



Extending the European Competence Framework for Quantum Technologies: new proficiency triangle and qualification profiles

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Abstract

With the increasing industrial relevance of quantum technologies (QTs), a new quantum workforce with special qualification will be needed. Building this workforce requires educational efforts, ranging from short term training to degree programs. In order to plan, map and compare such efforts, personal qualifications or job requirements, standardization is necessary. The European Competence Framework for Quantum Technologies (CFQT) provides a common language for QT education. The 2024 update to version 2.5 extends it by the new proficiency triangle and qualification profiles: The proficiency triangle proposes six proficiency levels for three proficiency areas, specifying knowledge and skills for each level. Nine qualification profiles show prototypical qualifications or job roles relevant to the quantum industry, with the required proficiency, examples, and suggestions. This is an important step towards the standardization of QT education. The CFQT update is based on the results of an analysis of 34 interviews on industry needs. The initial findings from the interviews were complemented by iterative refinement and expert consultation.

Keywords: Quantum technologies; Competence framework; CFQT; Qualification profiles; Proficiency triangle; Quantum industry; Education; Interview analysis; LLM

1 Introduction

Modern Quantum Technologies (QTs), such as quantum computers, quantum sensors or quantum communication devices, are gaining increasing industrial relevance. Building the future quantum workforce requires not only intensive educational efforts such as training and study programs. QT education also needs a common language as well as standardization efforts to make education and qualifications comparable: The European Competence Framework for Quantum Technologies (CFQT) [1] is the “reference framework for planning, mapping and comparing QT-related educational activities, personal qualification and job requirements”. This paper documents the update from version 2.0 [2] to version 2.5 [1] and the advances in the new version.

The CFQT aims to structure QT competences as well as related competences relevant to the future quantum workforce. It was already used, for example, to map course content [3], to plan new courses [4], to categorize research [5], or as the backbone for a curriculum

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transformation framework [6]. Version 2.5 (2024) of the CFQT was published by the European Commission, EU Publications Office (see Ref. [1]). It was developed within the European Quantum Flagship [7] Coordination and Support Action (CSA) projects QTedu [8] and QUCATS [9]. Within the QUCATS project, the European Quantum Readiness Center (EQRC) [10] has been launched to establish best practices, including standardization, using the CFQT as a tool.

The objective of the update to version 2.5 was to provide more detailed and substantiated descriptions for the proficiency levels, as well as a new version for the qualification profiles from 2022 [beta version, 11]. General descriptions for six proficiency levels were already added in the CFQT update to version 2.0, but needed further refinement and specification for QT – as in the new *proficiency triangle* (see Sect. 3). The proficiency triangle enables the specification of proficiency or qualification in three dimensions, covering (I) quantum concepts, thus physics fundamentals, (II) QT engineering competences, including QT functionalities, and (III) QT applications and strategies, i.e. the business perspective, including aspects such as impact and ethics. By assigning a proficiency level for each of these three proficiency areas, an individual's qualification can be specified, for example.

A total of nine new *qualification profiles* were identified and visualized with the proficiency triangle (see Sect. 4). They represent prototypical qualifications relevant to industry. However, to really specify such a qualification, a second measure is needed: A selection from the *content map*. It structures content relevant in the context of QT and was in the focus of the update to version 2.0 [2, 12]. The content map and the details for the eight content domains remained consistent from version 2.0 (2023) to 2.5 (2024). In the new version, two examples are given of how to combine such a selection from the content map and a profile based on the proficiency triangle. Appendix A.1 provides an overview of the general structure of the CFQT document, from the content map and the proficiency triangle to the qualification profiles and examples.

Crucial input for the CFQT extension in version 2.5 came from the analysis of 34 interviews focusing on QT educational needs in industry. The primary objective of the interview analysis was to report on the qualification and training needs in industry, as documented in Ref. [13]. However, the insights from the interviews provided great input for the CFQT update: key competences were identified and incorporated into the proficiency level descriptions, and the jobs and roles discussed in the interviews led to the first draft of the new qualification profiles. In addition to the manual analysis, a GPT was employed to analyze anonymized interview transcripts and extract typical job roles to improve the initial qualification profiles.

2 Methods and procedure for updating to version 2.5

The development of the CFQT started with an iterative study in 2020/2021 [14], leading to version 1.0 [15] compiled within the QTedu CSA. Within the QUCATS project, it was updated to version 2.0 [2], as documented in Ref. [12]. In this update, the content map was revised and descriptions of six proficiency levels A1 to C2 were added. The proficiency level descriptions were based on the European Qualifications Framework (EQF) [16], thus specifying the required knowledge and skills for each proficiency level, adapted to QT in general.

The proficiency level labels A1, A2, B1, B2, C1 and C2 are associated with the levels commonly used to specify qualifications in languages in Europe [17]. The DigCompEdu [18]

framework was used as a template which also provided the initial version of the level keywords, e.g. awareness for level A1. These keywords were also updated in version 2.5 to better match the level descriptions.

The update to version 2.5, which brought the proficiency triangle and qualification profiles into the framework, was released in April 2024. The process and results of the update are documented below, including some excerpts from the CFQT document for illustration. A version history and related publications are given in Appendix A.2.

2.1 About the interviews: introduction of ‘competence types’

In summer 2023, 34 interviews with industry representatives were conducted and analyzed to answer research questions including *What QT qualification and training needs are reported by industry?* An in-depth analysis is documented in Ref. [13], including details about the methodology, which was based on qualitative content analysis [19]. The interviewees represent QT companies or companies with QT departments from different European countries, from start-ups to very large companies, covering technical, management or business roles.

In some of the interviews, a slide about the ‘competence types’ (reproduced in Fig. B1) was shown to stimulate the flow of the interviews – others were conducted without this input, e.g. if the interviewee expressed very clear or different views in the previous questions. This material introduced a structure of competence descriptions for three levels for each of the three ‘types’ *overview, communicate* (level N, O, P), *build, develop* (level B, C, D) and *use, adapt* (level U, V, W):

Overview, communicate (overview on applications and use cases)

- N Notice the basic idea and potential of an application and (possible) use cases.
- O Overview of an application’s landscape and use cases, critical perspective on potential and limitations, know and communicate with basic quantum vocabulary.
- P Perform a comparison of different applications based on a deeper understanding of the various functions, assess which application is suitable for which use case.

