Nuclear Engineering and Design 415 (2023) 112734

Contents lists available at ScienceDirect

Nuclear Engineering and Design

journal homepage: www.elsevier.com/locate/nucengdes

Know-why? and know-how? in the development of nuclear talents: An analysis of recent nuclear engineering Ph. D. research

Leon Cizelj *, Ivo Kljenak, Iztok Tiselj

Jožef Stefan Institute, Reactor Engineering Division, Jamova cesta 39, 1000 Ljubljana, Slovenia
University of Ljubljana, Faculty of Mathematics and Physics, Jadranska ulica 19, 1000 Ljubljana, Slovenia

ARTICLE INFO

Keywords:
Education
Training
Basic research
Applied research
Conceptual knowledge
Procedural knowledge
Nuclear engineering
Careers of nuclear graduates

ABSTRACT

The relationship between the industry and academia is widely considered the key driver or obstacle in producing and using new knowledge. This is, at least in part, a consequence of different forms of knowledge being of different utility for the industry and academia (conceptual, e.g., why? and procedural, e.g., how?). In so-called "high-tech" industries, where the attraction and development of new talents are in significant part carried out through academic research-based higher education system, successful cooperation in the development of new knowledge automatically results in successful attraction and development of new talents. In well-established, strongly regulated, and very procedural industries, such as nuclear power, the pragmatic focus on procedural over conceptual knowledge may also result in the pathways of talent development outside of the research-based higher education system. Some definitions, features, and risks of different approaches to conceptual and procedural knowledge are outlined and discussed in the paper and an attempt is made to connect them with the notions of basic and applied research. It is suggested that suitable sequences and balance of know-why? and know-how? may lead to the best results in the attraction and development of new nuclear talents, while minimizing the risks of reduced ability to manage unexpected, reduced need for innovation and weakening the nuclear knowledge centers outside of the industry and regulators. This is supported by an analysis of 51 Ph.D. theses in nuclear engineering developed in Slovenia since 1993 to discern their contributions towards basic or applied research. The Pasteur's quadrant, developed by (Stokes, 1997), was used as the underlying framework. Ph.D. graduates and supervisors were independently asked to evaluate the basic and applied contributions through three variables, describing the stages of the creative research process: input, processing, and output, respectively. The predominantly mixed (basic and applied) contributions of the analyzed Ph.D. theses indicate that academic nuclear engineering education is an enabler of successful careers in academia and industry.

1. Introduction

The relationship between industry and academia in the development and use of new knowledge has received significant attention by researchers in both academic and industrial environments. One of the main challenges appears to be linked to the theory–practice divide, which only partially addresses the heterogenous nature of the new knowledge produced (Crespin-Mazet and Ingemansson-Havenvid, 2020). One may relate the heterogeneous nature of the knowledge to different forms of research, namely basic/fundamental research, and applied/practical research. While applied/practical research appears to be well suited for the industry, (Bentley et al., 2015) suggest strong presence of basic research in universities. Further, (Bentley et al., 2015) note that at the individual level, most academics engage in a combination of basic and applied research. Those specializing in basic research tend to receive less external funding and hold weaker professional obligations to apply their knowledge to the problems in society.

The coexistence of the basic and applied research has been also noted by (Stokes, 1997), who proposed to visualize it in a two-dimensional space with the "Quest for fundamental understanding" spanning the abscissa and the "considerations of use" the ordinate (Fig. 2, Section 3). It is Pasteur's quadrant, which accounts for the use inspired basic research and was used by Stokes as the title of his book (Stokes, 1997).

A vivid illustration of the existing tensions between basic and applied academic researchers was suggested by (Evans, 2010), noting that "industry partnerships draw high-status academics away from confirming

* Corresponding author at: Jožef Stefan Institute, Jamova cesta 39, 1000 Ljubljana, Slovenia.
E-mail address: Leon.Cizelj@ijs.si (L. Cizelj).

https://doi.org/10.1016/j.nucengdes.2023.112734
Received 12 September 2023; Received in revised form 31 October 2023; Accepted 1 November 2023
Available online 6 November 2023

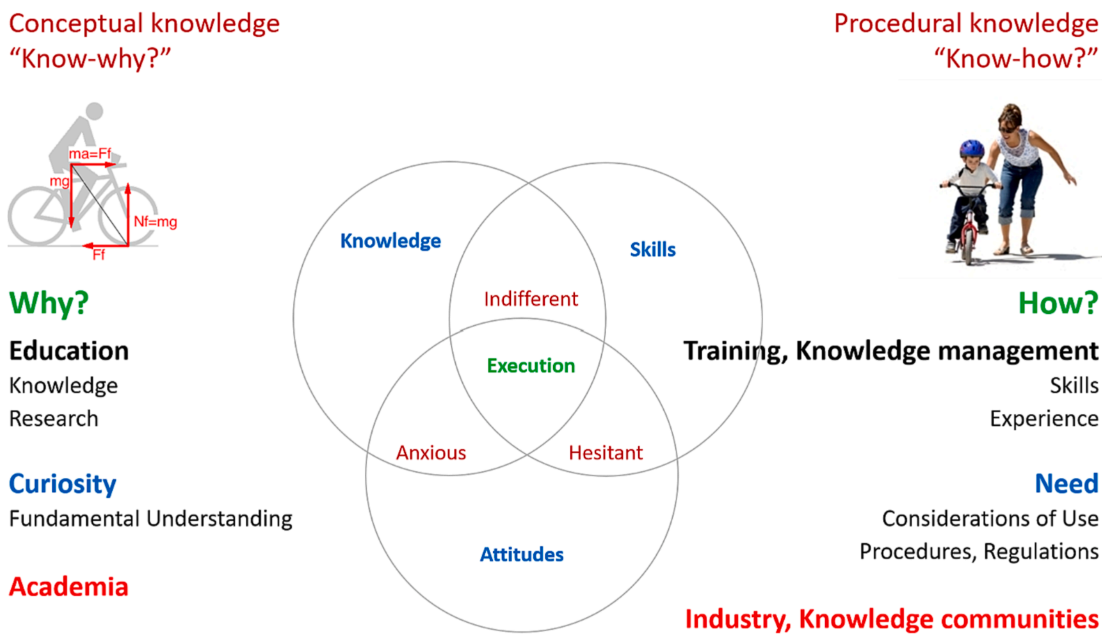

Fig. 1. Main features of the "know-why?" and "know-how?". ().
Adapted from Cizelj, 2019

