.uk/online/postgraduate/safety-risk-reliability-engineering.htm
Process safety management	Master on Safety Engineering Leuven (B) https://onderwijsaanbod.kuleuven.be/opleidingen/e/SC_51016865.htm Master on Risk Management and Safety Engineering Lund University (Lund, Sweden) http://www.lunduniversity.lu.se/lucat/group/v1000311 Advanced Master on Safety Engineering and Management INSA (Toulouse, France) http://www.insa-toulouse.fr/en/formation/specialized_masters/advanced_master_in_risk_engineering.html
Environmental risk management	Post master on Management in Safety, Health and Environment (MoSHE) Delft (Delft, Netherlands) https://www.tudelft.nl/en/tpm/education/post-graduate-programmes/post-initial-education/management-of-safety-health-environment Master on Risk management and circular economy (Tampere, Finland) https://www.tuni.fi/en/study-with-us/programmes/masters-programmes-tamk/risk-management-and-circular-economy Master on Process Safety and Environmental Engineering University of Magdeburg (Magdeburg, Germany) https://www.uni-magdeburg.de/unimagdeburg/en/psee-path-1,3,26476,39794,25852-p-40152.html Master professional on Health, Safety and Environment, University of Ostrava (Ostrava, Chech Republic) https://www.fbi.vsb.cz/en/study/offers-of-studies/master-degree/
Disaster risk management	Master on Risk, Disaster and Resilience UCL (London, United Kingdom) https://www.ucl.ac.uk/risk-disaster-reduction/graduate-study/masters-programmes/msc-risk-disaster-and-resilience Civil and Industrial Safety Engineering University of Padova (Padova, Italy) https://www.unipd.it/en/educational-offer/master-s-degrees/school-of-engineering?ordinamento=2016&key=IN2291&tipo=LM&scuola=IN PhD Program on Security, Risk and Vulnerability - curriculum Risk and Resilience Engineering for the Natural, Industrialized and Built EnvironmentsCivil, Chemical and Engineering Department DICCA University of Genova (Genova, Italy) https://sicurezza.unige.it/rrenib.html
Industry 4.0	Master on Nanotechnology and occupational risk prevention – Nanoscience and Nanotechnology (Barcelona, Spain) https://www.ub.edu/web/ub/en/estudis/oferta_formativa/master_universitari/fitxa/N/M0802/index.html Master on cybersecurity EPFL and ETH (Zurich, Switzerland) https://www.epfl.ch/education/master/programs/cyber-security/Advanced master on Innovation and Secure IoT systems INSA (Toulouse, France) http://www.insa-toulouse.fr/en/formation/specialized_masters/advanced-master-innovative-and-secure-iot-systems.html Master on Security and Risk management University of Leicester (Leicester, United Kingdom) https://www.onlinestudies.com/University-of-Leicester-MSc-in-Security-and-Risk-Management/United-Kingdom/Stafford/Master on Applied Global Security Engineering and Management (IMSGA) University of Troyes (Troyes, France) https://www.utt.fr/formations/master/ingenierie-et-management-en-securite-globale-appliquee Master on Security and Risk management-Security governance (SAFER) University of Tampere (Finland) https://www.tuni.fi/en/study-with-us/security-and-safety-management-security-governance Master on Information Systems Security University of Troyes (France) https://www.utt.fr/formations/master/securite-des-systemes-d-information Master on Computer Science Industry 4.0 University of Pau (France) https://www.masterstudies.com/Master-in-Computer-Sciences-(Industry-4.0)/France/Universit%C3%A9-de-Pau-et-des-Pays-de-lAdour/Master-on-Data-Engineering-University-of-Bremen-(Germany) https://www.masterstudies.com//M.Sc.-in-Data-Engineering/Germany/Jacobs-University/International Master on Big Data Politecnico Milano (Italy) https://www.masterstudies.com/International-Masters-in-Big-Data/Italy/MIP/Master on Sustainable Development University of Sussex (UK) https://www.onlinestudies.com/Sustainable-Development-MSc-(online)/United-Kingdom/University-of-Sussex-Online/Master-on-Pedagogy-and-Teaching-for-Sustainability-University-of-Eastern-Finland https://www.masterstudies.com/Master-in-Pedagogy-and-Teaching-for-Sustainability/Finland/University-of-Eastern-Finland/Master on International Security and Development (ISAD) University of Krakow (Poland) https://www.masterstudies.com/Master-in-International-Security-and-Development/Poland/Jagiellonian-University/Master on Photonics for Security, Reliability and Safety University of Saint Etienne (France) https://www.masterstudies.com/Master-in-PSRS-Photonics-for-Security-Reliability-and-Safety/France/Universit%C3%A9-Jean-Monnet-Facult%C3%A9-des-Sciences-et-Techniques/Master on Engineering Technology for Strategy and Security (STRATEGOS) University of Genova (Italy) https://www.masterstudies.com/Master-Program-in-Engineering-Technology-for-Strategy-and-Security/Italy/University-Of-Genoa-(Universit%C3%A0-Degli-Studi-Di-Genova)/

listed according to the respective area orientations commonly found in university syllabuses, such as industrial risk management, reliability and safety management, process safety management, disaster risk management and environmental risk management. An additional category dedicated to specialities in the field of Industry 4.0 has been included in Table 3. Other post graduate training courses in Europe can be found on the Keystone website (https://www.masterstudies.com/).

It is possible to compare the detailed contents of the selected courses by activating the corresponding links. Overall, all the classical courses show the presence of several common elements and tools in their syllabuses. Nevertheless, some differences exist due to the specificities of the host departments, institutes and universities' laboratories, geographical locations and fields of research.

The last topic "Industry 4.0″ of Table 3 lists a selection of courses covering linking principles and practices of process safety with the requirements of Industry 4.0. The key Industry 4.0 topics are security, cybersecurity, sustainability, big data, nanotechnology, security and IoT systems.

4. Discussion

In the following first the results of the surveys of employees and of process safety experts in industry and academia are discussed. From one side the results may represent a benchmark for future statistical investigations, from the other one they are considered a basis for introducing a new pedagogical approach to process safety education.

4.1. State of process safety knowledge among graduates in engineering

The results of the survey of employees shows that only a fraction of graduates have working knowledge of the process safety topics considered important based on the survey of industrial and academic safety experts. Not surprisingly, the experts consider all topics of process safety important and well relevant for safety education, while none was scored as unimportant - see Fig. 6. In fact, it is noteworthy mentioning that the foundation of a great safety culture in the process industries begins and is shaped in the classrooms and is then refined in the industrial setting as long as the industry is committed and invests in on-the-job safety education with a focus on individual safety for all employees (Hendershot et al., 2007). 4.2 State of post-graduate education in process safety The survey of employees shows that the majority of post-graduate education is provided by employers to equip employees with working knowledge in relevant areas. The contribution of professional institutions, colleges and universities and other external providers is surprisingly low, maybe

because employers consider training provided by universities not practical enough. The same could be true for professional institutions and other external providers. This viewpoint was also proposed by Gyenes (2019) following a European benchmark exercise, in which some respondents commented that universities may not teach process safety because the lecturers may not have worked in industry, so that they do not necessarily prioritise process safety to the same level as industry does, or it might be due to the lack of competent staff to teach it. Training based on the company's specific process safety documentation and on the company's internal information would a priori benefit from a better prejudice.

Questionnaire analysis evidenced some limitations of the study, suggesting as well possible improvements for a future survey on Process Safety Education in Europe. The effectiveness of education and training intervention should be considered, adding pertinent questions regarding how much of the undergraduate experience was from the placement, and how much from the University. Other items relevant for survey improvement pertain the distributions of knowledge, possible breakdown about the time post graduates are working in industry, breakdown of countries (i.e., whether the responses are country specific) and the actual way employers provide training and education. The manner of recruitment of individuals for the survey can be improved as well, including detailed report of the dropout rate.

At this stage, it must therefore be noted that there are significant differences between the process safety knowledge from education indicated by the survey results and the selected technologies of Industry 4.0 listed in Table 2. This situation indicates the need to update process safety education in line with Safety 4.0.