Build, develop (build application)

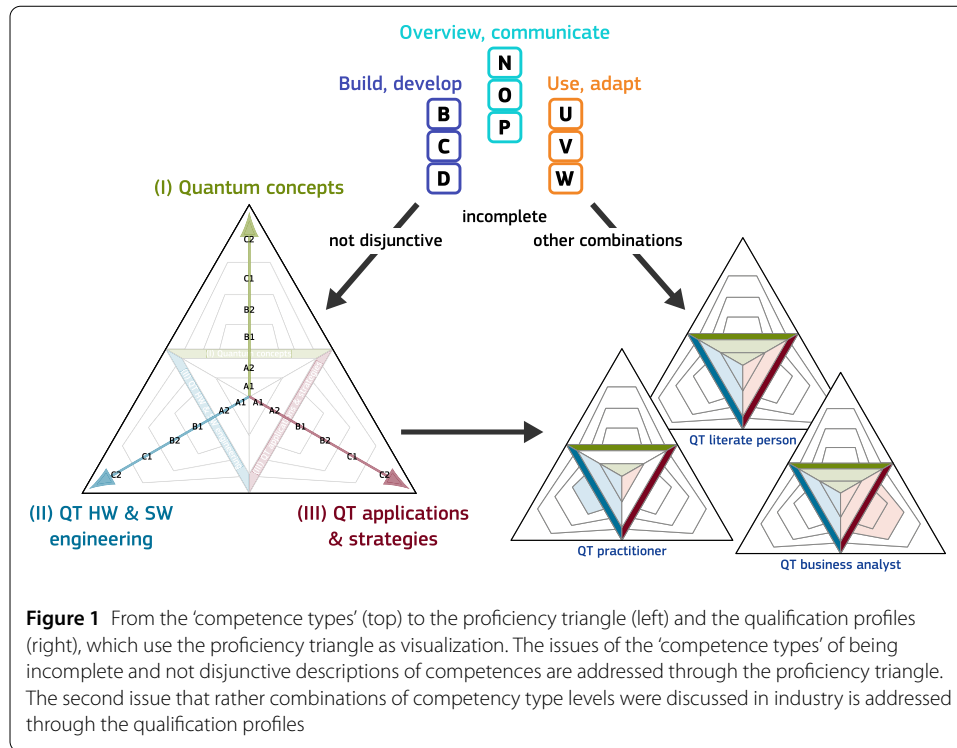
- B Build an application component, assemble.
- C Component improvement for an application.
- D Develop new components or applications through research, selection and integration of components.

Use, adapt (use an application)

- U Use/run an application for one specific use case that is customized for that use case.
- V Vary/adapt an application for several related use cases.
- W Wrap applications and components together to enable new use cases.

This was an outline for structuring typical competences that we expected to be relevant in industry. Thus, the key competences and qualifications discussed in the interviews were categorized according to this structure, regardless of whether the material was used in the interview or not.

It turned out that this structure was incomplete and not disjunctive, so refinement was needed. More concretely, the structure of the competence types was the starting point for developing or extracting both, the proficiency triangle and the qualification profiles, as discussed in the next sections and visualized in Fig. 1: The proficiency triangle addresses the issue of disjunctive proficiency areas with independent proficiency levels for each area.



In contrast, the qualification profiles show typical combinations of these levels, visualized as coverage of the proficiency triangle, for a more complete picture than the ‘competence types’ provided.

2.2 From ‘competence types’ to the proficiency triangle

Key competences were identified in the interview transcripts and analyzed not only in terms of the corresponding proficiency level, but also in terms of the three categories, which were initially the three ‘competence types’ that iteratively evolved into the three proficiency areas:

- from “overview [...] communicate with basic quantum vocabulary”, plus additions to proficiency area (I) *quantum concepts*,
- from ‘build, develop’ and ‘use, adapt’ to (II) *QT hardware (HW) & software (SW) engineering*, and
- aspects from ‘overview, communicate’, e.g. “critical perspective on potential and limitations”, plus additions to (III) *QT applications & strategies*.

Through another iterative process, the graphical appearance of a triangle was constructed. In this way, the initial structure of the ‘competence types’ was refined into what we named the *proficiency triangle*, see Sect. 3. It consists of three proficiency areas with six proficiency levels each.

For each proficiency level, a competence statement was formulated using action verbs [20]. They are complemented by descriptions of knowledge and skills based on the EQF levels [16], as were the general level descriptions in version 2.0 [2, 12]. In contrast to the descriptions in version 2.0, the proficiency levels are now specified for the three proficiency areas and are based on the key competences identified through the interview

analysis. Further details, such as relations to the content map, are also provided. All details for one proficiency level are given as an example in Sect. 3.

2.3 From the identification of job roles to qualification profiles

During the qualitative content analysis of the interview transcripts, twelve categories related to job roles were used. These categories were mainly based on the structure of the ‘competence types’ (Sect. 2.1/Fig. B1), as well as some frequently discussed combinations of two ‘competence type’ levels as additional categories.

In Appendix B.2, these job role categories are shown, together with references to related ‘competence type’ levels. For example, the category “engineer with overview on QT [O/B]” is related to the “O – Overview...” and “B – Build...” and evolved to profile P4 of the QT practitioner, including also the “advanced user [V]”, related to “V – Variate...”. Iteratively, the categories from the interview analysis evolved to the qualification profiles.

To support this process, 30 anonymized interview transcripts were analyzed using a large language model (LLM, namely GPT3.5) to identify frequently mentioned job roles representing categories or clusters. This resulted in the descriptions of the 10 roles provided in Appendix B.3. These roles were checked against the initial job role categories, in addition to intensive discussion of the initial categories. On this basis, the job role categories were refined, and a second iteration of categorizing the interview passages was performed. Several categories in the second iteration are already named similarly to the final profiles, as documented in Table B1. Based on these categories, or more precisely, the categorized interview passages, the qualification profile descriptions version 2.1 were prepared.

These profiles were then refined through discussions with several colleagues and by gathering feedback from experts in both academia and industry. For example, the profile names were changed to better represent industry roles, and the required proficiency levels for the profiles were discussed and adjusted based on these discussions. In addition to invited discussions with individual experts, an open event was conducted in March 2024 to gather feedback from the QTedu community [8, subpage Events].