theories and toward speculation". (Tijssen, 2010), for example, derived a comprehensive system for the classification of scholarly journals according to their "application orientation". Further, (Crespin-Mazet and Ingemansson-Havenvid, 2020) suggest that "academia-industry collaboration may be a useful but also an insufficient platform for academic and managerial theorizing". Long-term and interactive relationships involving third parties (e.g., regulators and civil society) appear to be necessary to develop mutual trust and successful cooperation in an inherently unpredictable research environment.

A strong connection between the research activities in the academia and attraction and development of new talents is intuitively obvious. The existing tensions between academia and industry along the theory–practice divide may therefore also strongly influence the attraction and development of new talents. (Leshner, 2015), for example, suggested rethinking the graduate education to better prepare the students for the non-academic or industrial careers. (Chung, 2006) proposed a "four-season" model, which connects the attraction and development of the nuclear workforce to the stages of the maturity of the nuclear industry and research. Spring (in USA 1940–1950) was enabled through strong (basic and applied) research activities. Summer (in USA 1960–1980) followed by fast industrialization, reaching Autumn (1980) and saturation both in construction of new plants and in recruitment. The first signs of the decline in nuclear research and education activities noted in autumn then started to be fully developed in the Winter (1990–2000), as documented for example in (OECD/NEA, 2000). Indeed, the EU R&D Scoreboard (Grassano et al., 2022) monitoring industrial R&D in high-tech industries notes rather modest R&D investments in the Energy sector and does not mention Nuclear energy. In other words, the industrial R&D investments in nuclear energy appear to be below the resolution of the official statistics.

In this paper, we are discussing some conceivable connections between the basic and applied research on one side and different forms of knowledge, in particular conceptual knowledge (i.e., knowing why) and procedural knowledge (i.e., knowing how) (Cheung, 2021), on the other side. Some potential risks of inadequate balance between the know-why? and know-how? in the academia and industry are also discussed. An analysis of 51 Ph.D. theses in nuclear engineering completed in Slovenia since 1993 follows to discern their contributions towards basic or applied research, and, to some extent, the potential of graduates to pursue careers in research or academia. The Pasteur's quadrant, developed by (Stokes, 1997), is used as the underlying framework. The analysis by (Kljenak et al., 2020), reviewing 26 Slovenian doctoral theses in some nuclear engineering fields to correlate them with the career choices of the graduates, is expanded and refined by asking Ph.D. graduates and supervisors to independently evaluate the basic and applied contributions through three variables, describing the stages of the creative research process: input, processing, and output, respectively.

2. Know-why and know-how

Competent people are at the core of the successful utilization of high technologies, including nuclear power. (IAEA, 2022) defines competence as the ability to apply skills, knowledge and attitudes in order to perform an activity or a job to a specified level in an effective and efficient manner. Competence may be developed through education, experience and formal vocational training.

The crucial distinctions between education and training are well known and well discussed in the literature. An interesting and very clear perspective was offered by (Higley, 2017) for the case of health physics: individuals trained in health physics can safely manage daily operations under routine conditions. But academically educated individuals are much more successful in dealing with many unexpected events. Very similar observation is offered also by (Cheung, 2021), who also relates different forms of knowledge, in particular conceptual (i.e., knowing why) and procedural knowledge (i.e., knowing how) with academic education, vocational training and the (dis)ability of trainees to generalize the procedural knowledge towards the solution of challenges, that differ from those mastered during the trainings.

For the purpose of this paper it may be therefore useful to distinguish the "know-why?" and "know-how?", as depicted in Fig. 1:

- "know-why?" is closely related with conceptual knowledge, academic education and research. It is mostly driven by curiosity or, in the words of (Stokes, 1997), the quest for fundamental understanding.
- "know-how?" is closely related with procedural knowledge, including procedures and regulations, training, knowledge

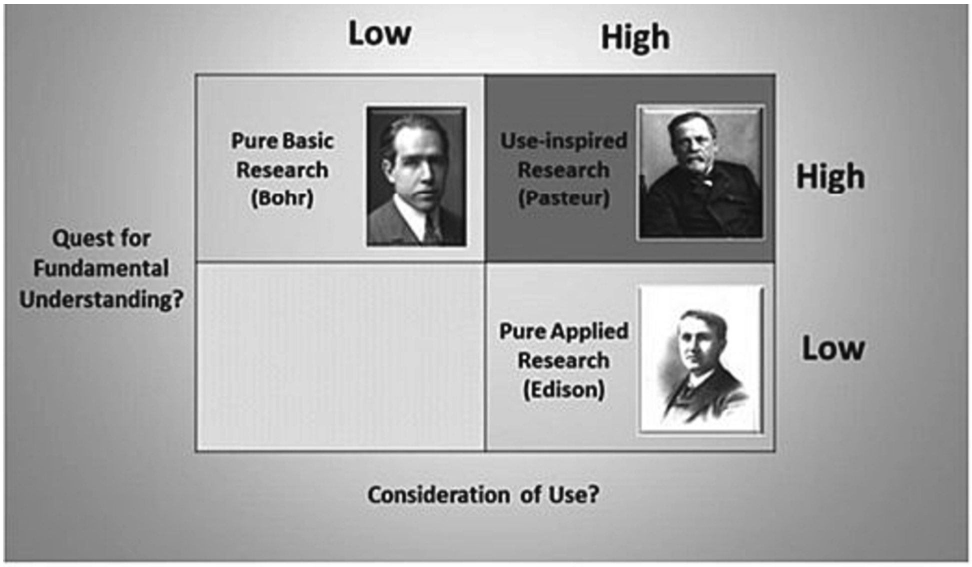

Fig. 2. Research Quadrants (().
Adapted from Stokes, 1997

management and practical (industrial) uses. It is mainly driven by the need or, in the words of (Stokes, 1997), by the considerations of use.