4.2. Pedagogical approach to process safety education for safety 4.0

Gajek (2019) stated that training methods and organizational solutions, especially in process safety, play a key role because they have to translate into the ability to use the acquired knowledge in practice, in a real situation, acting under the pressure of an event at the moment of an accident. Educational objectives, systematic training and continuous improvement with new emerging concepts can be developed in the light of Bloom's updated taxonomy of the cognitive (knowledge), affective (emotion) and psychomotor (action) domains. Another possibility is application of Niemierko's taxonomy that refers to three learning objectives: mental skills (knowledge-based skills), practical skills (action-based skills) and personality skills (emotion-based skills), which can be related directly to the process safety, as it is shown in Fig. 7.

The consideration of the Bloom's taxonomy of educational objectives can help to elucidate the instructional objectives and learning outcomes. For example, Kletz and Amyotte (2010) describes learning outcomes specifically dedicated to Inherently Safer Design (ISD):

- knowledge base: explain the bow-tie methodology for process hazard assessment;
- use of engineering tools, problem analysis: use the bow-tie methodology and the full hierarchy of controls to model hazardous scenarios related to process safety;
- teamwork, communication skills: collaborate with team members to develop bow-tie diagrams for risk communication.

In the same way, in a Dalhousie process safety course for undergraduate students, Amyotte et al. (2019) retained revised learning outcomes based on Bloom's taxonomy as indicated in Table 4.

The key goal of the education process is to use all three aspects of Niemierko' taxonomy. The application of Niemierko's taxonomy allows students to understand the correlation between theory, practice and commitment in the field of major accident prevention. This paradigm is

Table 4
Example of a revised learning outcomes in a Canadian undergraduate program (Amyotte et al., 2019).

Learning outcomes	Taxonomy	Graduate attribute
1. Define industry standards terms such as process safety, occupational safety, hazard risk, inherently safety and hierarchy of controls	Remember	Knowledge base of engineering
2. Explain the basic principles of ISD using both every-day life and technical examples	Understand	Knowledge base of engineering
3. Identify root causes of process incidents by means of a loss causal model	Apply	Knowledge base of engineering
4. Critical process industry cases studies and recommended alternative risk reduction with respect to core concepts such as management system elements, ISD and the hierarchy of controls and fire and explosion safety	Analyse Evaluate	Impact of engineering on society and the environment Economics and project management
5. Appraise the issue of conflicting demands of safety and production using process industry case studies drawn from various regions of the world 6. Formulate a hazard identification protocol to access potential hazards in a given industrial process	Evaluate Create	Impact of engineering on society and the environment Design Use of engineering tools

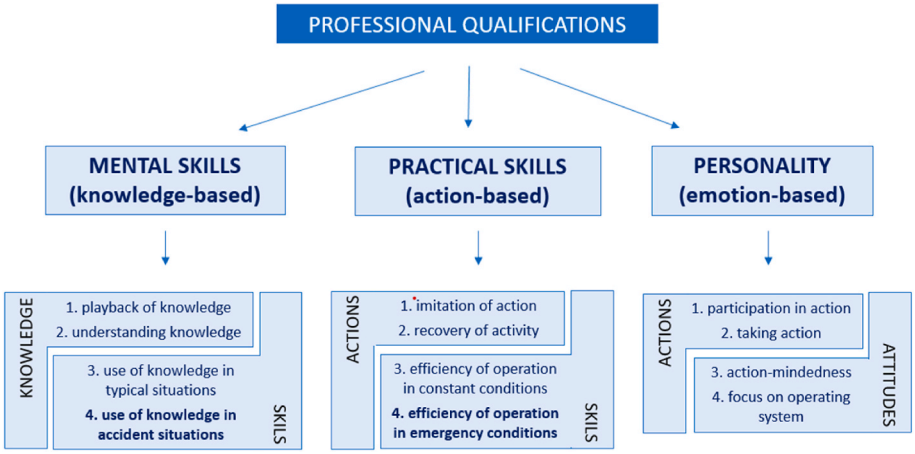


Fig. 7. Niemierko's taxonomy (Gajek, 2019).

applied in Poland in post graduate courses organized by Central Institute for Labour Protection – National Research Institute and Technical University of Lodz in relation to teaching the legal aspects of preventing major industrial accidents. Presentation of major accidents (photos, films, simulations accompanied by most significant figures), including Flixborough, Seveso, Bhopal etc followed by a discussion in which students are asked to put themselves in the situation of directors of workplaces, ordinary workers and other people involved in the event is aimed at evoking emotional reaction. These students cannot remain indifferent. Clear demonstration of the link between specific major accidents and the relevant amendments to the Seveso Directive allows students to understand the reasons for the development of the regulations. In this way, the emotional commitment increases students' interest in the theoretical aspects.

Definitions and interpretations are always the key to understanding the theory. Often a complex definition that is difficult to understand must be divided into parts. For instance, the definition of a major accident in Polish regulations:

> 'major accident' is an event, in particular an emission, fire or explosion, occurring during an industrial process, storage or transport, in which one or more hazardous substances are present, leading to an immediate danger to human life or health or the environment or to such a danger with a delay

can be divided into four parts. A major accident in Poland is an event that will meet all four criteria:

a) an emission, fire or explosion,
b) during an industrial process, storage or transport,
c) one or more hazardous substances are present,
d) leading to an immediate danger to human life or health or the environment or to such a danger with a delay.

The students' ability to effectively apply the newly acquired knowledge is tested when they have to answer simple questions e.g. Is a fire in a textile warehouse a major accident according to the definition? Students thinking about dangerous substances that can be created during a fire shows their ability to analyse the situation from a broader perspective.

The practical aspect is developed in the process of analysis of case studies, when students have to prepare a notification of the establishment based on a list of dangerous substances, CLP regulation and qualification criteria (Polish implementation of Annex 1 to Seveso Directive).

Pasman and Fabiano (2021) reported that the new challenge in the process industries 4.0 is represented by a full transition towards the neologistic Safety 4.0. They illustrated the concept of safety 4.0 through the jump and the technological link between the third and fourth industrial revolutions. Laciok et al. (2021) explained the new concept of Safety 4.0. This neologistic term concerns a full methodological and conceptual transition and a new series of paradigm shifts towards the novel safety concept. The authors defined "Safety 4.0″, with four guide words, as a "proactive shift to the science of process and occupational safety, which focuses on system resilience and dynamic risk management and is based on interoperability (IoT), information transparency (digital twins), technical assistance and decentralized details".

How can Bloom's general, pedagogical approach and the "Safety 4.0″ concept be used to promote an updating, a notorious renewal, or better still a creation of process safety education integrating the principles and requirements of the new 4.0 industry practices? How can the new process safety topics 4.0 be included in chemical engineering courses? The answers to these questions are not trivial. As a matter of fact, Industry 4.0 provides an actual opportunity to develop a more integrated approach to engineering activities associated with design, operation and optimization of processes which provides the chance of developing more integrated perspectives on operational management whereby process safety, process operations and process optimization are taught as integrated content. In this regard, given the SARS-CoV-2 pandemic, innovative learning methods, with active virtual contribution are becoming more and more popular, based on selected approaches, as introduced by Woods (2014). They offer new challenges and include for example collaborative learning with students remotely interacting and solving safety and process/plant design tasks in an effective and stimulating way (Gillies, 2019). As a drawback, it should be observed the timetables of scientific courses at universities are not seldom overloaded, so that it is already difficult to include traditional process safety courses. These necessary prerequisites do not militate in favour of easy updating. A notorious renewal seems more accessible. For example, Laciok et al. (2021) detailed the modifications of program "Fire protection and industrial safety" for moving to a new curriculum "Sustainability" education. On the other hand, the creation of new content seems to be the most common solution adopted, as shown by the new courses listed in Table 3. An interesting example is illustrated by the content of the Master "Industry 4.0 - Industrial Security and Safety" proposed by the University of Augsburg (Germany). Over the course of three semesters, students acquire the skills necessary to come up with interdisciplinary solutions to security and safety problems in the areas of industrial automation, control systems and critical infrastructure. This practical degree program focuses on a range of subjects including IT security, data protection, functional security, IT law and employee management. After completing this degree programme, graduates can take on positions with a high level of responsibility, such as the position of security analyst in the IT sector, developer of safe and secure production and assembly lines, or safety and security consultant at management and process consulting companies.

Table 5
Example of the "Lean production and management" Industry 4.0 course.