Table 1 shows the evolution of the profile titles from version 2.1 to the published version. The titles and descriptions were refined, and example personas/job roles and suggestions were added based on the results of the interview analysis documented in Ref [13].

Table 1 Evolution of titles of the qualification profiles. Although the titles may not have changed between two iterations, the descriptions may have changed significantly. These descriptions of the profiles in versions 2.1, 2.2, and 2.3 are available in the supplementary material on Zenodo [21]

No.	v2.1	v2.2	v2.3	v2.5 (published in Ref [1])
1	QT aware person			
2	QT aware decision maker			QT informed decision maker
3	QT-literate communicator	QT communicator		QT literate person
4	QT (market) analyst		QT business analyst	renumbered to Profile 5
5	QT user, engineer working with QT		QT technician	Profile 4 QT practitioner
6	QT engineer (generalist)		QT engineer/scientist (generalist)	QT engineering professional
7	senior QT engineer/QT architect			QT (HW or SW) specialist
8	QT strategist			QT (product) strategist
9	QT core innovator			

2.4 Limitations

The update of the CFQT is primarily based on the analysis of 34 interviews with participants from the quantum industry. This is a strength of the dataset, as it is directly constructed from interviews with experts in the field. However, we should anticipate and acknowledge that there may be a bias due to the group of interviewees, as discussed in Ref. [13]. Most of the perspectives included come from people who have a very positive perception of QTs, both in the interviews and in the iterative refinement. Therefore, they may identify QT-related job roles more readily than those without direct involvement in the industry would.

The extraction of job roles from the interview transcripts by an LLM improves the objectivity of the qualitative content analysis by having a kind of second coder analyze most of the interviews (the 30 transcripts that could be anonymized) and prepare a second set of categories. However, the experts involved in the refinement of the qualification profiles must be expected to have a similar bias as the interviewees, since they have a similar background and experience.

In addition, the QT field is very active and rapidly changing. As the interviews were conducted in 2023, the identified needs that influenced the CFQT update may also change in a short period of time. To capture these dynamic developments, annual updates of the CFQT are planned as part of the QUCATS project, with the next one due in April 2025, and feedback is taken continuously.

3 Proficiency triangle

The new proficiency triangle adds a second dimension, proficiency, to the content map from the CFQT version 2.0. It consists of three proficiency areas (I) quantum concepts, (II) QT HW & SW engineering, and (III) QT applications & strategies. The proficiency areas are described in the CFQT document, for example:

Area (III) QT applications & strategies addresses the business dimension of QT applications (5.6, 6.7, 7.4, 7.6). It focuses on the question of “how to generate value with QT” (domain 8). This also includes considerations of impact and responsibility, extending to the exploration of novel applications and the design of new products utilizing QT. [quoted from 1, p. 14]

The proficiency of an individual may grow in these three proficiency areas independently, however, typically someone working in the QT industry would have proficiency in all three areas. For each of these three areas, six proficiency levels A1 (Awareness), A2 (Literacy), B1 (Utilization), B2 (Investigation), C1 (Specialization) and C2 (Innovation) are specified. Together they form the proficiency triangle shown in Fig. 2. With the coverage of the triangle, a QT-specific set of knowledge and skills, or a qualification can be visualized, as in the qualification profiles, see Sect. 4.

Each proficiency level consists of a competence statement, as well as knowledge and skills descriptions based on the EQF level definitions (as described in Sect. 2.2). The competence statements are reproduced in Table 2. In addition, for each of the proficiency levels, relations to the content map (sub)domains (5.6, 6.7, ...) and examples of how the levels could be reached are given.

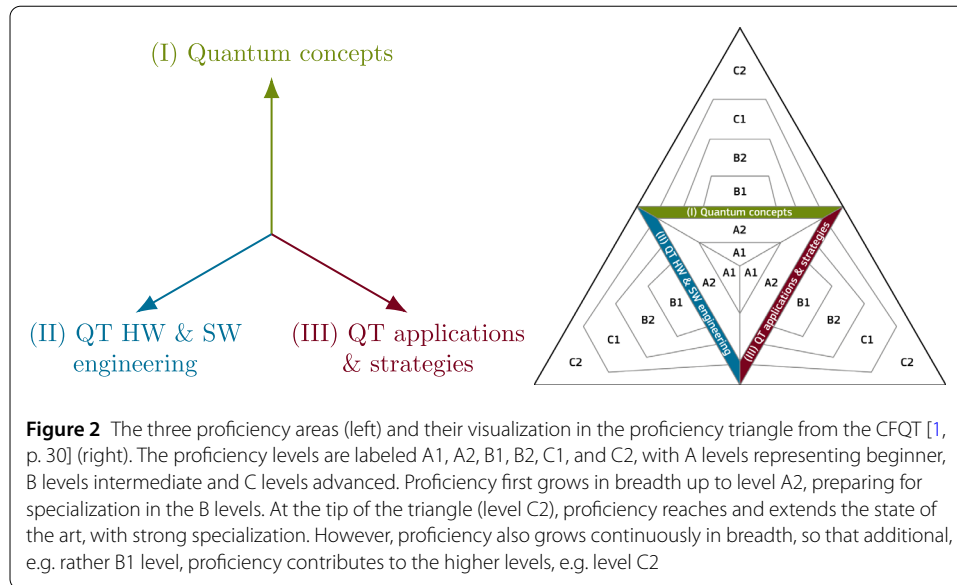


Table 2 Competence statements (short version) from the CFQT [1, p. 14]. There are three additional pages in the CFQT that provide more detail on the proficiency levels. A ‘QT facet’ stands for a QT core, component, system, or application which can be HW and/or SW focused

