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NATIONAL DEVELOPMENT OF QUANTUM TECHNOLOGIES, OPTIMAL STRATEGY FOR THE REPUBLIC OF CROATIA

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Abstract

This article concerns about an optimal strategy for development of quantum technologies with an emphasis on their dual purpose. This paper sought to quantify how important it is in these strategies to develop a national expert base, relying on the existing higher education system. The specificity of the Republic of Croatia is that it is a smaller country without a highly developed technology base, but as a member of NATO and the EU, it has the opportunity to participate in collaborative projects that require adaptation of ministerial responsibilities and administrative processes. Delay and neglect of participation in the development of quantum technologies inevitably leads to economic dependence, large expenditures, technological dependence and the creation of serious defence and security weaknesses. Bearing all this in mind, a bibliometric study was conducted that pointed to the current state of national scientific research work and education in the field of quantum technologies and this study identify areas in which significant progress has been made by the Croatian academia which can be a foundation for the further development. The second research uses the Analytic Network Process (ANP) method to indicate the optimal organizational framework for the strategy of initiation and development of quantum technologies at the national level. The analytical network model has pointed out the exceptional importance of higher education in supporting defence and security as well as the national economy. At the same time, in the tripartite synergy of their respective ministries, higher education will achieve significant progress in high technologies. The result of this model is a proposal for developed and active interdepartmental cooperation, without the need to establish new administrative units and institutions.

Keywords: *dual use technologies; quantum technologies education; bibliometrics; analytic network process.*

Introduction

The authors noticed a significant effort in the systematization of quantum technologies made during the last five years and decided to use it for research in order to gain insight into the current state of development of quantum technologies in the Republic of Croatia, acknowledging the need for participation in scientific and research work in the field of quantum technologies (de Touzalin et al., 2016), but also taking into account all the specificities of the Republic of Croatia as a smaller NATO and EU member state. Research was also conducted into the optimal national strategy for initiating and maintaining national activities in the field of quantum technologies. Several methods of classification of quantum technologies were available to the authors; RAND's (Parker, 2021), a method from the Czech Faculty of Nuclear Sciences and Physical Engineering (Krelina, 2021) and the Joint Research Centre of the European Commission (JRC, 2024). Despite their mutual minor differences, all three methods agree on the grouping of quantum technologies into three large entities:

1. quantum computing
2. quantum communications
3. quantum sensors.

Quantum technologies do not have to be exclusively related to one of the mentioned entities, on the contrary, they can extend through several entities (Jeager, 2018; Müller and Greinert, 2024), this is the reason why the authors gave up proposing their own method of classifying quantum technologies, but opted for the JRC method, which is supported by bibliometric application that, from the databases of scientific and professional works; Cordis, Patstat and Scopus, finds reference articles and creates a social network of collaborators on their creation. The JRC divides quantum technologies into 17 categories (details in the next chapter of this article) that can be observed in their original form or connected to the three entities mentioned. The possibility to repeat this research in a few years, for the purpose of researching the shift in relation to the year 2024, definitely prevailed in the decision to use the JRC method of classification of quantum technologies.

Research methods

In this article we will explore the activity of the Croatian scientists across the 17 quantum technologies, as monitored by the European Commission, through the regular tasks of the European Joint Research Centre, all within the framework of the "Knowledge for policy" European Union policy (European Commission, 2018). Based on an insight into the current scientific production, globally and locally, research was conducted with the aim of determining the optimal strategy of the Republic of Croatia for sustainable activities in the field of quantum technologies. The quantum technologies are important for the Republic of Croatia for the development of new defence and security capabilities, both national and as a result of NATO and EU membership obligations (Lele, 2021). Research and development in the field of quantum technologies requires significant national resources; primarily human, then material and organizational. This effort would not have to be an additional cost to society, but more likely an investment in the development of new technologies, which mostly have a dual purpose (Banafa, 2023; Pal et al, 2024). The return on investment and eventual gains will be all the greater the sooner the economy gets involved in research and development of quantum technologies (Gunashekar, 2022).