The Venn diagram in Fig. 1 indicates that proper balance of knowledge, skills and attitudes leads to successful execution, as anticipated in the definition of competences (IAEA, 2022). Also, an indication of potential immediate consequences of the imbalance in knowledge, skills and attitudes is offered: Knowledge with skills without attitudes may result in indifference, skills with attitudes without knowledge in hesitance, and knowledge with attitudes without skills in anxiousness.

So-called "high-tech" industry, including nuclear, depends on people with very diverse degrees and specialties of education and training. The quest for efficiency, stimulated in part by decades of declining nuclear education (OECD/NEA, 2000), the pressures by competition and evolving regulations, to mention a few, might steer the industry towards more internal training, directed naturally much more towards "know-how?" than "know-why?". An important driver towards such developments may also be the fact that the highly safe industries (e.g., nuclear power and aviation) strongly rely on "know-how?" documented in considerable details in operating procedures and regulations. As noted vividly by (Sanchez-Alarcos, 2020): "In some ways, the safest way to avoid human manual error is to »handcuff« the operator, but at the same time, that operator will be unable to solve the problem when required. Handcuffs can be physical, such as programming the plane to disobey the pilot because someone decided that the sensors of the plane would know better, or cognitive, providing operating know-how instead of know-why.".

In the short term, the prevalence of the "know-how?" approach may appear to increase the efficiency and the safety record of the industry. In the medium and longer term, however, the prevalence of the "know-how?" acquired in mostly proprietary in-house trainings may contribute to some important risks, which might develop gradually and intensify with time as a surprise to the community. These potential risks include:

- Reduced ability to manage the unexpected situations, namely the "unknown-unknowns". For further discussion see for example (Higley, 2017), (Cheung, 2021) and (Saito, 2016).
- Reduced potential and/or need for innovation. This is usually followed by the loss of competitiveness, especially against other competing technologies, and the loss of interest of young creative talents. This suggestion is to some extent supported by the fact that the R&D investments of nuclear industry are not reported among the energy industry investments in R&D (Grassano et al., 2022). Also, it might offer a plausible explanation for the persistent diffusion of nuclear experts from EU-based nuclear utilities to other service providers in the period 2010–2018 (Eriksen et al., 2019).
- Perception of high expertise and low credibility of the nuclear industry in the public (Turcanu et al., 2018). Preferential internal and proprietary training could namely, as collateral damage, further disable the interest for and performance of the publicly available nuclear higher education. After a decade of two of such developments, one might notice an absence of nuclear expertise outside of the industry and the regulator, which may seriously degrade the public perceptions on the safety, reliability and credibility of all nuclear facilities. Further, as noted by (Saito, 2016) and (Uršič et al., 2021), this may also degrade the competence in organizational levels of defense in depth outside the nuclear industry, namely in the regulatory bodies, technical support organizations and last, but not least, in the last level of defense: public at large, including academia.

It clearly follows that successful development of talents requires suitable sequences and a balance of know-why? and know-how?. In other words, it is coherent to deliver the conceptual knowledge in dedicated academic education before the professional training towards mastering the procedural knowledge related to specific technology. Vivid and well-known illustrations of this principle include "We were trading the rules for common sense" (Semler, 2001) and "If we have our own why in life, we shall get along with almost any how." (Nietsche and Large, 1998).

A well-designed and well-balanced combination of academic education (know-why?) and industrial training (know-how?) is therefore considered one of the essential building blocks of any future nuclear talent attraction and development scheme.

3. Pasteur's quadrant

(Stokes, 1997) argued that basic and applied research coexist. In essence, the drivers of research define the basic or applied value of the results obtained much more than for example the topics or methods. Following this reasoning, Stokes proposed to visualize the coexistence of the basic and applied research in a two-dimensional space with the

Table 1
Variables and questions for the »Consideration of use«. All three variables are weighted equally.

Input: Nature of the problem	
Which of the answers below most closely describes the nature of the problem investigated in the Ph. D. Thesis)?	
1	Totally theoretical
2	More theoretical than practical
3	Balanced between theoretical and practical
4	More practical than theoretical
5	Totally practical
Process: Nature of the performed research	
Which of the answers below most closely describes the nature of the research performed to complete the Ph.D. Thesis?	
1	Pure basic research without aiming for immediate economic and/or social benefits or for solutions to the practical problems
2	Basic research aiming at knowledge construction for use in an undefined future
3	Basic research aiming at knowledge construction for use in the near future
4	Applied research to solve problems defined in the present
5	Development to obtain new products, processes etc. or their improvement in the present
Output: Perspective of immediate use	
Which of the answers below most closely describes the perspectives of immediate use of results of the Ph.D. Thesis?	
1	Theoretical foundations for other theoretical studies
2	Theoretical foundations for other theoretical and experimental studies
3	Incorporation in technologies on the laboratory scale
4	Incorporation in technologies on a pilot scale
5	Incorporation in technologies for commercial use

Table 2
Variables and questions for the »Fundamental understanding«. All three variables are weighted equally.