Proficiency level	Area (I)	Area (II)	Area (III)
A1 Awareness	<i>Reproduce</i> basic quantum concepts & terminology	<i>Reproduce</i> basic functionalities of a QT facet	<i>Recognize</i> potential of QT
A2 Literacy	<i>Describe</i> fundamental quantum concepts	<i>Perform</i> basic tasks on a QT facet	<i>Identify</i> value of QT
B1 Utilization	<i>Apply</i> quantum methods to problems	<i>Modify/apply</i> a QT facet	<i>Classify</i> available QT applications/approaches
B2 Investigation	<i>Analyze</i> problems with quantum	<i>Analyze</i> performance, improve QT	<i>Analyze</i> QT market and opportunities
C1 Specialization	<i>Refine</i> and extend quantum methods	<i>Conceptualize</i> integrated QT systems	<i>Advise</i> on QT appl. selection or strategies
C2 Innovation	<i>Develop</i> innovative solutions	<i>Develop</i> new QT facet	<i>Develop</i> and assess QT (product) strategies

For example, the description of the lowest proficiency level A1 (with K: knowledge and S: skills) for the proficiency area (III) QT applications & strategies is [quoted from 1, p. 17]:

A1 Awareness: Recognize potential of QT

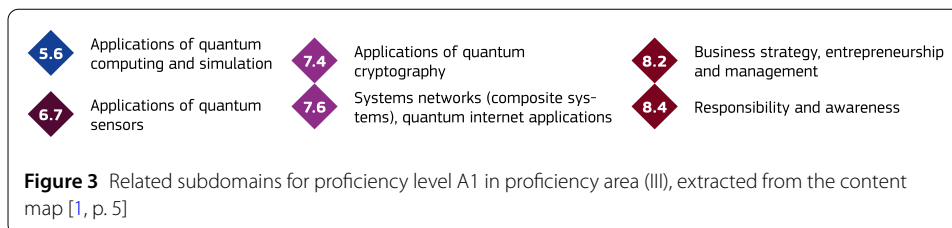
K: *Basic idea of the potential of QT systems and applications, overview of possibilities, challenges and limitations.*

S: *Ability to follow public media and discussions with critical awareness of hype.*

For each level, related content (sub)domains & examples are given, in this case:

Applications for a QT, see 5.6, 6.7, 7.4, 7.6, or a selected (sub)topic (concrete application area, e.g. quantum optimization in logistics 5.6), with relevance for business 8.2 or education 8.4; hype (especially for computing).

Examples of how to test or measure whether someone has reached a proficiency level are also provided. For this example, it is: *Multiple choice questions on possibilities/limitations.* These remarks are a first step toward a certification scheme that will specify the measurement of proficiency in more detail.



The descriptions of the proficiency levels are formulated independently of any particular QT pillar. To specify, for example, a specific qualification of a person or the aim of a course or the requirements for a job, the proficiency triangle must be combined with a selection from the content map. For each level, there are references to related content (sub)domains. In the example above, these are the subdomains 5.6, 6.7, 7.4, 7.6, 8.2 and 8.4. They are visualized in Fig. 3.

All these subdomains of the content map influence the ‘flavor’ of an individual’s experience or the learning outcomes of a course, i.e. the specific technologies or concepts covered. A course may cover only applications in quantum computing (subdomain 5.6), or even only quantum optimization in logistics and thus only (sub)topics from subdomain 5.6 regarding applications. However, to cover level A1 in the business-related proficiency area (III), the relevance to business (8.2) needs to be covered with a critical perspective, e.g. addressing the hype in quantum computing. The focus would be on the value and impact of QT for an industry sector or the own company/business.

Alternatively, the focus could be on the value and impact for society and education, i.e. subdomain 8.4 instead of 8.2. With 8.4 one can map qualifications outside of industry, e.g. a secondary school teacher who recognizes the potential of QT as a context for teaching quantum concepts and who has an overview of how QT can impact society as a whole. This would be relevant, e.g., to discuss QT and their expected impact already in high school and thus to get more school students interested in quantum (and STEM). Raising this interest was rated as very necessary (40 of 52 participants rated ‘high need’, 11 rated ‘low need’, one rated ‘no need’) in our follow-up survey to the interview analysis, see Ref. [13, p. 25].

4 Qualification profiles

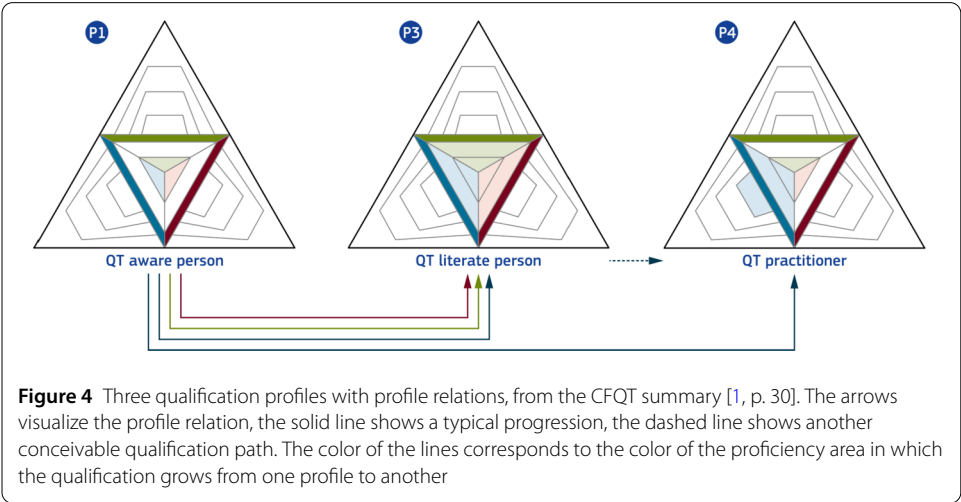
The qualification of an individual or the objectives of a training, for example, can be visualized by a coverage of the proficiency triangle, which specifies the proficiency level for each of the three proficiency areas. Since these are formulated independently of the concrete subject matter, they have to be combined with a selection from the content map. Nine qualification profiles included in the CFQT version 2.5 show the prototypical coverage of the proficiency triangle. They are listed in Table 3 with the required proficiency levels for each of the three areas.

An overview page shows these nine profiles with the different, partly colored proficiency triangles as well as the relations between the profiles [1, p. 18]. Relations mean how people may evolve from one profile to another. As in the example in Fig. 4, such a potential evolution is visualized by arrows.