Research on the optimal strategy was carried out using the Analytical Network Process (ANP) method with three levels; two levels of criteria (strategic and control criteria) and the level of alternatives (Saaty and Vargas, 2013). Alternatives are organizational models at a strategic level that include responsible government departments and the industry, private and public. The method of the analytical network procedure reveals the most favourable alternative and ranks the remaining alternatives with a quantitative evaluation of their success.

Results

Three studies were conducted in this work; the first refers to scientific activities in the field of quantum technologies in the neighbourhood states of the Republic of Croatia, the second to the scientific activity of Croatian scientists in relation to the world production of works, and the third is a multi-criteria analysis whose goal is to propose the best strategy for the relative relationship between the involvement of defence, economy and science. The first two studies were conducted as bibliometrics, using the TIM tool, Tool for Innovation Monitoring, developed for the needs of the JRC (JRC, 2024). For the third research, an ANP network with alternatives, policies for the national development of quantum technologies were conceived and developed.

Quantum technologies activities in the neighbourhood states

According to the TIM tool, in the first research a monitoring scientific production until the end of 2024 for following sixteen countries (Table 1): Albania (AL), Austria (AT), Bosnia and Herzegovina (BO), Bulgaria (BG), Czech Republic (CZ), Greece (GR), Croatia (HR), Hungary (HU), Italy (IT), Montenegro (ME), North Macedonia (MK), Serbia (RS), Slovenia (SI), Slovakia (SK) and Turkey (TR) the marks in the Table 1 show the quantum technologies with at least one scientific, professional, project or technological document was published in the monitored country. Austria, Czech Republic, Italy and Turkey have published papers in all 17 quantum technologies. This indicates the wide interest of experts and comprehensive support for the quantum related research. In the regional framework, these are the centres towards which countries with less developed quantum technology research should strive for cooperation. Bulgaria, Greece, Hungary, Romania, Slovenia and Slovakia follows with representation in more than 75% of technologies. They are also interesting for cooperation because they can be complementary, countries can encourage the development of some of the unrealized technologies through joint activities. Albania, Bosnia and Herzegovina and North Macedonia are countries with a small number of quantum technologies covered with published works and until the end of year 2024 Montenegro still have no published quantum technology related works.

This approach to assessing the state's technological maturity is a better indicator for the lack of activity appoints than relative scientific activity comparison. Croatia is currently in the middle in terms of activities in quantum technologies so it will be necessary to investigate in more detail the number of papers and the continuity of research. In the continuation of the work, a more detailed study was conducted for the Republic of Croatia.

Table 1. Representation of quantum technologies in the works of researchers in the geographical proximity of the Republic of Croatia until the end of 2024 (JRC, 2024)

Quantum technology	AL	AT	BA	BG	CZ	GR	HR	HU	IT	ME	MK	RO	RS	SI	SK	TR
Quantum dots		x			x	x		x	x			x	x	x	x	x
Quantum chip		x		x	x	x		x	x			x				x
Quantum memory		x		x	x	x	x	x	x			x	x	x	x	x
Quantum computer		x		x	x	x	x	x	x			x	x	x	x	x
Q. simulation		x		x	x	x	x	x	x			x	x	x	x	x
Quantum clock		x	x	x	x	x		x	x			x	x	x	x	x
Q. cryptography		x	x	x	x	x	x	x	x		x	x	x	x	x	x
Q. key distribution	x	x	x	x	x	x	x	x	x			x	x	x	x	x
Post-quantum crypto		x	x	x	x	x	x	x	x		x	x	x	x	x	x
Quantum repeaters		x	x		x	x	x	x	x						x	x
Quantum Internet		x		x	x	x	x	x	x			x	x	x	x	x
Q. teleportation		x		x	x	x	x	x	x			x	x	x	x	x
Quantum radar		x			x				x					x		x
Quantum sensing		x		x	x	x	x	x	x			x		x	x	x
Quantum imaging		x			x	x	x	x	x			x			x	x
Quantum INS		x		x	x	x	x		x			x				x
Q. metrology	x	x		x	x	x		x	x			x	x	x		x
Involvement	12%	100%	29%	76%	100%	94%	71%	88%	100%	0%	12%	88%	65%	76%	76%	100%