Input: Knowledge requisites	
Which of the answers below most closely describes the knowledge requisites required to initiate the research in the Ph. D. Thesis?	
1	No theoretical and in-depth knowledge in many knowledge areas
2	Limited theoretical and good practical knowledge in few areas
3	Limited theoretical and practical knowledge in some specific knowledge areas
4	Good theoretical and practical knowledge in some specific knowledge areas
5	Profound theoretical-practical knowledge in a specific area
Process: Knowledge generation process	
Which of the answers below most closely describes the knowledge generation process utilized to complete the Ph.D. Thesis?	
1	Experimentation and aggregation of new knowledge to a broader knowledge base as the initial research problem
2	Experimentation and aggregation of existing knowledge to the same knowledge base as the initial research problem
3	Integration and/or classification and/or systemization of existing knowledge
4	Deepening the existing understanding and knowledge on the wider knowledge base than the initial research problem
5	Deepening the existing understanding and knowledge on the same knowledge base as the initial research problem
Output: Knowledge progress	
Which of the answers below most closely describes the contribution(s) of the Ph. D. Thesis?	
1	Extraordinary technological advancement (e.g., change in the quality of life)
2	Significant technological advancement (e.g., publications in the upper half of the SCI journals, international patents)
3	Moderate scientific and/or technological advancement (e.g., international or national patents)
4	Significant scientific advancement (e.g., publication in the upper half of the SCI journals)
5	Extraordinary scientific advancement (e.g., publications in top journals, for example Nature)

"Quest for fundamental understanding" spanning the abscissa and the "Considerations of use" the ordinate (Fig. 2). Three quadrants appeared in this visualization scheme: the top left quadrant is dedicated to the pure basic research and is named after Bohr. The bottom right quadrant is dedicated to applied research and is named after Edison. The upper right quadrant accounts for the use-inspired basic research and is named after Pasteur. The Pasteur's quadrant was used by Stokes also as the title of the book (Stokes, 1997). Namely, Luis Pasteur made a purely basic discovery of the microorganisms while on a practical mission to improve the brewing process. Further, Niels Bohr pursued basic research without any considerations of use. Finally, Thomas Alva Edison was known for his passion for application without the need for deeper understanding of the causes.

The concept of Pasteur's quadrant has not yet been widely accepted by the research funding agencies worldwide. It has however already been reported as a successful framework to analyze scientists who have committed themselves to the collaboration between academia and industry (Yasuda, 2011). Furthermore, a Brazilian research group active in nuclear energy has already implemented Pasteur's quadrant to assess the basic and applied dimensions of a set of Ph. D. theses (Hoppe de Sousa et al., 2009).

3.1. The method

The question that we would like to answer, at least in part in some quantitative manner, is whether the contemporary graduate education in nuclear engineering at the Ph. D. level enables graduates to embark a career in academia, industry or regulatory/government agency. The first step in this analysis is the quantification of the basic and/or applied nature of the research attempted in the Ph.D. thesis.

The method implemented in this paper is based on (Hoppe de Sousa et al., 2009), who have put in practice the Pasteur's quadrant assessment of the Brazilian Ph. D. theses in nuclear energy. The method is, for the sake of completeness, briefly outlined below. Please note that some minor adaptations, mainly in the wording of questions and predefined answers (Table 1, Table 2), have been developed for the purpose of this analysis.

(Hoppe de Sousa et al., 2009) broke down each of the axes in Fig. 2 in three separate variables, describing the three stages of the creative research process: input, processing and output, respectively. These variables were then evaluated through questionnaires with predefined answers. Each of the answers assumed an integer value, as outlined in Table 1 for the Consideration of use and Table 2 for the Fundamental understanding.

The values of the two sets of three variables are therefore defined by the person answering the questionnaire. Those are summed up (with equal weights) resulting in a point in the two-dimensional space limited by (1, 1) and (15, 15). Equal spacing has been chosen for the quadrants. The Pasteur's quadrant amplifying both "considerations of use" and "fundamental understanding" is therefore limited by the points (8, 8) and (15, 15).

Students and supervisors have been asked to evaluate each of the dissertations independently relatively soon (e.g., with the delay of up to about three years) after the successful defense of the thesis.

3.2. The data

Fifty-tree (53) Ph. D. theses have been completed between 1993 and 2023 in the Nuclear Engineering program jointly operated by the Faculty of Mathematics and Physics of the University of Ljubljana, Slovenia, and Jožef Stefan Institute. Twenty-one (21) supervisors participated in this process.

For 51 theses, both the student and the supervisor answered the questionnaire (Table 1 and Table 2, respectively) independently of each other. These 51 theses have been further analyzed in this paper. Timeline of these Ph. D. theses, with about 2 completed theses per year in average, is depicted in Fig. 3.

Twenty (20) supervisors answered the questionnaire. Seven (7) of them supervised 1 thesis, 7 supervised 2 theses, 2 supervised 3 and 5 theses, respectively, and 1 supervised 4 and 10 theses, respectively.