For each profile, a detail page provides the partially colored proficiency triangle with the descriptions of the highest proficiency level covered for each of the three proficiency areas. The profile is described generally, and example personas/job roles provide more

Table 3 Qualification profiles and related proficiency levels for proficiency area (I) quantum concepts, (II) QT HW & SW engineering and (III) QT applications and strategies in the CFQT version 2.5

No.	Profile title	Proficiency level in area		
		(I)	(II)	(III)
P1	QT aware person	A1	A1	A1
P2	QT informed decision maker	–	–	A1
P3	QT literate person (QT literate business role, advocator, enthusiast)	A2	A2	A2
P4	QT practitioner (working with QT, technician, QT user)	A1	B1	A1
P5	QT business analyst	A2	A2	B2
P6	QT engineering professional (e.g. QT engineer, quantum computer or information scientist)	B1	B2	A2
P7	QT (HW or SW) specialist (e.g. senior QT engineer, QT architect)	B2	C2	B1
P8	QT (product) strategist (e.g. advisor, business development expert)	B2	B2	C2
P9	QT core innovator	C2	B1	A2



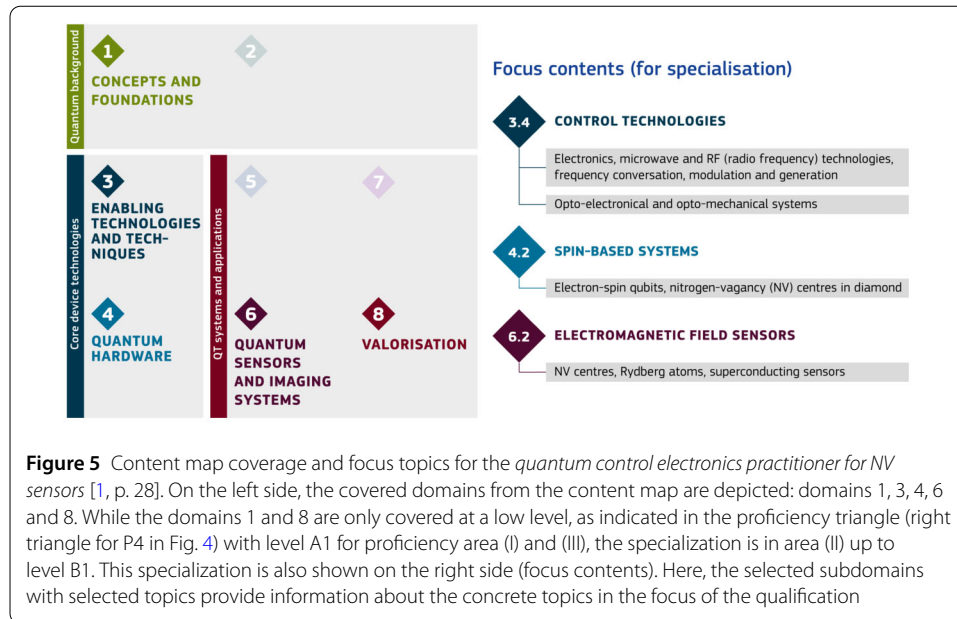
concrete descriptions of what a job with that qualification might look like, for example for profile 4:

General description *The **QT practitioner** is someone who works around the development, assembly and operation of QT (technicians or ‘classical’ engineers with some QT specific additional qualifications), or uses QT with some customization:*

- *is QT aware, thus is able to follow team discussions and has an idea of the potential of the QT working on,*
- *has an overview of the relevant parts (hardware and/or software) for QT, and*
- *focuses on the specific QT relevant to their own work, and knows how to work with it.*

Example personas *(‘Classical’ engineer with QT add-on, QT lab technician (e.g. for operation and maintenance), QT assembly and test technician, ...)*

*An **engineer working on QT development**, could be an electronic or mechanical engineer or a software engineer/computer scientist, working on the control hardware/software for a qubit, needs mainly traditional engineering skills, but works together with the quantum people, so needs an idea of the special challenges in QT development (but does not need to understand the details, has a supervisor who ensures compliance with quantum requirements) and also has an idea of the applications etc. to know what they are working for. [...]* [1, p. 22]



The profile description is complemented by a ‘needs and suggestions’ section, describing the suggested previous qualification (i.e. another profile and/or a specific background), training modules to reach the profile starting from the suggested previous qualification. In addition, recommendations regarding language and certificates are provided. All these suggestions are based on the interview analysis. Some of the results documented in Ref. [13] are included in these sections of the qualification profile detail pages. They include what training is considered relevant or what language is deemed appropriate.

Finally, it should be emphasized that the qualification profiles are formulated independently of the specific technology in which they are applied, as is the description of the proficiency levels. In order to describe a specific qualification, the profile – or, more generally, the coverage of the proficiency triangle – must be combined with a topical selection from the content map.

Two examples of such combinations are given in the CFQT: the *quantum control electronics practitioner for NV sensors* and the *quantum optimization in logistics & production analyst* [1, p. 28 & 29]. Figure 5 shows the coverage of the content map along with the focus topics for the first of these examples. The clear focus on quantum sensing and control technologies is visible. They complement the partially colored proficiency triangle for the QT practitioner (P4, right triangle in Fig. 4): it shows the coverage of proficiency level A1 for the proficiency areas (I) and (III) along with level B1 in area (II). Each of the two examples is completed by a description of the example and the associated QT specific qualification.

5 Discussion and conclusion

Prior to implementing new courses and programs to develop the workforce pipeline in QT, it is critical to answer a key question: What specific knowledge and skills are needed for industry growth? Different studies were conducted to analyze these needs [14, 22–26], including our analysis of 34 interviews with industry representatives [13]. This research provided the primary input for the extension of the CFQT with the proficiency triangle and

qualification profiles. The proficiency levels organized in the proficiency triangle cover key knowledge and skills discussed in the interviews, and the qualification profiles are supplemented by example personas/job roles and needs and suggestions extracted from the interview analysis.

The CFQT provides a common language for QT-related qualification and education. It is a tool for planning educational activities such as workshops, training or study programs. It can be used to specify the qualification of an individual, or what is required for a job. For example, it is useful for ...

- ... educators to plan educational activities and map their objectives;
- ... individuals to specify what qualification they have and what they want to achieve;
- ... learners to identify what training or course they should take;
- ... companies to specify what qualifications an employee or team covers and compare that to what they would need to identify what qualifications are missing;
- ... companies to specify job requirements and compare them with a candidate's qualifications;
- ... job seekers to map their qualifications and compare them to job requirements.