Areas of the Croatian activities in the quantum technologies

The comparison of the activities of Croatian researchers with global trends was carried out as the second research through eleven quantum technologies in which Croatian researchers showed activity (Table 2). Each of the technologies is tracked chronologically and globally through the number of works, presentations, participation in conferences, book chapters, patents and EU projects according to data from the TIM tool. Based on this data, the area of quantum technologies in which Croatian scientific institutions have the greatest expertise was identified; quantum key distribution and quantum internet.

Table 2. Comparison of total world publication activity with Croatian scientists in the fields of quantum technologies (CEMS - Centre of Excellence for Advanced Materials and Sensing Devices, Zagreb); years of the first and last published works of the Croatian scientists and total number of works published in the world; the institutions are named when they are in the leading role, in the case when the Croatian scientists are co-authoring with other institutions the "International cooperation" is marked (JRC, 2024)

Technology	World	Institution	First	Last	Works
Quantum memories	3502	Rudjer Boskovic Institute	2013	2014	4
		Institute of Physics	2022	2022	1
		CEMS	2023	2023	1
		University of Rijeka	2024	2024	1
		International cooperation	2013	2024	5
Quantum computers	5537	University of Zagreb	2007	2022	2
		Rudjer Boskovic Institute	2022	2022	1
		International cooperation	2007	2007	1
Quantum simulations	4679	International cooperation (MOQS)	2020	2020	1
Quantum clock	1069	Institute of physics	2022	2022	1
Quantum cryptography	8232	Rudjer Boskovic Institute	2012	2021	4
		University of Zagreb	2011	2019	2
		CEMS	2021	2021	1
		Sedmi odjel & Random Red	2023	2023	1
		International cooperation	2011	2023	6
Post-quantum cryptography	3199	Sedmi odjel & Random Red	2023	2023	1
Quantum key distribution	11045	Rudjer Boskovic Institute	2012	2023	18
		University of Zagreb	2019	2023	4
		CEMS	2018	2023	3
		International cooperation	2012	2023	26
Quantum repeater	1218	University of Zagreb	2000	2000	1
Quantum Internet	4928	Rudjer Boskovic Institute	2016	2023	16
		CEMS	2022	2023	3
		University of Zagreb	2022	2024	3
		International cooperation	2016	2024	14
Quantum teleportation	4466	University of Zagreb	2003	2011	2
		International cooperation	2011	2011	1
Quantum sensing	3333	International cooperation	2016	2017	2
Quantum Inertial Naviational Systems	240	International cooperation	2017	2017	1

Quantum key distribution

Quantum key distribution (QKD) technologies have been extracted out from quantum cryptography due to their extreme importance (Dragun, 2022). Not only telecommunications depend on the secure delivery of keys, but all value transactions and electronic signatures, i.e. document authentication, are based on them. QKDs are founded on the quantum state no-cloning theorem and are closely related to quantum repeater technology. In theory, QKD prevents the so-called “man-in-the-middle” attack techniques in which an eavesdropper inserts himself into the communication channel and spoofs both parties. With the application of QKD, any measurement of the quantum state will be detected, without the possibility of its cloning. At the time of writing this paper, QKD is among the most developed quantum technologies (Krelina, 2021 p.13).

According to the data in Table 3, institutions from China, the United States, Canada and Singapore dominate the national representation of institutions that published works on the topic of QKD by the end of 2024. In the same period, Croatian scientists were also active (Table 2), in continuous work confirming that they are the most developed, in relation to all quantum technologies that have been developed in the Republic of Croatia.