Twenty-six (26) Ph. D. theses (out of the 51 with answers by both supervisor and students) were evaluated previously predominantly by expert opinion of (Kljenak et al., 2020) as basic (13 theses), application oriented basic (11 theses) and applied (2 theses). The authors of this

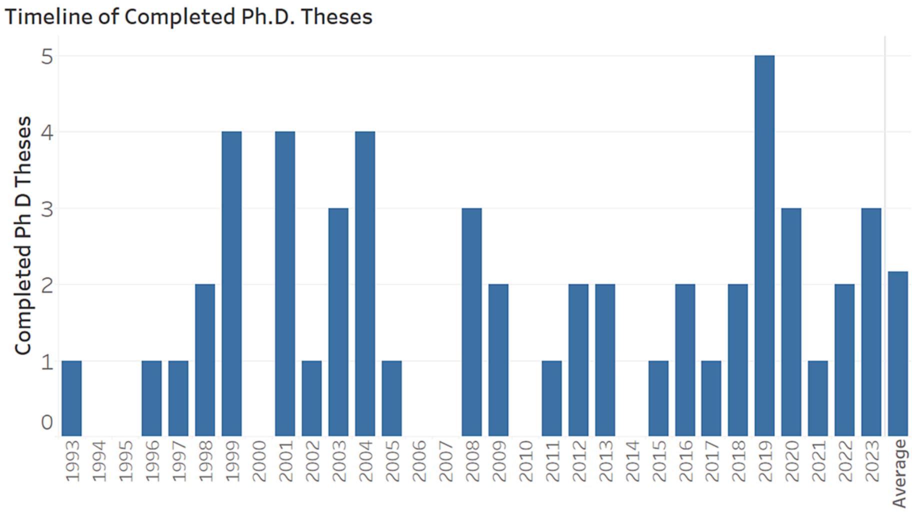

Fig. 3. Timeline of completed Ph.D. theses (average just over 2 per year).

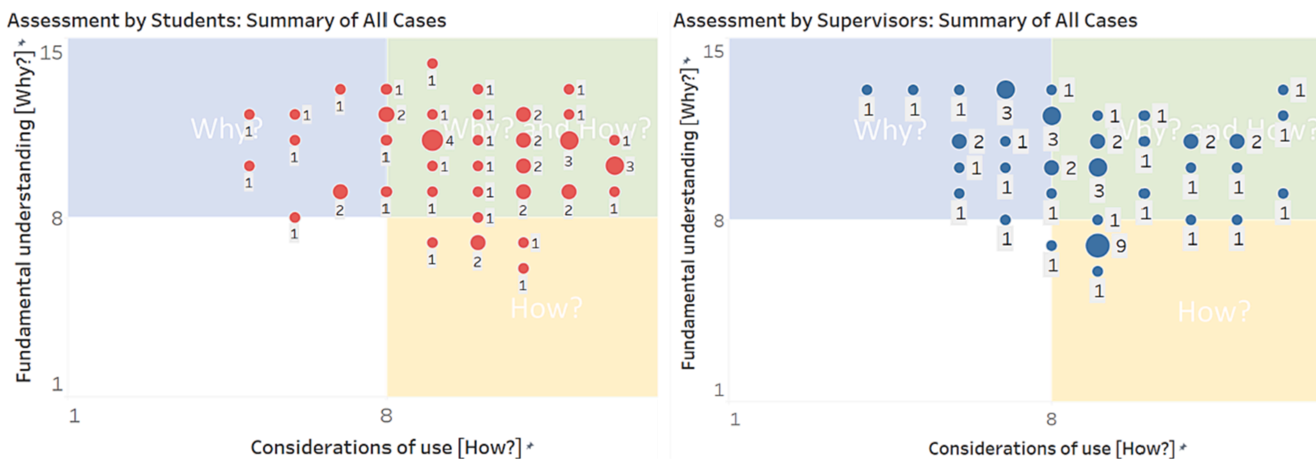

Fig. 4. Summary assessments by students (left) and supervisors (right). All 51 data points. Numbers at and size of points indicate the number of dissertations with equal coordinates.

evaluation are among the 20 supervisors, who also participated in the analysis for this paper: they did supervise 20 out of the 26 evaluated theses.

Out of the 51 Ph.D. graduates, 31 pursued careers predominantly in academia, 17 in industry and 3 in the regulatory or other government agencies.

3.3. Results

The 51 data points are deemed not sufficient for a valid statistical analysis. Nevertheless, valuable insights may be deducted also from such a small sample through visualizations and quantitative assessment, as outlined below.

The assessments (answers) obtained from the students and supervisors are summarized in Fig. 4. The students placed most of their dissertations (38) into the Pasteur's (Why? And How?) quadrant with 8 dissertations in the Bohr's (Why?) and 5 in the Edison's (How?) quadrant. The points at the border between quadrants are accounted in the Why? and How? quadrant. The assessment by supervisors puts the majority of 27 dissertations in Pasteur's quadrant with 13 and 11 placed into Why? and How? quadrant, respectively.

The assessments by students and supervisors were obtained independently and were therefore expected to exhibit some differences. The main similarity appears to be in attributing much more than half of the dissertations to the Why? and How? (Pasteur's) quadrant and comparable shares of the remaining ones into Why? and How? quadrants, respectively. The average shift of the assessments by supervisors as compared to the students is 1.02 points (out of 15 possible) towards the Why? and 0.33 points towards the How?. Plausible reasons for this include generally better awareness of the supervisors about the expectations linked to funding sources and about the trends in their specific areas of research.

Fig. 5 relates the expert evaluations in (Kljenak et al., 2020) and the analysis developed for this paper. The expert evaluation appears to be practically independent from the more elaborate assessments by students and supervisors: the assessments by students and supervisors namely fall into all three quadrants with patterns comparable to those in Fig. 4 regardless of the evaluations by (Kljenak et al., 2020). The only exception and at the same time the best agreement could be seen in the assessment of students (row 3, left) in Fig. 5, where all dissertations evaluated as application oriented basic also fall in the Why? and How? quadrant.