Early users are educators [e.g. 3, 4, 6]. Two EU-funded projects agreed to use the framework to map their activities: DigiQ [27], developing 16 QT master's programs across Europe, and QTIndu [28], developing industrial training courses on QT. Additionally, first companies showed interest in using the CFQT for their workforce development.

The CFQT is an important step towards the standardization of QT education. This need was also addressed in one of the interviews analyzed for the update to version 2.5:

I think it is always better to have a standard. So the question is how to standardize these trainings? [...] It comes back to the ECTS systems from education. I mean, they are standards. [quote from an interview with a QT start-up; 13, p. 24]

For the update to version 2.0, we already aligned the proficiency level descriptions with the EQF and thus the European Credit Transfer and Accumulation System (ECTS), as described in Ref. [12, p. 3]. Following the EQF [16, p. 16], the three highest EQF levels are associated with the first, second and third cycles of the Qualifications Framework of the European Higher Education Area, which are based on the ECTS. Therefore, as the CFQT levels are formulated based on the EQF, the level B2 is linked to bachelor, C1 to master and C2 to doctoral programs. However, it should be emphasized that this mapping is not necessarily one-to-one, and that a degree program is not the only way to reach these levels. Especially in the business-related proficiency area (III), the high levels are more likely to be achieved through years of experience.

In version 2.0 of the CFQT, these links were explicitly stated in the proficiency level descriptions. For example, it was noted for level B2: *e.g. through a short research project as for a bachelor thesis, internship with project* [2, p. 5]. As mentioned above, this brings the risk of assuming a study program as the only way to reach a level, while there is a variety of opportunities to gain such a qualification.

In version 2.5, such comments are less prominent and vary across the three proficiency areas. For the same proficiency level B2 Investigation, these comments are for proficiency area (I) *Short research project with documentation, e.g. student research project or bachelor thesis*, for area (II) *Write report on requirements analysis and performance results*, and for area (III) *Document an analysis for a concrete potential use case covering potential*

advances, risks, [...] [1, p. 15-17]. With the update, the focus in these remarks shifted from an approximate duration to what an individual should be able to answer, perform or prepare for a qualification covering the corresponding proficiency level. Suggestions for training formats, the need for study programs or work experience are provided for the qualification profiles, rather than being fixed for a proficiency level.

The updated CFQT is the starting point for a certification scheme to ensure comparability of industry training across Europe. This scheme is currently being developed within the Quantum Flagship coordination project, QUCATS [9], associated to standardization activities. As in technology standardization, the first step is typically to address terminology, already at very low technology readiness, followed by test and measurement standards [29]. Similarly, with the CFQT we started to focus on the common language for QT education, based on the structured topics in the content map as well as the proficiency level descriptions. In version 2.5, there are already short, additional remarks on the aspect of testing or measuring if someone has reached a certain level. This aspect will be further elaborated in the certification scheme, a second step towards the standardization of QT education and qualification.

As a part of the QUCATS project, the EQRC highlights “accords” (best practices) in QT education of organizations across the EU [10, subpage Accords]. Within these accords, the CFQT is a tool to provide structure and standardization. As a recent example, the accord submitted by the QuantUM Group at the University of Minho provides a profile of a software engineer in quantum computing as a representative graduate from the new master degree established there [10, subpage Accords: Educational Accords]. In addition, the EQRC website hosts a curated playlist of videos, sorted based on the content map of the CFQT [10, subpage Resources].

The CFQT, consisting of the content map and the proficiency triangle with associated qualification profiles, provides a reference framework for greater standardization across Europe. However, adoption is critical to its success. Industry representatives seeking new employees should consider using the CFQT to understand their needs and to formulate the required QT qualifications in their job advertisements. Educational institutions also have an important role to play. Here, the qualification profiles can be a step towards the future of standardized learning outcomes in QTs.

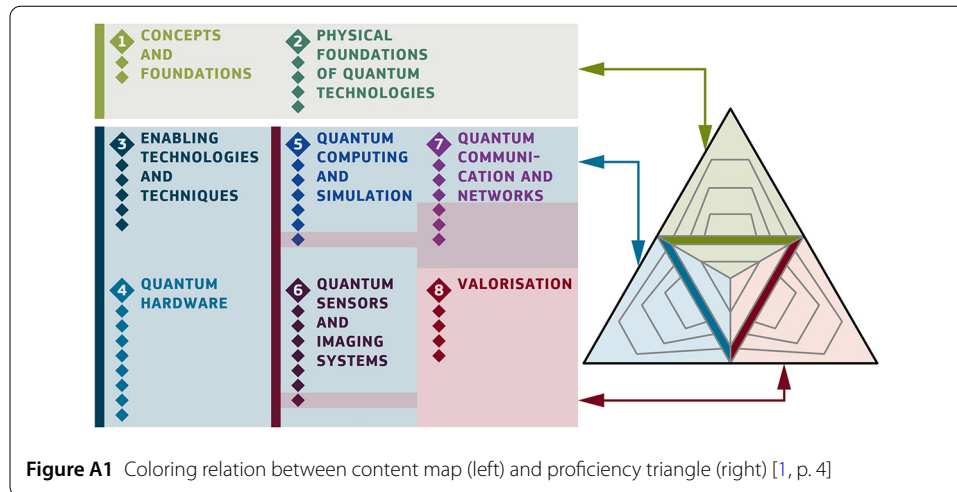
Further research is needed on the application of the CFQT. Whether it is used to prepare educational activities or within workforce development, accompanying research will be needed to identify issues and approaches for improving the CFQT. In addition, regular updates will be needed to reflect technological changes and innovations as well as new challenges and needs in the quantum industry.

Appendix A: Structure and version history

A.1 Principal structure of the CFQT

The CFQT [1] consists of three main parts:

1. The *content map* provides a structured overview of QT related topics and contents. It is a kind of extended table of contents with up to four layers: domains 1, 2, ..., 8 with 42 subdomains 1.1, 1.2, ..., (p. 5 in the CFQT document) and, on the detail pages for each domain (p. 6–13), additional topics and sometimes subtopics provide more details for the subdomains. A selection of domains from the content map and of subdomains with topics are included in an example shown in Fig. 5.