Table 3. Published QKD documents till the end of 2024 according to ten top institutions engaged (JRC, 2024)

Institution	First	Last	Documents
University of Science and Technology of China	1996	2024	592
QUANTUM CORP	2001	2024	535
Beijing University of Posts and Telecommunications	2003	2024	430
China University of Mining and Technology	2009	2024	224
Tsinghua University	2002	2024	220
University of Waterloo	2004	2024	216
Chinese Academy of Sciences	2001	2024	212
Toshiba Corp	2002	2024	200
Central South University	2007	2024	179
National University of Singapore	2003	2024	173

Quantum internet

In its bibliometric research, the JRC singles out the quantum Internet as a separate technology. This is the specificity of the JRC approach because the quantum Internet represents the integration of the successful mastery of quantum technologies in the domains of quantum computing and quantum telecommunications. China, United States, Netherlands, and United Kingdom predominate among the ten scientific institutions that are most productive in works on the subject of the quantum internet by national representation (Table 5). The "Ruđer Bošković" Institute from Zagreb, Croatia is active in quantum internet technology research continuously until 2016, and two more institutions; University of Zagreb and CEMS joined it in 2022 (Table 2).

Table 4. Published documents from quantum internet technologies for the ten most active scientific institutions in the world until the end of 2024 (JRC, 2024)

Institution	First	Last	Documents
University of Science and Technology of China	2002	2024	253
QUANTUM CORP	2007	2024	201
Massachusetts Institute of Technology	2001	2024	140
Chinese Academy of Sciences	2003	2024	123
California Institute of Technology	1997	2024	120
Delft University of Technology	2010	2024	112
Shanxi University	2011	2024	107
Harvard University	2005	2024	103
University of Oxford	1996	2024	94
Tsinghua University	2006	2024	84

Analytical network process

Continuing with the results of the activities of Croatian scientists in the field of quantum technologies, research was conducted with the aim of recommending the optimal strategy of a national organization which, in addition to the development of defence and security capabilities, will encourage and promote further research, all in the context of international cooperation and creation of the applicable material and other benefits for the economy and the academic community. For this purpose, an ANP network was created with three layers of criteria; strategic, control and alternative layer (Figure 1). The topology from the layer of strategic to the control criteria is hierarchical, but in the layer of control criteria a network structure was used because interdepartmental cooperation directly affects higher education, which subsequently enables the sustainability of the ability to develop quantum technologies through the creation of the necessary staff. Likewise, interdepartmental cooperation creates a number of political gains; on the domestic political scene, in the closer geopolitical environment and in the wider international context.