Learning outcomes	Taxonomy	Attribute - element
1. Explain the elementary terms digitalization, industry 4.0,	Remember	Terminology
2. Analyse and interpret the paradigm change going on in industry because of industry 4.0	Understand	Wider usage of Internet in the work processes in relevant areas and systems
3. Understand and explain the new level of technical and software communication, based on different data formats, between the cyber physical system and the internet or internet of things	Understand and Apply	Data availability of sensors, actuators and process data in production systems: production planning system, manufacturing execution system, supervisory control and data acquisition, enterprise resource planning
4. Have the capacity to use IT instruments in the work with automated systems	Evaluate	Data handling, saving data, cloud computing, data security, data mining, big data
5. Are able to use, understand and work with the different types of data formats and data safety systems	Create	Process management – development of innovative projects

5. Conclusions

The Industry 4.0 revolution will cause significant effects, such as the new occupations and job profiles, changes to employment forms and a

Table 6
Overview of a potential learning course on process safety in industry 4.0

Areas	Attributes - Elements
Knowing	Actualize, promote, create plans of teaching programs to become more familiar with emerging technologies 4.0 for process safety
Acting	Prescribe the mandatory safety knowledges concerning industry 4.0: digital high reliability organizations - decomposing risk – risk matrix – bow-tie analysis with industry 4.0 – Process design 4.0 – Analytic monitoring – Implementation – Developing duty holder review (DHR) – Process safety return on investment (ROI) (Petrusich and Schwartz 2017)
Being	Accept good engineering practices – build communities training – manage cost efficiency – coordinate worker training in safety projects – disseminate game based learning – provide for emergency crisis … Approach industrial companies, public and private research laboratories, governmental institutions to establish strength cooperation (external lecturer, training period, internship, software, project, agreement, accreditation …)

more important role for the platform economy, generating challenges for social policy. The development of human capital and consumer behaviour will be impacted. The educational profile of the human capital is necessarily changing and new approaches to education systems must be introduced. Education should respond to this evolution by adapting curricula, teaching methodologies and strategies to address the challenges and opportunities posed by this revolution and hopefully provide an answer regarding process safety skills important for a new engineer from the point of view of the potential employer 4.0. From this perspective, our concern is the examination of the current situation of process safety education. Results of the surveys, which were responded to by current employees, university teachers and governmental institutions, have shown strengths and weaknesses of the focus of current process safety training. In particular, the scarcity and weakness of co-occurrence of topics as indicated by keywords in publications between writings on industry 4.0 and on process safety were highlighted by the surveys. Responses from the employees' survey can be considered for future use as benchmarking and as a tool to identify strengths and weaknesses of education and training. On the other hand, the updated review of certain recent university training courses has shown the emergence of new highly specialized courses in some of the specific topics of industry 4.0. As an example, Table 5 provides the introduction of a course titled "Lean production and management", properly revamped according to Bloom's recommended taxonomy and showing specific learning outcomes and their actual links with the corresponding industry 4.0 elements.

In addition to such specialized graduates, a path is needed for the onboarding of industrial employees with a general culture provided by a systemic approach to Safety 4.0 elements. This should allow for an integration of all intergenerational stakeholders. Worker 4.0 interactions take place at different levels of the organization, e.g. on the plant floor, plant manager and chief executive officer (CEO). The changes generated by the Industry 4.0 revolution create a very different generation of employees from the ones of path decades. Today's students are continuously connected through advanced technology and social intra-company networks. In this context, it will be necessary to rethink traditional learning methods also to attain transferable skills such as creativity, problem solving, critical and system thinking and emotional intelligence. As far as we have been able to ascertain the open literature does not report any examples of this global approach towards Industry 4.0 ready employees. It is therefore essential to develop training content based on elements from a Safety 4.0 roadmap.

Adopting the "Knowing - Acting and Being" taxonomy in training is essential. Table 6 presents a new global proposal for an integrated curriculum for the "Safety 4.0″ concept, which can respond to the revolution of the 4.0 industry. Its flexible adaptation to a particular advanced technology is possible.

The generation of employees, who have been involved in working life for some time, likely will experience a transition process that will be gradual and probably long. However, depending on the human, material and financial availability of educational structures, two training approaches can be recommended. The former consists of coupling the current classical process safety education, with one of the specialities responding to the needs of industry 4.0. The latter, more revolutionary for young people who are already familiar with modern technologies, is to provide integrated teaching of the joint subjects of "Safety 4.0″ and Industry 4.0. Recently Khan et al. (2021) called for integration process digitalization as an element in the core chemical engineering curriculum, either as specialized courses or as topics in existing core chemical engineering courses to facilitate a background in process safety. Similarly, phenomena based on design and optimization should be elements of core process design and optimization teachings to facilitate both process safety and process sustainability (Lutze et al., 2013).

To sum up, updated information must be provided on the changes needed in process safety education programs, in order to meet the needs of Safety 4.0 in the age of Industry 4.0. Only then can the education community meet the needs of their industrial colleagues as they move their processes and plants towards Industry 4.0. More research and validation against benchmarks should be encouraged to find practical solutions to the challenges in safety education for chemical and process engineering raised in this paper.

Disclaimer

The views and opinions expressed in this article are those of the authors and do not necessarily represent those of others.

Author statement

Agnieszka Gajek: Conceptualization, Methodology & Writing – original draft. Bruno Fabiano: Supervision, Conceptualization, Methodology & Writing. André Laurent: Supervision, Writing-original draft, Reviewing & Editing. Niels Jensen: Methodology and questionnaire design, Reviewing & Editing.

Declaration of competing interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

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Appendix A

A - Blank questionnaire for survey of Engineers exposure to Process Safety.

Engineers Exposure to Process Safety Survey

Welcome to the survey of engineers exposure to process safety, which is being performed by the European Federation of Chemical Engineers Working Party on Loss Prevention and Safety Promotion. The survey contains four sections of question about your training at university and after, your work, the organisation you are part of, and you.

The purpose of this survey is to gather information about the exposure of young engineers to safety during their education and later during their carriers

There are 24 questions in this survey.

Relevance of the university education you received to current employment

Education prepares you for understanding why task A should be performed in a particular way to avoid problems. Training prepares you to perform task A in a particular way to avoid problems.

Fig. A.1. Survey questionnaire page 1.



3.3.2021 LimeService - Your online survey service - Engineers Exposure to Process Safety Survey

Here we would like you to rate the level of education you received during the studies for your degree(s). *

Please choose the appropriate response for each item:

	Not in syllabus	Not relevant	Appreciation	Working knowledge
Ethics	○	○	○	○
Process terminology	○	○	○	○
Risk and perception	○	○	○	○
Environmental protection	○	○	○	○
Health protection, e.g. PPE	○	○	○	○
Safety legislation, e.g. Seveso, Atex, REACH	○	○	○	○
Safety management systems	○	○	○	○
Inherently safer	○	○	○	○
Hazard identification	○	○	○	○
HAZOP	○	○	○	○
FMEA	○	○	○	○
Reliability	○	○	○	○
Logic trees	○	○	○	○
Discharge and dispersion of gas / vapour	○	○	○	○

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Fig. A.2. Survey questionnaire page 2.

	Not in syllabus	Not relevant	Appreciation	Working knowledge
Fire and explosion - incl. vapour cloud explotion and dust explosion	◯	◯	◯	◯
Toxicology	◯	◯	◯	◯
Design standards	◯	◯	◯	◯
Electrical area classification	◯	◯	◯	◯
Protective systems	◯	◯	◯	◯
Cost benefit analysis	◯	◯	◯	◯
Human factors and ergonomics	◯	◯	◯	◯
Safety culture	◯	◯	◯	◯
Permit to work	◯	◯	◯	◯
How accidents happen (case studies)	◯	◯	◯	◯
Process safety in design	◯	◯	◯	◯
Mechanical design aspects	◯	◯	◯	◯
Emergency planning	◯	◯	◯	◯

Fig. A.3. Survey questionnaire page 3.