It is suggested to put more trust to the more elaborate methods of assessment as the one proposed by (Hoppe de Sousa et al., 2009) that was used in the present analysis. The main reason would be in the expectation that more structured assessment, e.g., 6 specific questions, would exhibit better repeatability among different experts than one generic question. This is further supported by the fact that the 4 expert

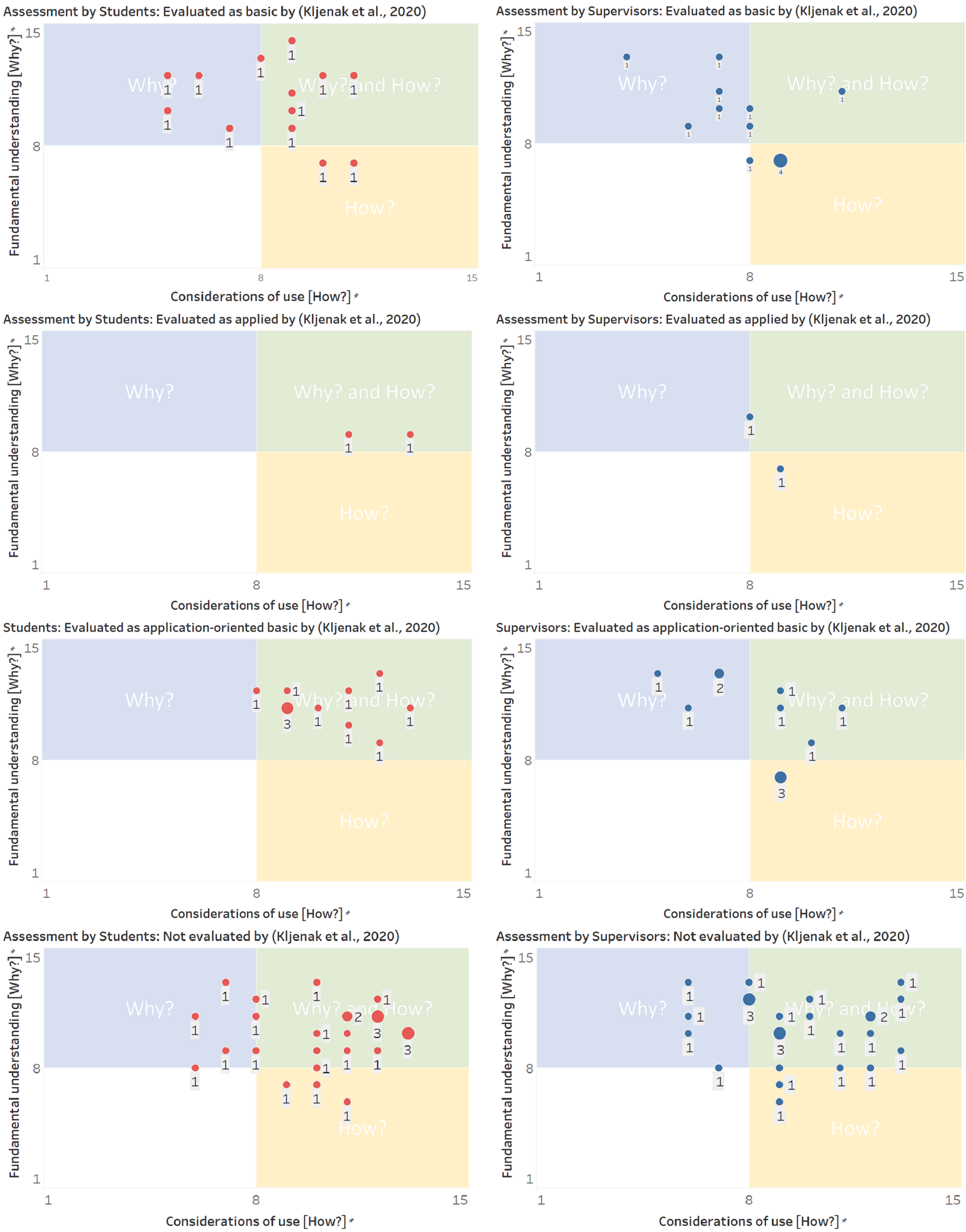

Fig. 5. Comparison with evaluations by (Kljenak et al., 2020): basic (top), applied (second row), application-oriented basic (third row) and not evaluated (bottom). Assessments by students (left) and supervisors (right). Numbers at and size of points indicate the number of dissertations with equal coordinates.