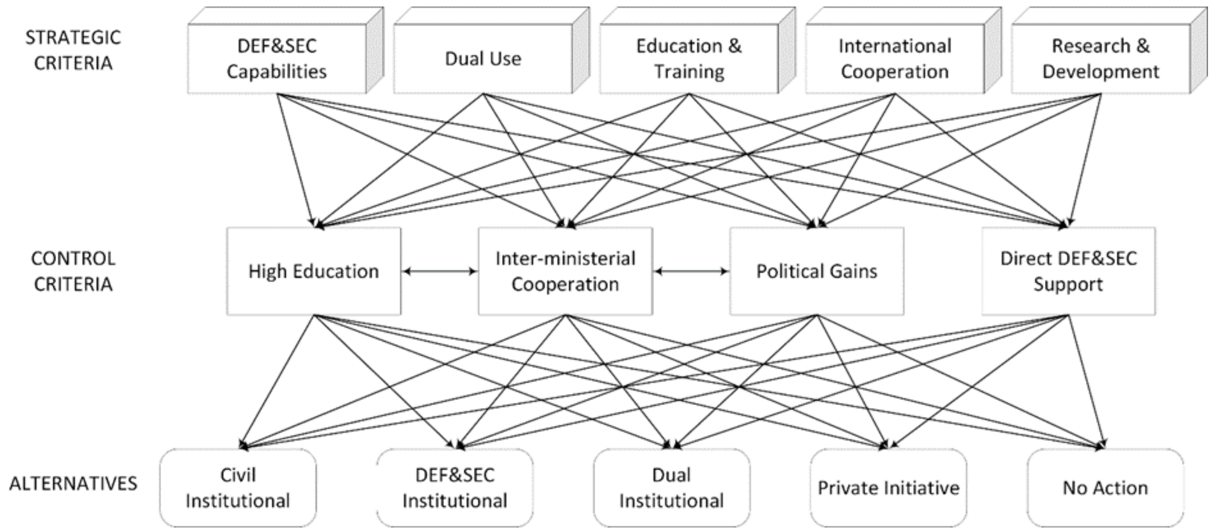

Figure 1. ANP network to search for the optimal organization to encourage and promote quantum technologies in Croatia, the network has three layers; strategic, control and alternatives layer, the network topology was used in the control criteria layer, while the connections from the strategic to the control layer and from the control to the alternative layer are hierarchical

At the strategic level, five criteria are recognized, one of which is already active; research and development. Existing research activities can be used as support for the development of other strategic criteria, first in education and training and international cooperation, and then for the development of necessary new defence and security capabilities and dual purpose with gains for the economy. The control criteria govern in what way and in what proportion the strategic criteria will be realized; on the one hand, it is direct support for solving problems related to the specific requirements of the Armed Forces, the development of combat and support systems based on quantum technologies, or the response to the potential adversary's development of the same. Given that the defence and security system in the Republic of Croatia does not have large research and development and production capacities of its own, cooperation must be foreseen from the beginning; at the national level with the departments of the economy, academic community and European integration and funds, but also at the international level through participation in collaborative activities with related scientific and research organizations of partner and friendly countries.

Alternatives are the concepts of organization, that is, the division of competences and responsibilities among existing ministries. The alternative of creating new organizational entities whose activities would focus only on the development of dual-purpose technologies was not considered because it is supposed to be a too expensive solution in terms of all required resources. Viewed from the point of view of state management of the development of quantum technologies, the alternative of maintaining the existing situation is a passive strategy that surely leads to technological backwardness and, consequently, defence and security weaknesses. The alternative of leaving it to private initiative is, from the point of view of state management, reactive; it is all about reacting to market opportunities recognized by the economy and looking for a way to fit them into the development of defence and security capabilities. The remaining three alternatives are proactive, from the point of view of the governmental authority, planning and management are carried out through the responsible ministries. At the same time, the development of quantum technologies can be under the responsibility of the civilian ministries of economy and science, which quickly and effectively exploits their potential. Placing the development of quantum technologies under the jurisdiction of the defence and security ministries has its advantages, since these are emerging and disruptive technologies (EDT), extremely important for defence and security that must be appropriately controlled and managed. In the ministries of defence and security, the best security protection of people and processes can be achieved. The disadvantage is that the Republic of Croatia does not have, like the most developed countries, significant defence research and production capacities. Bearing all this in mind, an alternative of developed and intensive interdepartmental cooperation on the realization of dual-purpose projects was recognized.

The strategic criterion "Direct support for defence and security" refers to the developed ability to quickly react to the needs of the defence and security system; in response to a partner's request to participate in the development of a capability, either as an opportunity to participate in the development of a defence-security capability or as a need for a quick response to a threat due to the development of some quantum technology from competing or hostile countries. The assessment of pairs of control criteria with regard to the strategic criterion "Defence-security capabilities" (Table 5) shows the priority according to interdepartmental cooperation; for example, interdepartmental cooperation is slightly more important than political gains and it is only slightly more than equally important than direct support for defence and security; intensities of importance in the Tables 5 to 13 are; 1 – equal, 3 – moderate more important, 5 - strongly more, 7 – demonstratable more important and 9 – dominantly more important, values 2, 4, 6 and 8 lies between the main importances in the case when we cannot decide (Saaty, 2001). Reciprocal values indicate greater importance of the criteria in the columns; for example, political gains are strongly more important (1/5), and interdepartmental cooperation is demonstratable important (1/7) than higher education. The inconsistency is acceptably low and amounts to 0.06789.