Did you receive any education in or experience with process safety during any industrial placements as part of the first degree program? *

Please choose **only one** of the following:

◯ Yes

◯ No

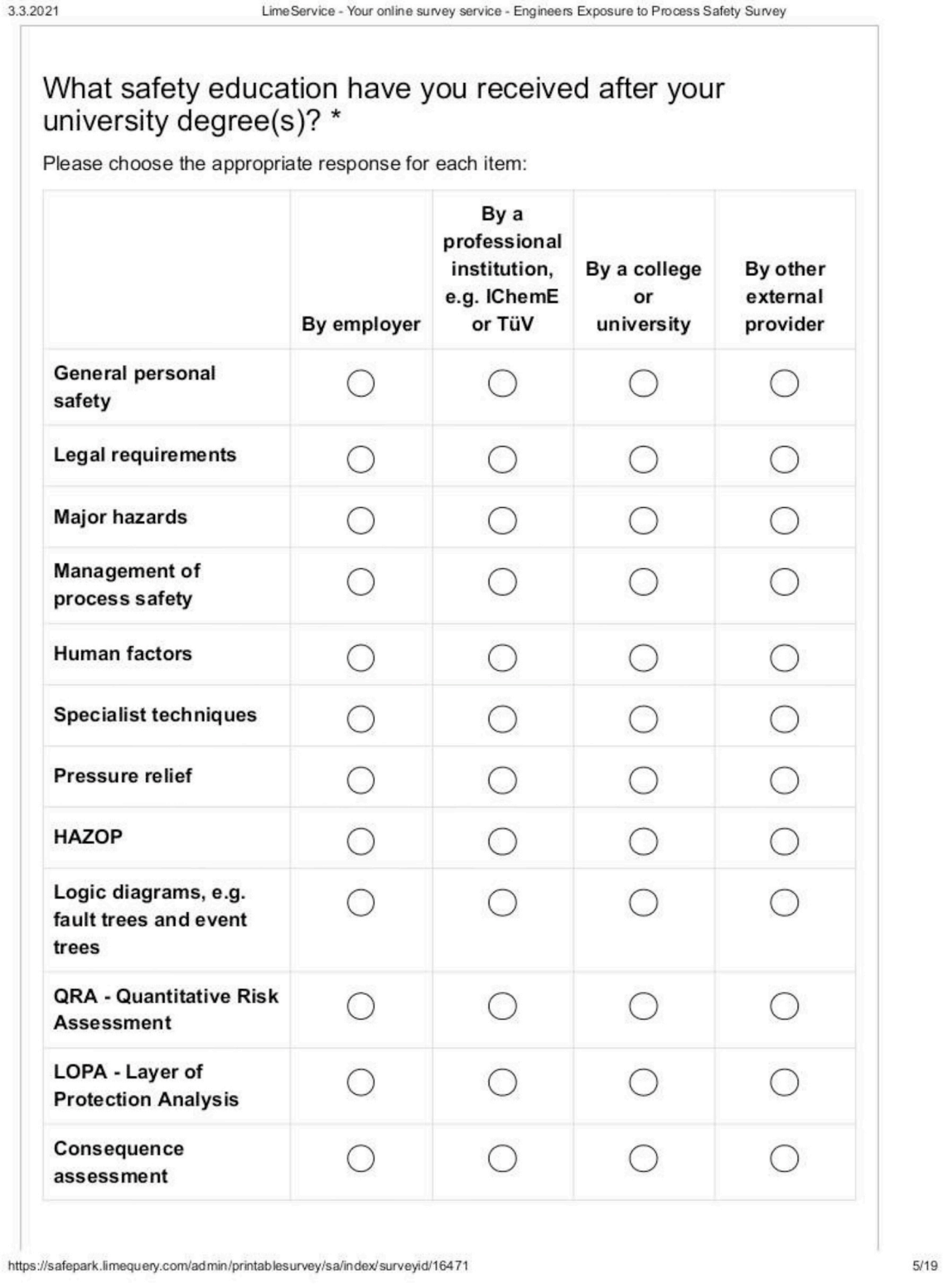
Are there any specific areas where you consider that your education could have been improved?

Please write your answer here:

Process safety education after your university degree(s)

This group of questions relate to the process safety education you have received after university.

Fig. A.4. Survey questionnaire page 4.



3.3.2021 LimeService - Your online survey service - Engineers Exposure to Process Safety Survey

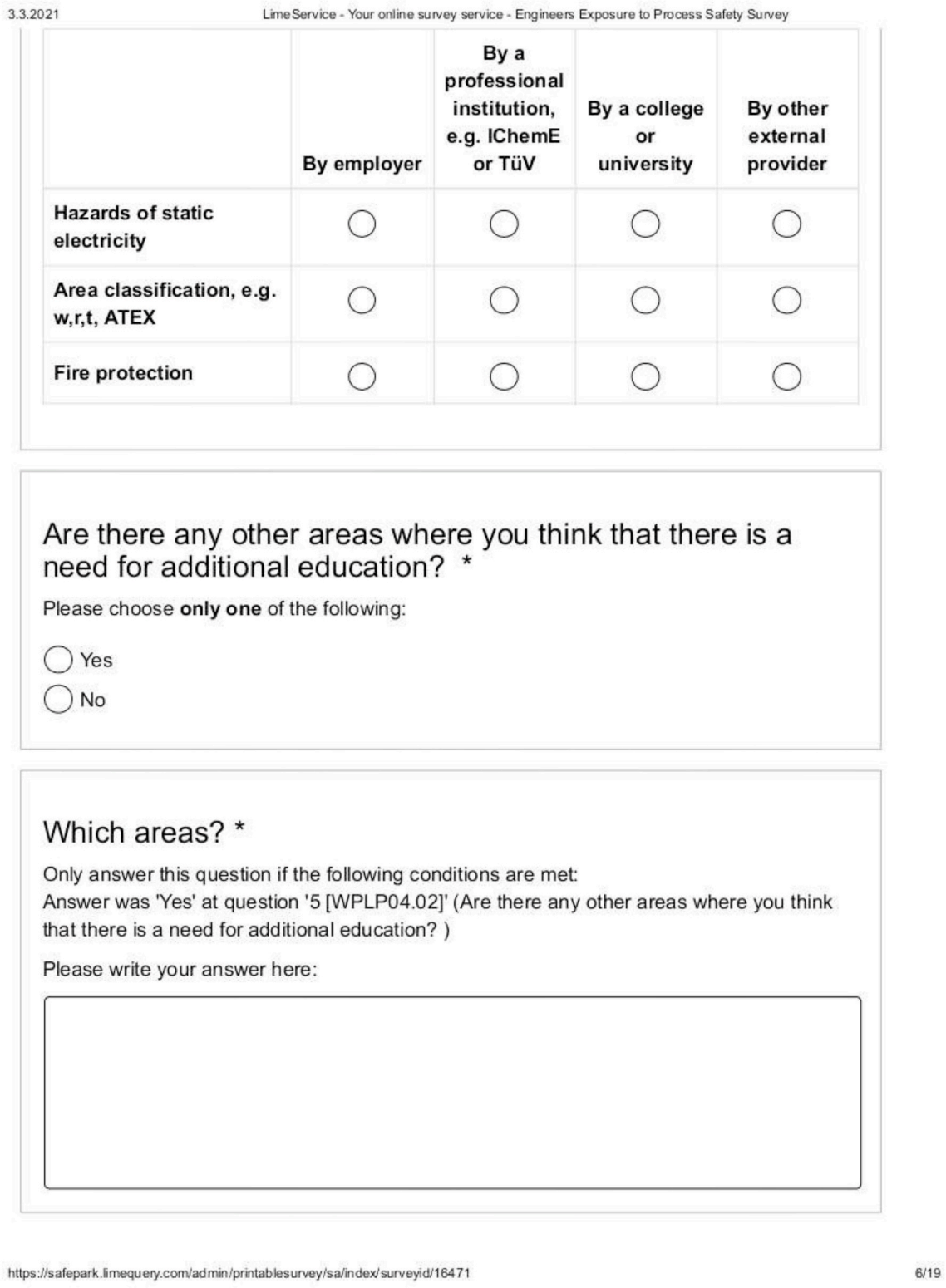
What safety education have you received after your university degree(s)? *

Please choose the appropriate response for each item:

	By employer	By a professional institution, e.g. IChemE or TüV	By a college or university	By other external provider
General personal safety	○	○	○	○
Legal requirements	○	○	○	○
Major hazards	○	○	○	○
Management of process safety	○	○	○	○
Human factors	○	○	○	○
Specialist techniques	○	○	○	○
Pressure relief	○	○	○	○
HAZOP	○	○	○	○
Logic diagrams, e.g. fault trees and event trees	○	○	○	○
QRA - Quantitative Risk Assessment	○	○	○	○
LOPA - Layer of Protection Analysis	○	○	○	○
Consequence assessment	○	○	○	○

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Fig. A.5. Survey questionnaire page 5.