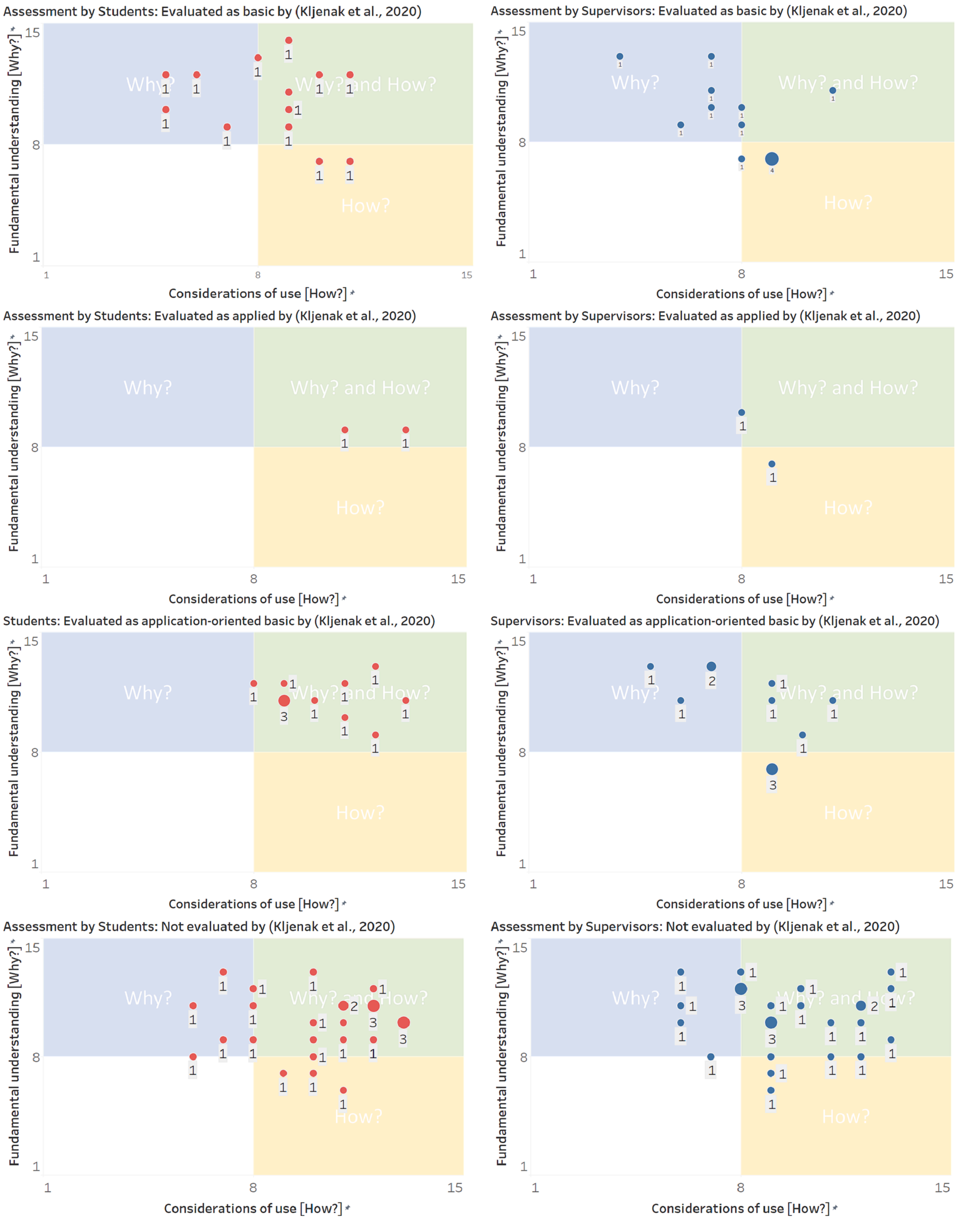

Fig. 6. Assessments by students (left) and supervisors (right) in comparison with the predominant careers of students: industry (top), academia (middle) and regulatory and government agencies (bottom) Numbers at and size of points indicate the number of dissertations with equal coordinates.

evaluators in (Kljenak et al., 2020) actually arrived at different conclusions when answering the 6 structured questions as when answering a single generic question.

The relation between the careers pursued after the graduation and the type of research in the thesis is depicted in Fig. 6. Again, the type of the these appears not to be related to the subsequent careers in industry and academia. Namely, the assessments by students and supervisors fall into all three quadrants with patterns comparable to those in Fig. 4 regardless of the career type. Only the theses of graduates with careers in the regulatory or government agencies appear to be clustered consistently in the Why? and How? (Pasteur's) quadrant as perceived by students and supervisors. Yet, with only three such cases, it may be prematurely to suggest this as a reliable observation.

No data clustering has been noted by supervisors or the year(s) of completion the Ph. D. in this analysis.

4. Discussion

The main postulate of the discussion is that diverse careers in nuclear engineering require different competences, or in other words, different blends of Know-why?, Know-how? and attitudes. There are various ways to obtain the required competences, including academic education and industrial training, to mention the most common ones. We may briefly defer the discussion on the attitudes and start with the Know-why? and Know-how?.

Potential risks of relying too much on Know-how?, or, as it matters, on industrial training, are identified and briefly discussed in Section 2. It is suggested there that suitable sequences and balance of know-why? and know-how? may lead to the best results in the attraction and development of new nuclear talents, while minimizing the risks of reduced ability to manage unexpected, reduced need for innovation and weakening the nuclear knowledge centers outside of the industry and regulators.

Such a balanced approach requires robust and durable cooperation between the academy, providing research-based academic education, and industry, being the main guardian and developer of know-how? and related trainings. With industry mostly in need of research towards (immediate) application and academia being proud of its curiosity-driven basic research, the middle ground might be given by a sensible combination of both. The analysis of the 51 Slovenian Ph.D. theses in nuclear engineering (Section 3) clearly indicates, that Ph. D. research combining elements of curiosity and need, falling mostly in or close to Pasteur's quadrant (Fig. 4) enabled graduates to embark on careers in academia, industry and regulatory agencies alike. We may therefore suggest that the current nuclear academic education system is reasonably well conceived and could be further improved through more intensive research interactions with the industry and regulatory agencies. Long-term and interactive relationships involving also third parties from international academia, industry and regulatory community, appear to be ideal to develop mutual trust and successful cooperation in an inherently unpredictable research environment. Further analysis involving more Ph.D. theses from a wider international environment may be necessary to arrive at more solid conclusions in the future.

Assuming that attitudes are in a large part formed through experience in the education, training and active (professional) life, well balanced education and training may also naturally result in well balanced attitudes. Experience of progressing through trial and error in the academic research might also be useful in the error preventing procedural safety culture environments. If it is true that "to err is human", then errors will naturally also occur in the error preventing environments. An experience in error detection and management could therefore actually enhance the attitudes towards safety culture.

5. Conclusions

The relations between the conceptual (know-why?), and procedural (know-how?) knowledge with curiosity-driven basic and need-driven applied research are discussed. Some potential risks resulting from overreliance on industrial training (know- how?) are outlined.