Table 5. Assessment of the importance of the strategic criterion "Defence and security capabilities"

Inconsistency: 0.06789	**Inter-ministerial cooperation**	**Political gains**	**Direct defence and security support**
High education	1/7	1/5	1/4
Inter-ministerial cooperation		3	2
Direct defence and security support			1/3

The strategic criterion "Dual use" proves to be extremely important because it points to the possibility of dual application of developed technologies, which is an opportunity to create real value through the economy, as well as science. On the other hand, regular monitoring (so called TechWatch) of the state and development of quantum technologies makes it possible to promptly recognize the particular quantum technology that could become an EDT in the foreseeable future. A prerequisite for dual purpose is the developed inter-ministerial cooperation of the responsible ministries (defence, internal affairs, economy and sustainable development, science, European integration and funds, ...) which has a stronger importance (value 1/5) compared to higher education, a moderate importance (1/3) in relation to possible political gains and barely noticeable (1/2) in relation to direct support for defence and security (Table 6). According to the evaluations of the criteria, a satisfactory consistency was achieved (0.07612) with the greatest emphasis on interdepartmental cooperation, followed by political gains and a somewhat greater importance of direct support for defence and security, and higher education has the least importance because it takes advantage of favourable circumstances only after all the previously mentioned criteria have been achieved, as prerequisites.

Table 6. Assessment of the importance of the strategic criterion "Dual purpose"

Inconsistency: 0.07612	**Inter-ministerial cooperation**	**Political gains**	**Direct defence and security support**
High education	1/5	1/3	1/2
Inter-ministerial cooperation		3	2
Political gains			1/3

"Education and training" is a strategic criterion that has a double importance; for higher education institutions where direct scientific research work takes place and through the development of existing and creation of new professional staff, which is the most important prerequisite for the sustainability of the capabilities of quantum technologies. This strategic criterion includes all forms of acquiring knowledge about quantum technologies; in addition to higher education, training through civil and military international cooperation is also included, which especially relates to the preparation and implementation of international projects. From the perspective of education and training, higher education has the biggest gain, whose criteria have greater importance in relation to political gains, direct support for defence and security, and even interdepartmental cooperation (Table 7). A low inconsistency (0.03831) was achieved when evaluating the importance of the criteria.

Activities related to quantum technologies require large and permanent investments. This is too demanding for small countries, therefore "International cooperation" is a necessary strategic factor. International cooperation should be implemented through the institutional framework of European funds for science and research (for example; H2020, EDF, HEDI) as well as complementary NATO initiatives and organizations (namely; PfP, STO, DIANA). In addition to sharing resources and costs, international cooperation significantly supports the creation and development of the necessary personnel.

Table 7. Assessment of the importance of the strategic criterion "Education and training"

Inconsistency: 0.03831	**Inter-ministerial cooperation**	**Political gains**	**Direct defence and security support**
High education	5	4	3
Inter-ministerial cooperation		2	1/2
Political gains			1/3

A prerequisite for successful international cooperation is competent interdepartmental cooperation, which according to the criteria (Table 8) has the greatest importance, followed by political gains and direct support for defence and security and higher education. The reason for this is that interdepartmental cooperation must first be developed and a political consensus obtained in order to achieve the prerequisites for the realization of activities around quantum technologies through direct support for the development of defence and security capabilities and the development of higher education. When evaluating the criteria, an extremely low inconsistency was achieved (0.00925).