3.3.2021 LimeService - Your online survey service - Engineers Exposure to Process Safety Survey

	By employer	By a professional institution, e.g. IChemE or TüV	By a college or university	By other external provider
Hazards of static electricity	◯	◯	◯	◯
Area classification, e.g. w,r,t, ATEX	◯	◯	◯	◯
Fire protection	◯	◯	◯	◯

Are there any other areas where you think that there is a need for additional education? *

Please choose **only one** of the following:

◯ Yes
◯ No

Which areas? *

Only answer this question if the following conditions are met:
Answer was 'Yes' at question '5 [WPLP04.02]' (Are there any other areas where you think that there is a need for additional education?)

Please write your answer here:

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Fig. A.6. Survey questionnaire page 6.

What gaps do you see in the present methods by which engineers gain their knowledge of safety?

Please write your answer here:

Your work

This group of questions are about your job and the degrees, which prepared you for the job

Fig. A.7. Survey questionnaire page 7.

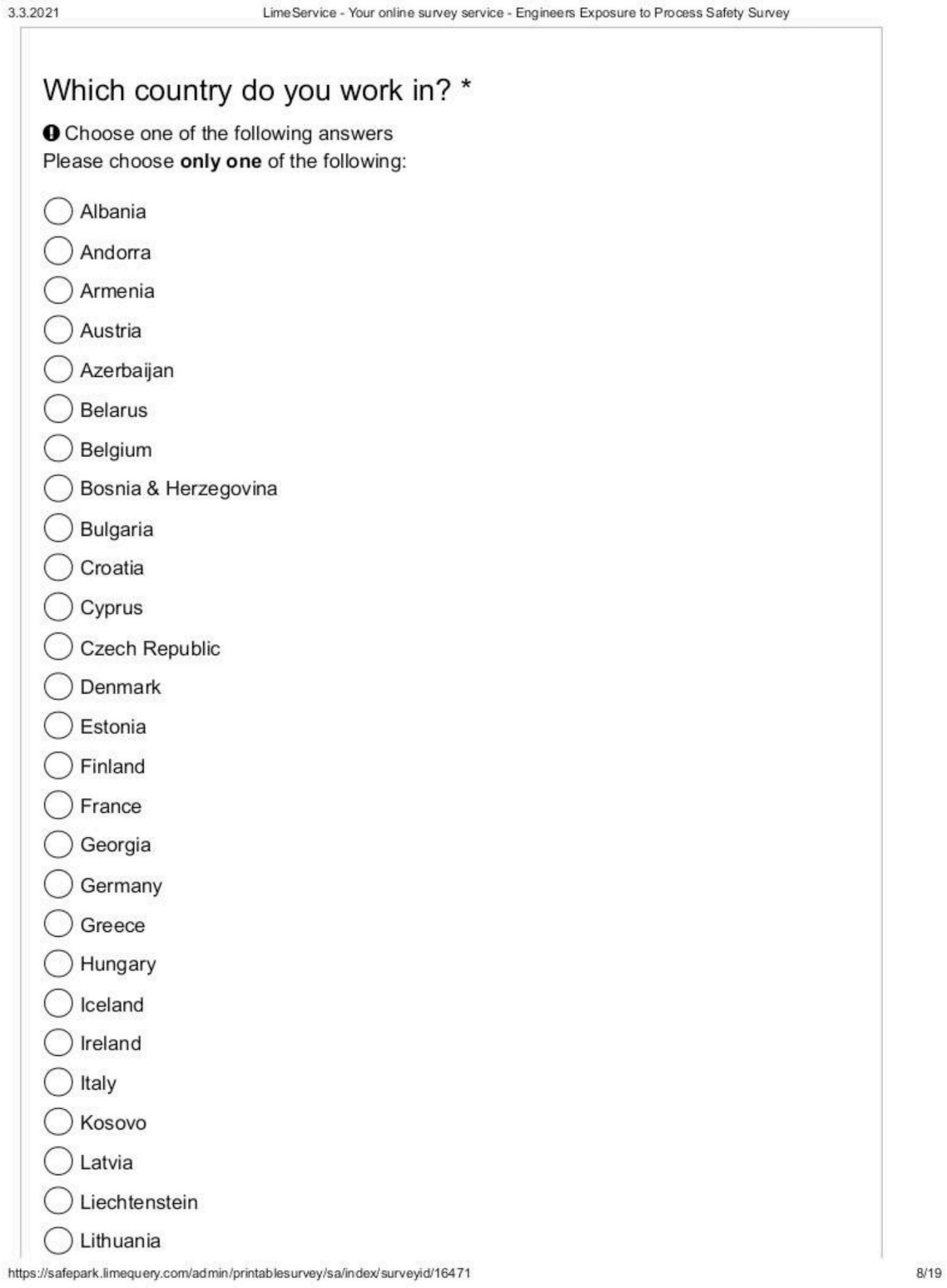


Fig. A.8. Survey questionnaire page 8.

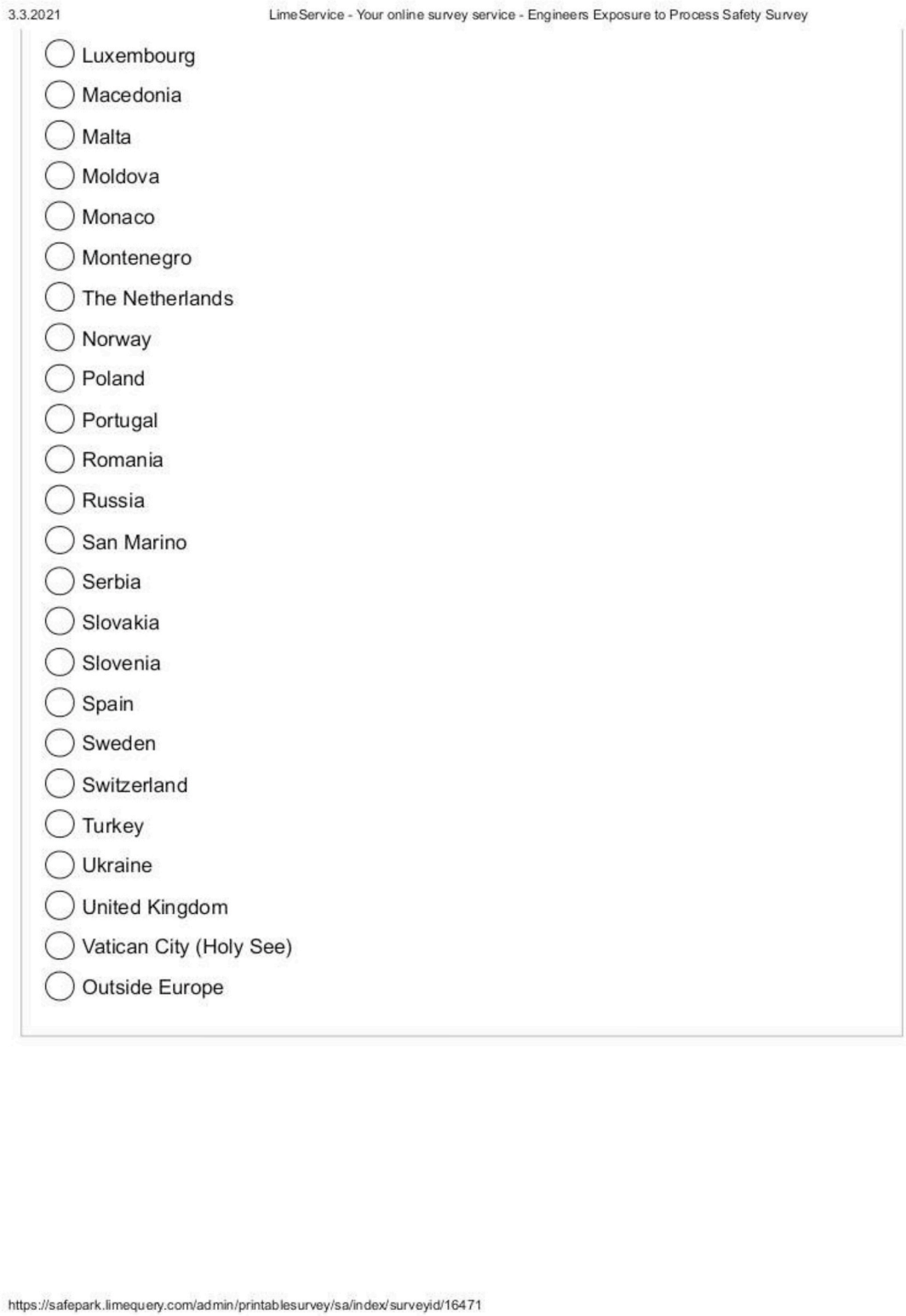


Fig. A.9. Survey questionnaire page 9.