2. The *proficiency triangle* visualizes six proficiency levels for three proficiency areas (p. 14; Fig. 2). In-depth level descriptions and more are provided for each of the three proficiency areas (p. 15–17). See Sect. 3.
3. The *qualification profiles* show typical qualification, i.e. coverage of the proficiency triangle. An overview (p. 18) and detailed descriptions including example personas and (training) suggestions (p. 19–27) are available. See Sect. 4.

Furthermore, two examples how to combine a profile with a content selection are given (p. 28–29 in the CFQT). In addition, the CFQT pages 3 and 4 provide some information on how to use the framework, including an introduction of the terminology and the level system, and information on the methodology and related publications. The coloring of the proficiency triangle corresponds to the coloring of the content map as shown in Fig. A1.

A.2 Version history and related publications

For the Qualification Profiles, a beta version was published in 2022 [11] as a separate document based on the CFQT version 1.0. The new profiles replace this beta version, they are not an update of the beta version and were created with a completely different approach. While four of the six profiles in the beta version were those of an engineer in QT hardware or one of the QT pillars, the new profiles focus on the proficiency that a QT engineer needs in general. These four beta version profiles would be the same profile in the new version. Now the QT pillar is the context to be added by a topical selection of the content map. In the beta version, the profiles consisted mainly of the topical selection of the content map, and only provided a very limited specification with proficiency levels, which themselves were not specified at that time.

Version 2.5 of the CFQT was released in April 2024 on Zenodo [30] and in August 2024 as an ‘official version’ by the Publications Office of the European Union [1]. They differ only in the placement or addition of some editorial information (mainly moved from page 3 to the new page 1), but the framework itself has not changed between the EU and Zenodo publications. Table A1 provides a version history and an overview about related publications.

Table A1 Version history and publications related to the CFQT, with CFQT standing for ‘European Competence Framework for Quantum Technologies’ and ‘QT(s)’ for ‘Quantum Technology(-is)’ (in the titles). [*] Older versions of the CFQT are also available through the same Zenodo repository [30]

Date	[Ref.] Title/version	Comment
Dec. 2020	[31] Beta version of the CFQT	Content map with seven domains and details pages, one keyword for each of six proficiency levels. Available on request on Zenodo.
June 2022 (Nov. 2020)	[32] Requirements for future quantum workforce – a Delphi study	Interim report on the iterative study (Ref. [14]), conference proceedings of GIREP, Nov. 2020.
May 2021	CFQT version 1.0 (before graphical update)	Update of content map, restructuring the QT pillar domains to a total of eight domains. Only graphical update.
Sep. 2021	[*] CFQT version 1.0	
Sep. 2021	[15] Competence framework for quantum technologies: methodology and version history	Documentation of the development process until version 1.0, published by the EU Publications Office.
Jan. 2022	[11] Qualification Profiles for QTs (beta version)	Six profiles: content map selection with proficiency level indication, outdated.
June 2023 (Aug. 2022)	[14] Future quantum workforce: Competences, requirements, and forecasts	Paper on the iterative study collecting input for the CFQT beta version and also version 1.0, submitted in Aug. 2022
April 2023	[2*] CFQT version 2.0	Update of content map, addition of descriptions for six proficiency levels.
July 2023	[12] Towards a quantum ready workforce: the updated CFQT	Paper on the update to version 2.0.
April 2024	[30] CFQT version 2.5 (Zenodo)	Extension by proficiency triangle, new qualification profiles, content map unchanged.
July 2024	[13] Advancing QT workforce: industry insights into qualification and training needs	Preprint on the analysis of interviews with industry that were also used to update the CFQT to version 2.5
Aug. 2024	[1] CFQT version 2.5	Official published by EU publications office.

Appendix B: From competence types through categories to qualification profiles

B.1 Competence types

In some of the interviews (22 out of 34), the slide/material ‘competence types’ was shown, reproduced in Fig. B1. They formed the initial system that was refined and extended to the proficiency triangle through the CFQT update process.

B.2 Categories and qualification profiles

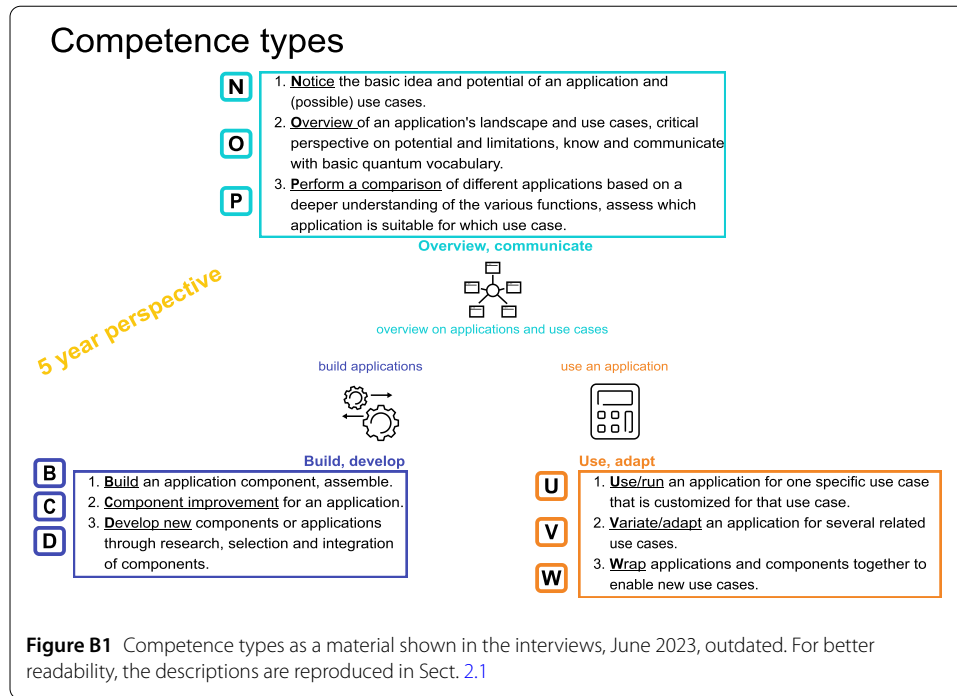
As described in Ref. [13], the interviews 34 interviews with industry representatives were analyzed using qualitative content analysis. Table B1 shows an extract from the category system related to the qualification profiles (left column) as well as a revised version of these categories used for a second iteration of the categorization (middle column). In addition, the qualification profiles in the CFQT version 2.5 are listed (right column). For the first iteration, also the related ‘competence type’ level is given, e.g. [B] for ‘Build an application...’, as specified in Fig. B1/Sect. 2.1. The progression from competence type levels to qualification profiles is visible in rows.