Table 8. Assessment of the importance of the strategic criterion "International cooperation"

Inconsistency: 0.00925	**Inter-ministerial cooperation**	**Political gains**	**Direct defence and security support**
High education	1/5	1/3	1/2
Inter-ministerial cooperation		1	2
Political gains			2

The strategic criterion "Research and development" refers to the national need to achieve a sufficient level of competence in quantum technologies in order to ensure the competitiveness of the economy and the necessary capabilities of the defence and security ministries. Viewed from the interest of the strategic criterion "Research and development", higher education will have the greatest importance and gain. This is the specificity of the Republic of Croatia, as the majority of scientific research work will be carried out in institutions of higher education and institutes under the authority of the Department of Science and Education. The importance of the criteria is followed by interdepartmental cooperation, direct support for defence and security, and political gains. When assessing the importance of the criteria, an extremely low inconsistency of 0.04544 was obtained (Table 9).

Table 9. Assessment of the strategic criterion "Research and development"

Inconsistency: 0.04544	**Inter-ministerial cooperation**	**Political gains**	**Direct defence and security support**
High education	2	3	2
Inter-ministerial cooperation		3	1/2
Political gains			1/3

When evaluating the control criteria, we use a hierarchical topology according to the alternatives, but also a network topology because "Inter-ministerial cooperation" affects the control criteria "High education" and "Political gains". Evaluating the criteria of the alternatives from the point of view of the control criterion "High education", the alternative of dually represented departments, i.e. interdepartmental cooperation of all ministries with complementary competences, was the best evaluated (Table 10). From the point of view of the interests of higher education, the lowest rated alternative is no action - maintaining the existing situation, followed by private initiative, followed by the alternative of developing quantum technologies through civil ministries, then through dedicated defence and security ministries, and as the best option, inter-ministerial cooperation through dually represented ministries. Criterion evaluations have a small inconsistency of 0.05372.

Table 10. Evaluation of the control criterion "Higher education" according to alternatives

Inconsistency: 0.05372	**Defence and security institutional**	**Dual institutional**	**No action**	**Private initiative**
Civil institutional	1/2	1/5	5	4
Defence and security institutional		1/3	7	5
Dual institutional			9	7
No action				1/3

The control criterion of inter-ministerial cooperation affects the control criteria "High education" and "Political gains". This is why the entire model has a network rather than a hierarchical topology. The reason why "Direct support to defence and security" is not included in the inter-ministerial cooperation is from the experience with similar requests from the departments of defence and internal affairs according to specific technologies that develop their capabilities; at the national level and according to NATO and EU requirements. These requirements are expressed through the so-called "Catalogues of capabilities" which are confidential documents, as well as EU-EDA development documents; Capability Development Plan and Coordinated Annual Review on Defence. Other ministries are not included in the details, since this means an unnecessary expansion of the circle of people with access to confidential information. The armed forces, through the Directorate for Planning of the General Staff, request opinions and studies from the Directorate for defence policy of the Ministry of defence of the Republic of Croatia, which coordinates further activities with other civilian departments. The assessment of the importance of the criterion "Higher education" in relation to "Political gains" from the point of view of "Interdepartmental cooperation" is that political gains are somewhat more important (value 3 in the Table 11) than higher education. The assessment of only two criteria does not enable the calculation of assessment inconsistency.

In relation to the alternatives, inter-ministerial cooperation absolutely dominates (value 9) in relation to maintaining the existing situation, dually represented ministries are a somewhat better alternative compared to military and security authorized ministries, a better alternative (value 5) compared to departments of civil jurisdiction and extremely better alternative (value 7) in relation to private initiative (table 11). An acceptable low inconsistency of the evaluation criteria of the amount 0.04734 was achieved.