What is your job title? *

Please write your answer here:

What is your current area of work within the organisation you are part of? *

Check all that apply
Please choose **all** that apply:

- [ ] Plant Design
- [ ] Plant Operation
- [ ] Safety
- [ ] Inspection
- [ ] Consulting
- [ ] Business
- [ ] Research
- [ ] Higher Education
- [ ] Other:

Please check all relevant areas, which are a significant part of your work.

What year did you graduate from university with your first engineering degree?

Your answer must be between 1900 and 2020
Only an integer value may be entered in this field.
Please write your answer here:

The first degree may be either a batchelor degree or a master degree.

Fig. A.10. Survey questionnaire page 10.

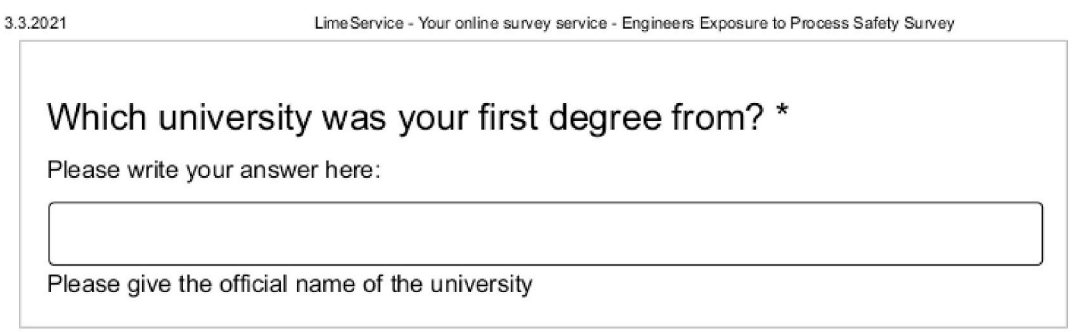


Fig. A.11. Survey questionnaire page 11.

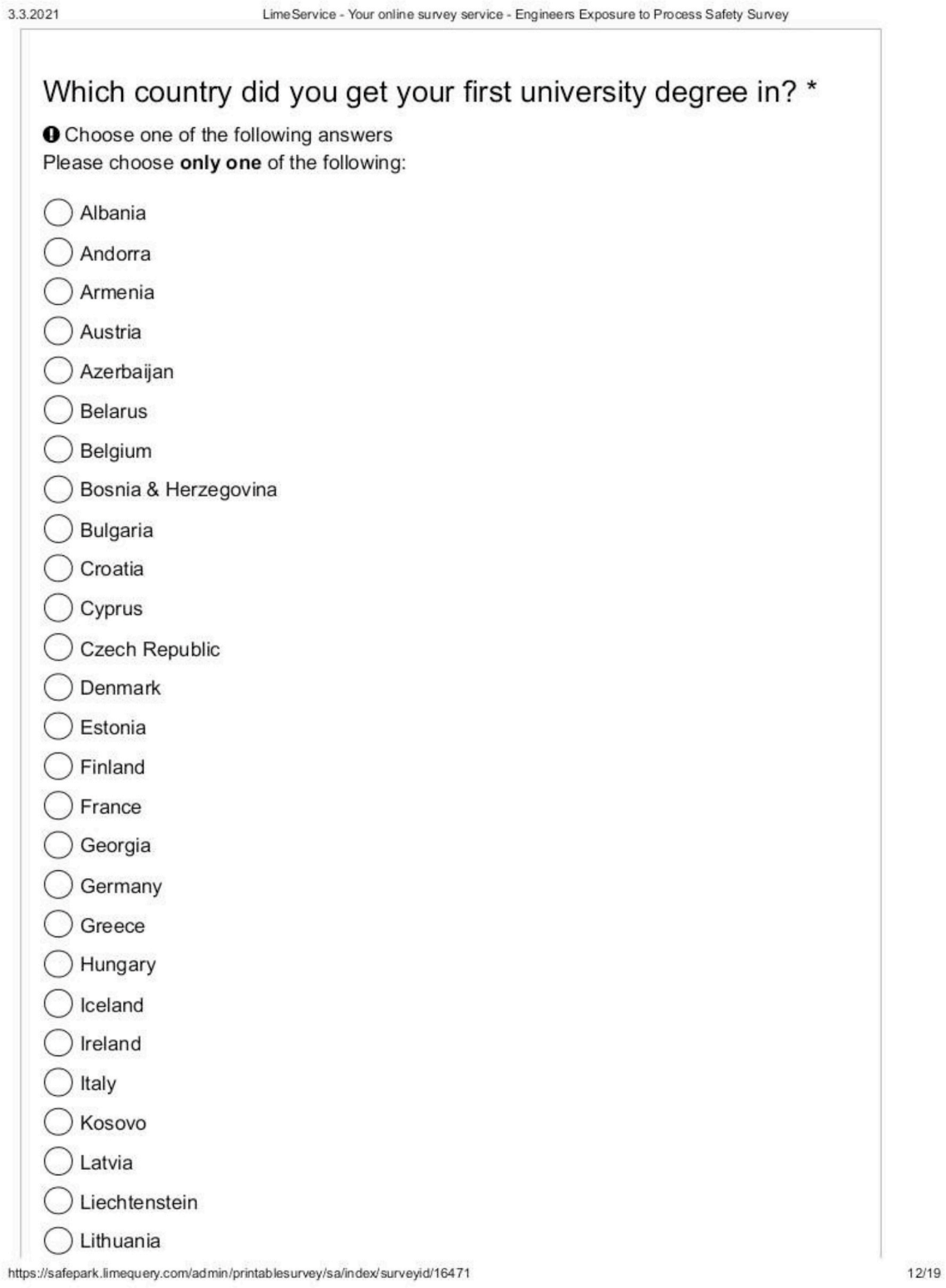


Fig. A.12. Survey questionnaire page 12.