B.3 GPT extracted job roles

As described in Sect. 2.3, 30 anonymized interview transcripts were provided to an LLM (gpt3.5-turbo-16k) to extract ten personas as typical job roles. The prompts were:

Prompt 1: *Here is an anonymised interview transcript. What are the key personas described in the interview? (e.g Engineers, Developers, Project Managers)?*

The outputs of prompt 1, for each transcript, were collated into a single list.



Prompt 2: *This document contains the key personas described in a series of interviews with companies in the Quantum Technology industry. Each interview begins with the text “INAXXX”. Based on these findings, please provide a list of 10 types of personas in the Quantum Technology industry, each with a 2 sentence description.*

The extracted roles are:

1. Quantum Engineers/Researchers/Scientists: These individuals are involved in the design and development of quantum technologies, requiring expertise in quantum physics, engineering, and material science.
2. Project Managers: Responsible for overseeing the successful development and implementation of quantum-enabled devices, coordinating efforts between different teams or departments.
3. Decision Makers/Management: Individuals in managerial or executive roles responsible for making strategic decisions based on market needs and technology trends in the quantum industry.
4. Training and Development Professionals: Facilitate the learning process for existing employees or new hires, designing hybrid training programs, online content, workshops, or lectures.
5. Generalists: Individuals with a broader understanding of quantum technologies, bridging the gap between technical and market-oriented aspects of quantum technologies.
6. Market Analysts: Assess market demand and guide the development of quantum-enabled devices by understanding market trends, potential applications, and customer needs.
7. Company Representatives: Engaged in technology development, consulting, and strategic planning for quantum technology companies, addressing workforce development and skilled personnel needs.

Table B1 Category system and statistics for the two iterations related to the development of the qualification profiles together with the final profile number (No.) title in the CFQT version 2.5. In the columns called N, the number of segments categorized in the category is given. If no number is given, the code is a supportive code only to structure the codes on the next level

First iteration		Second iteration		Qualification profile	
Category	N	Category	N	No.	Title in CFQT
<i>quantum aware workforce</i>					
basic user (click a button) [U]	6	other: not quantum specific/ no quantum needed	16		
engineers with (almost) no quantum [B]	22				
hype, basic idea (not) for all, incl. admin people [N]	24	QT aware person	18	P1	QT aware person
		QT aware decision maker, manager	17	P2	QT informed decision maker
<i>quantum literate workforce</i>					
management (non-QT comp.), business, sales, policy makers [N/O]	42	QT literate (sales) communicator	27	P3	QT literate person
use-case identifier [O/W]	19	use case identification	5		
eng. with overview on QT (also e.g. cryo physicists; incl. programming) [O/B]	73	QT user, engineer working with QT	69	P4	QT practitioner
advanced user (with adaption) [V]	23	QT user (with adaptation)	19		
<i>q. expert workforce (needs QT study program or PhD)</i>					
strategist, consultants [P] (comparison, assessment)	27	QT analyst (market, use cases, strategies)	15	P5	QT business analyst
		QT engineer (generalist)	6	P6	QT engineering professional
		<i>senior QT engineer, QT architect</i>		P7	QT (HW or SW) specialist
customer/sales eng. [C/V]	12	... focus on customer and applications (incl. consulting, perform comparison)	21		
quantum algorithm developers (high-level) [D]	22	QT application specialist (e.g. programming)	22		
systems eng. (integration, industrialization) [C]	13	... focus on systems and integration	12		
		QT strategist (e.g. consultant)	2	P8	QT (product) strategist
quantum experts/ expertise needs [D]	35	QT core innovator	29	P9	QT core innovator

8. End-users: Users in various industries, such as medical imaging, interested in understanding and benefiting from quantum-enhanced technologies.
9. Technical Developers: Involved in building physical devices and components for quantum technologies, such as lasers and high-precision optical and frequency components.
10. Sales Managers and Marketing Personnel: Responsible for understanding the market landscape, guiding sales engineers, shaping product strategy, and communicating the value of quantum technologies to potential customers.

These personas were used to refine the initial categories from the qualitative content analysis of the interviews (see Table B1) and thus influenced the preparation of version 2.1 of the qualification profile descriptions.

Abbreviations

CFQT, European Competence Framework for Quantum Technologies [1]; CSA, Coordination and Support Action; DigiQ, Digitally enhanced quantum technology master (project title) [27]; EQF, European Qualifications Framework [16]; EQRC, European Quantum Readiness Center [10]; HW/SW, Hardware/Software; LLM, Large Language Model, e.g., GPT

(Generative Pre-trained Transformer); QT/QTs, Quantum Technology/-ies; QTedu, Quantum Technology Education (QTedu CSA, project title) [8]; QTIndu, Quantum Technologies courses for Industry (project title) [28]; QUCATS, Quantum Flagship Coordination Action and Support (project title) [7]; STEM, Science, Technology, Engineering, and Mathematics.

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Author contributions

FG prepared, conducted and analyzed the interviews, prepared the CFQT drafts, collected feedback and wrote the original manuscript. SG conducted the LLM-based analysis (Sec. 2.3). All authors contributed to the study design and analysis, i.e. they discussed the methods and results, revised the manuscript, and read and approved the final manuscript.

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Data Availability

The three versions v2.1-v2.3 of profile descriptions are available on Zenodo, DOI <https://doi.org/10.5281/zenodo.13907420>. Here, also the data from the industry needs analysis is available.

Declarations

Ethics approval and consent to participate

Ethical review and approval was not required for the study on human participants in accordance with the local legislation and institutional requirements.

Financial interests

The authors have no relevant financial or non-financial interests to disclose.

Competing interests

The authors declare no competing interests.

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