Graduate academic nuclear engineering education was analyzed with respect to the basic and/or applied nature of the research developed the Ph.D. theses. Quantification of the nature of research was attempted for the 51 Slovenian Ph.D. theses in nuclear engineering using the Pasteur's quadrant proposed by (Stokes, 1997). The predominantly mixed nature of analyzed theses was shown to enable successful careers in academia, industry, and regulatory and/or government agencies. Based on the analysis, the current nuclear academic education system appears to be reasonably well conceived and could be further improved through more intensive research interactions with the industry and regulatory agencies in long-term and interactive research relationships.

Successful attraction and development of future nuclear talents call for suitable sequences and balance of know-why? and know-how?. It is suggested to deliver the conceptual knowledge in dedicated academic education (know-why?) followed by the professional training towards mastering the procedural knowledge (know-how?) related to specific technology.

Future work might involve analysis of larger set of Ph.D. theses from a wider international environment and might result in more solid conclusions.

CRediT authorship contribution statement

Leon Cizelj: Conceptualization, Data curation, Formal analysis, Funding acquisition, Investigation, Methodology, Project administration, Resources, Supervision, Visualization, Writing – original draft. **Ivo Kljenak:** Conceptualization, Investigation, Methodology, Validation, Writing – review & editing. **Iztok Tiselj:** Data curation, Investigation, Validation, Writing – review & 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.

Data availability

Data will be made available on request.

Acknowledgements

The authors are indebted to the students and supervisors of the Nuclear Engineering program jointly operated by the Faculty of Mathematics and Physics of University of Ljubljana, Slovenia, and the Jožef Stefan Institute, for their excellent research and their efforts to provide information utilized in this paper. Funding by the Slovenian Research agency through grant P2-0026 and European Commission through grants ENENPlus (H2020-EURATOM-NFRP-2016-2017-1-755576) and ENEN2Plus (HORIZON-EURATOM-2021-NRT-01-13 -101061677) is gratefully acknowledged.

References

Bentley, P.J., Gulbrandsen, M., Kyvik, S., 2015. The relationship between basic and applied research in universities. High. Educ. 70, 689–709.
Cheung, J.J.H., 2021. Knowing how and knowing why: integrating conceptual knowledge in simulation-based procedural skills training to support learning transfer. University of Toronto ON, Canada, Institute of Medical Science.

Chung, B.-J., 2006. Perspective of international activities on nuclear knowledge management and proposals for further refinements. Int. J. Nucl. Knowl. Manag. 2, 105–113.

Cizelj, L., 2019. The role of nuclear higher education in the future of nuclear power, Invited plenary lecture, International Conference on Nuclear Engineering ICONE-19. Tsukuba, Japan.

Crespin-Mazet, F., Ingemansson-Havenvid, M., 2020. Rethinking the theory-practice divide: How academia-industry collaboration contributes to theorising. Ind. Mark. Manag.

Eriksen, B., Christiansen, B., Ramos, R.C., Kalleveen, A.V., Hirte, B., 2019. Results of surveys of the supply of and demand for nuclear experts within the EU-28 civil nuclear energy sector. European Commision JRC.

Evans, J.A., 2010. Industry induces academic science to know less about more. Am. J. Sociol. 116, 389–452.

Grassano, N., Hernández Guevara, H., Fako, P., Nindl, E., Georgakaki, A., Ince, E., Napolitano, L., Rentocchini, F., Tübke, A., 2022. The 2022 EU industrial R&D investment scoreboard. Publications Office of the European Union.

Higley, K.A., 2017. Education vs. training: does it matter? Health Phys. 112, 165–171.

Hoppe de Sousa, W., Zamudio Igami, M.P., de Souza Bido, D., 2009. R&D management and the stokes diagram: an exploratory study. J. Technol. Manag. Innov. 4, 95–109.

Iaea, 2022. Recruitment. Qualification and Training of Personnel for Nuclear Power Plants, INTERNATIONAL ATOMIC ENERGY AGENCY, Vienna.

Kljenak, I., Cizelj, L., Tiselj, I., Mavko, B., 2020. Basic vs. applied doctoral theses in nuclear engineering – case study of theses completed in Slovenia. Nucl Eng Des 367, 110758.

Leshner, A.I., 2015. Rethinking graduate education. Science 349, 349.

Nietsche, F.W., Large, D., 1998. Twilight of the Idols: or How to Philosophize with a. Hammer Oxford University Press.

OECD/NEA, 2000. Nuclear education and training: cause for concern?.

Saito, H., 2016. Education as the weakest institutional link in japan's nuclear regulation. J. Soc. Studies Edu. 5, 33–55.

Sanchez-Alarcos, J., 2020. Aviation and Human Factors: How to Incorporate Human Factors into the Field. CRC Press, Boca Raton, FL, USA.

Semler, R., 2001. Maverick: the success story behind the world's most unusual workplace. Random House.

Stokes, D.E., 1997. Pasteurs quadrant: basic science and technological innovation. Brookings Institution Press, Washington, D.C.

Tijssen, R.J.W., 2010. Discarding the 'basic science/applied science' dichotomy: a knowledge utilization triangle classification system of research journals. J. Am. Soc. Inf. Sci. Technol. 61, 1842–1852.

Turcanu, C., Perko, T., Schröder, J., Abelshausen, B., 2018. The SCK•CEN Barometer 2018: nuclear technologies and society: a survey among the Belgian population. SCK-CEN, Mol, Belgium.

Uršič, M., Prošek, A., Cizelj, L., 2021. Technical and Scientific Support Organizations as an Independent Layer of Defence-in-Depth in Licensing of Nuclear Facilities. Nuclear Energy for New Europe, Bled, Slovenia.

Yasuda, S., 2011. Exploring a conceptual framework for academic entrepreneurship: beyond paster's quadrant. Int. Rev. Bussiness 11, 25–40.