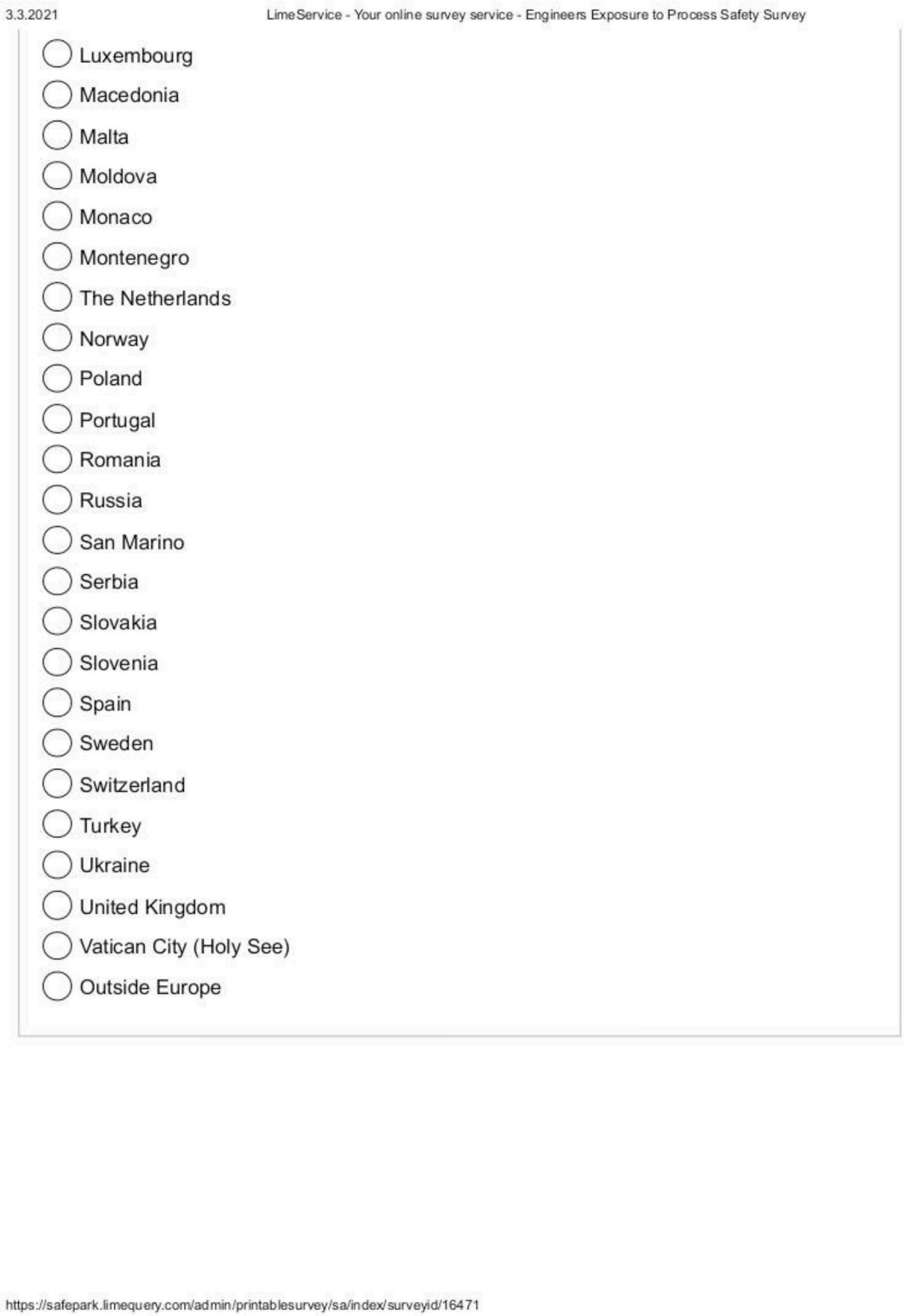


Fig. A.13. Survey questionnaire page 13.

Do you have a postgraduate degree? *

Please choose **only one** of the following:

◯ Yes

◯ No

A postgraduate degree can be a master degree or a doctorate degree (Ph.D.)

Which year did you get your highest graduate engineering degree? *

Only answer this question if the following conditions are met:
Answer was 'Yes' at question '14 [WPLP01.10]' (Do you have a postgraduate degree?)

❗ Your answer must be between 1900 and 2020
❗ Only an integer value may be entered in this field.
Please write your answer here:

Which university did you get your highest engineering degree from?

Only answer this question if the following conditions are met:
Answer was 'Yes' at question '14 [WPLP01.10]' (Do you have a postgraduate degree?)

Please write your answer here:

Fig. A.14. Survey questionnaire page 14.



Fig. A.15. Survey questionnaire page 15.

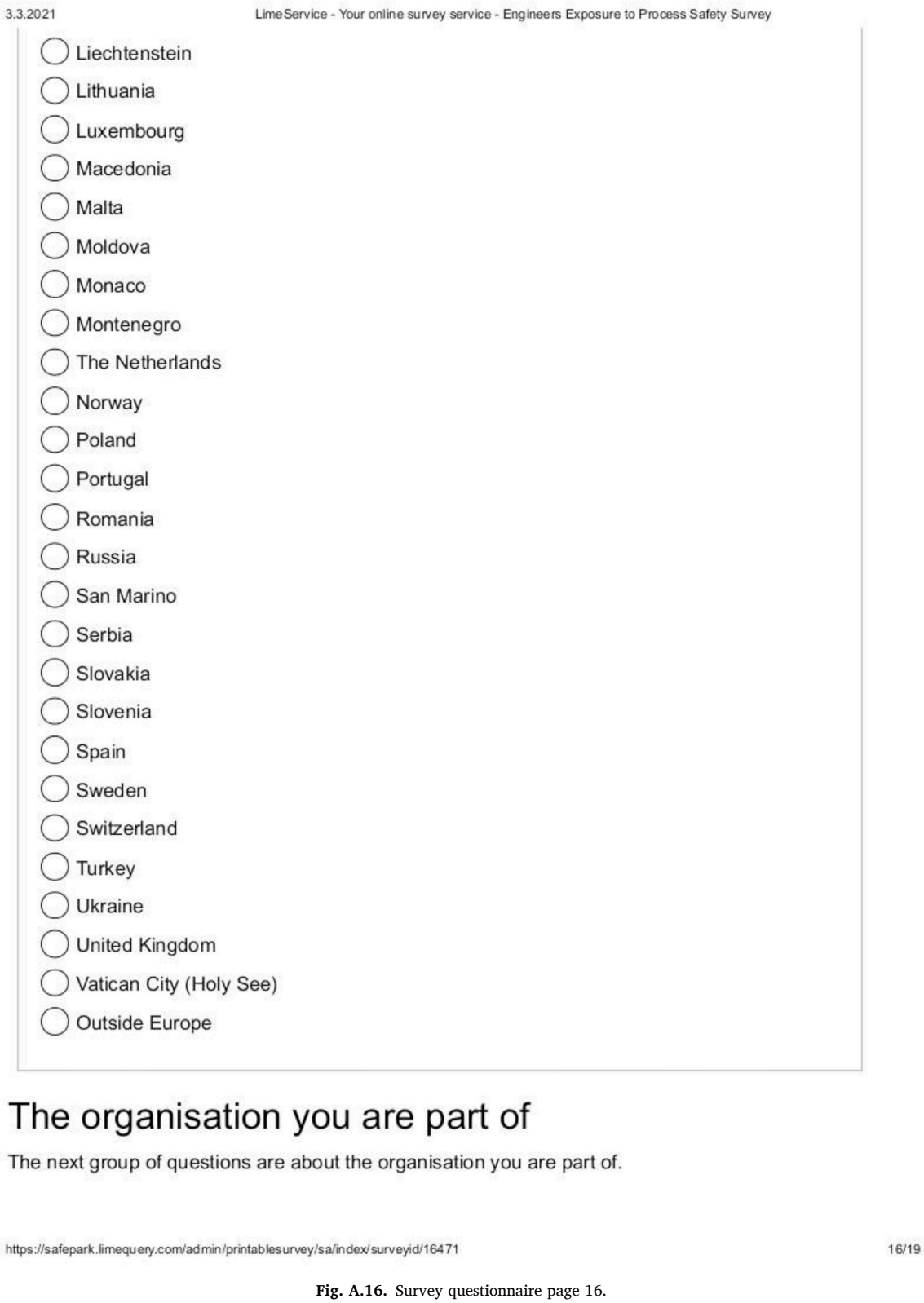
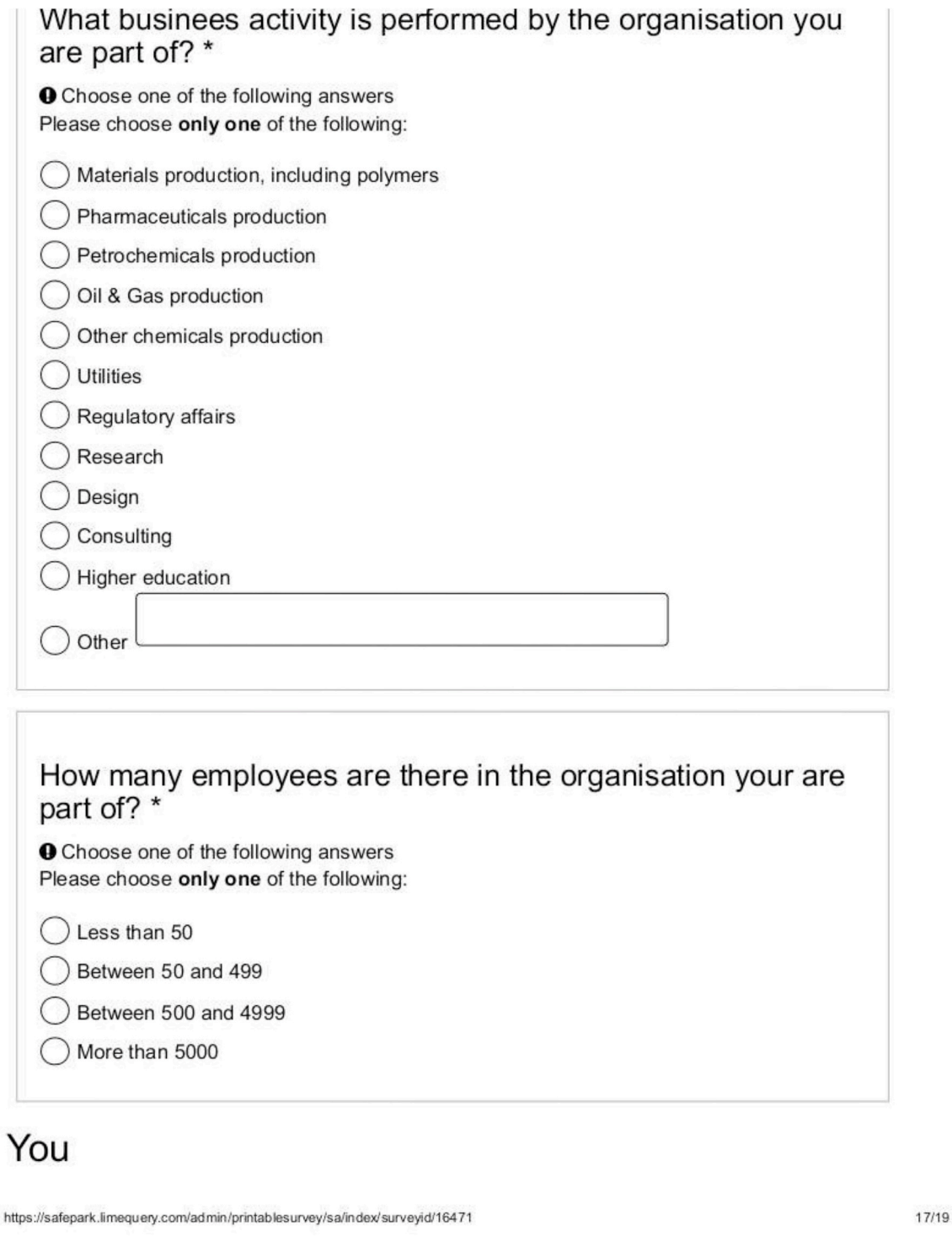


Fig. A.16. Survey questionnaire page 16.



What businees activity is performed by the organisation you are part of? *

Choose one of the following answers
Please choose **only one** of the following:

- ◯ Materials production, including polymers
- ◯ Pharmaceuticals production
- ◯ Petrochemicals production
- ◯ Oil & Gas production
- ◯ Other chemicals production
- ◯ Utilities
- ◯ Regulatory affairs
- ◯ Research
- ◯ Design
- ◯ Consulting
- ◯ Higher education
- ◯ Other

How many employees are there in the organisation your are part of? *

Choose one of the following answers
Please choose **only one** of the following:

- ◯ Less than 50
- ◯ Between 50 and 499
- ◯ Between 500 and 4999
- ◯ More than 5000

You

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Fig. A.17. Survey questionnaire page 17.

This group of questions are about you.

Are you a member of a professional society? *

Please choose **only one** of the following:

◯ Yes

◯ No

By professional society is ment organisations such as Institution of Chemical Engineers (IChemE) in the UK, Society of Danish Engineers (IDA) in Denmark, The Associaton of German Engineers (VDI) in Germany, French Society of Process Engineers (SFEP) in France to mention just a few.

Which professional society are you a member of? *

Only answer this question if the following conditions are met:
Answer was 'Yes' at question '20 [WPLP01.03]' (Are you a member of a professional society?)

Please write your answer here:

Please give the name of the professional society you are a member of.

If this society has different levels of membership please state your current level of membership. *

Only answer this question if the following conditions are met:
Answer was 'Yes' at question '20 [WPLP01.03]' (Are you a member of a professional society?)

Please write your answer here:

Fig. A.18. Survey questionnaire page 18.

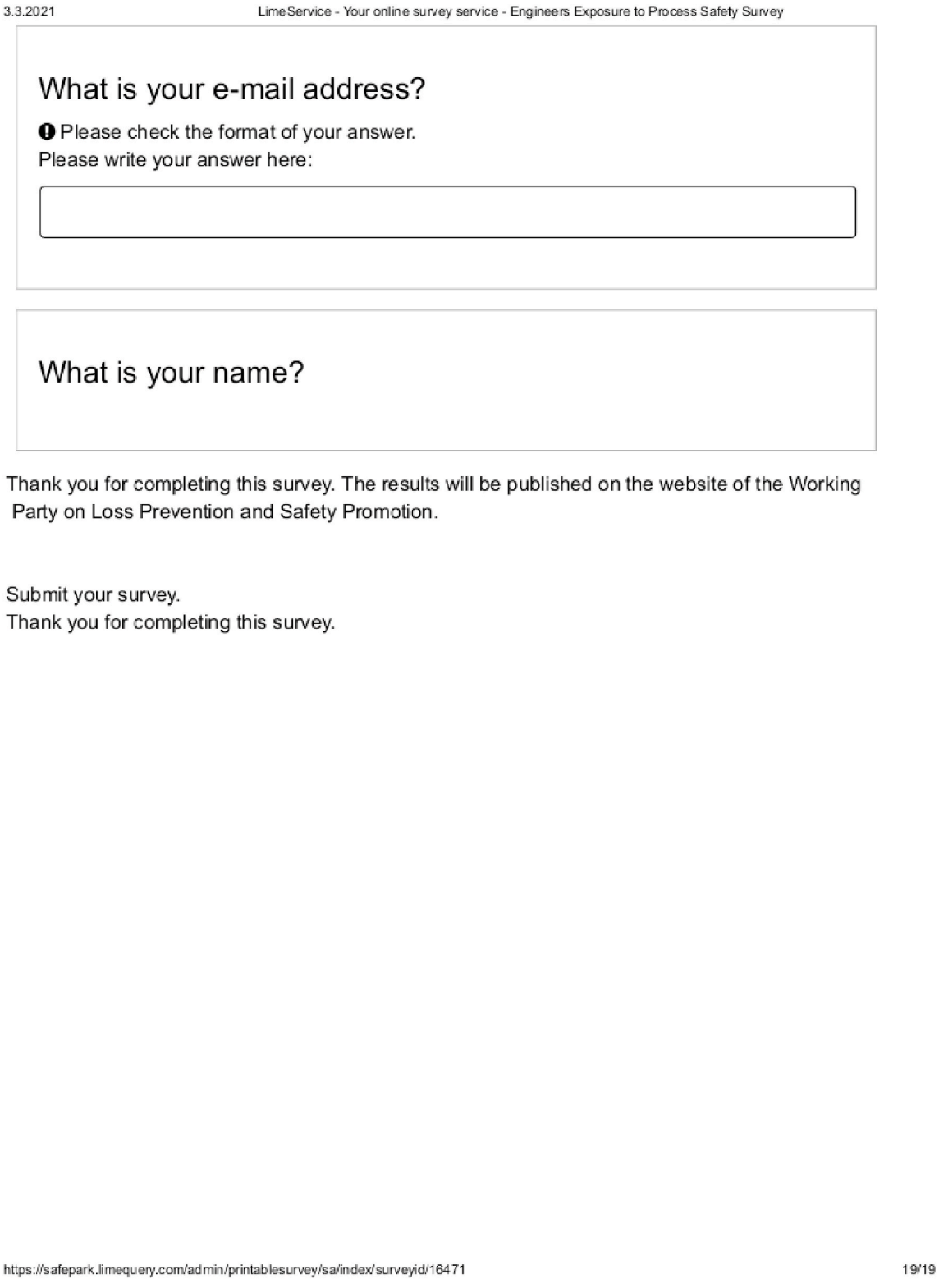


Fig. A.19. Survey questionnaire page 19.

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Glossary

ABET: Accreditation Board for Engineering and Technology
AEAC: Australian Engineering Accreditation Centre
AI: Artificial Intelligence
CEAB: Canadian Engineering Accreditation Board
CEO: Chief Executive Officer
CLP: Classification Labelling and Packaging regulation
CPD: Continuous Professional Development
DECHEMA: Deutsche Gesellschaft für CHemische Apparatewesen
EFCE: European Federation of Chemical Engineering
ETA: Event Tree Analysis
FMEA: Failure Mode and Effect Analysis
FTA: Fault Tree Analysis
HAZOP: Hazard And Operability Analysis IChem Institution of Chemical Engineers IIoT Industrial Internet of Things IoT Internet of Things
IT: Information technology
OECD: Organization for Economic Cooperation and Development
OJT: On the Job Training PPE Personal Protective Equipment
RFID: Radio Frequency IDentification SMS Safety management System