Table 11. Evaluation of the control criterion "Interdepartmental cooperation" according to alternatives

Inconsistency: 0.04734	**Defence and security institutional**	**Dual institutional**	**No action**	**Private initiative**
Civil institutional	1	1/5	5	3
Defence and security institutional		1/3	7	5
Dual institutional			9	7
No action				1/3

The political gains are national and international. At the national level, this is the affirmation of the national policy of developing science and the economy by creating opportunities for the academic community and the industry, especially for small and medium-sized enterprises, to achieve exact and measurable economic and academic achievements. The exceptional complexity and cost of investing in quantum technologies leads smaller countries to international cooperation, which results in political gains in terms of foreign policy affirmation in the region and globally. The assessment of the control criterion "Political gains" according to the alternatives differs to a lesser extent from the previous control criterion. The importance of defence and security departments was estimated to be slightly higher (value 1/3), the alternative of dually represented departments, followed by defence and security and civil departments was also the best evaluated alternative, while the alternatives of private initiative and maintaining the existing situation were rated the worst (Table 12). Alternative estimates have an inconsistency of 0.07132, which is within acceptable values.

Table 12. Evaluation of the control criterion "Political gains" according to alternatives

Inconsistency: 0.07132	**Defence and security institutional**	**Dual institutional**	**No action**	**Private initiative**
Civil institutional	1/3	1/5	6	3
Defence and security institutional		1/4	7	4
Dual institutional			9	6
No action				1/3

The remaining control criterion "Direct support for defence and security" was emphasized according to the experience of frequent requests for small and short-term projects, most often initiated by NATO and the EU. In these projects, a quick and concrete answer to a less complex technological problem is sought. This is a significant difference in the organizational approach compared to the comprehensive and permanent organization of the development of quantum technologies at the national level. In the case of a request for a quick response to a short-term project, which can also be initiated for national needs by the authorized ministries, it is necessary to have already developed capabilities and an active and expanded network of collaborators. According to experience so far, the private sector is in this somewhat more successful than the civil ministries, and assessments of the importance of alternatives still prefer dually represented ministries and defence-security ministries while maintaining the current situation as the least desirable alternative (Table 13). The inconsistency of the estimated criteria is acceptably low at 0.07937.

Table 13. Evaluation of the control criterion "Direct support for defence and security" according to alternatives

Inconsistency: 0.07937	**Defence and security institutional**	**Dual institutional**	**No action**	**Private initiative**
Civil institutional	1/6	1/7	3	1/3
Defence and security institutional		1/5	7	2
Dual institutional			9	4
No action				1/7

According to the data from tables 7 to 13 the synthesis of the ANP model was carried out, the result of which prefers the strategy of Dual institutional as the most favourable alternative for the development of quantum technologies with an emphasis on the needs of defence and security (Table 14). The "Raw" column shows the output values from the model in Figure 4. For their comparison, we first normalize them; divide each of the original results by the sum of all results to get a column in which there are "Normalized" values whose sum is 1.00000. Finally, we divide all normalized values by the highest ranked normalized value to obtain a column of "Idealized" values for quantitative comparison of alternatives.

Table 14. Synthesis of the ANP model of the optimal strategy of the institutional organization at the national level

Rank	**Alternative**	**Idealized**	**Normalized**	**Raw**
1.	Dual institutional	1.00000	0.52673	0.26337
2.	DEF&SEC institutional	0.42777	0.22532	0.11266
3.	Civil institutional	0.28438	0.14979	0.07490
4.	Private initiative	0.12357	0.06509	0.03255
5.	No action	0.06278	0.03307	0.01654

Dually represented ministries have developed and active inter-ministerial cooperation and enables the inclusion of all potentials at the national level, all with planning and management that achieves gains for the defence-security and civil sectors in the best way, it is a first-rate alternative. The 2nd rank alternative is for the defence and security ministries to be responsible for the development of quantum technologies, and this alternative is about 43% of the 1st rank alternative. Civil departments create frameworks for the development and application of quantum technologies through civil public and private institutions, organizations and companies. It is to be expected that most of the scientific and research work will be carried out in them, but without planning and support from the defence and security ministries, this alternative will not be able to adequately meet the development of the necessary defence and security capabilities, and it will be more difficult to meet the requirements for short-term projects with a quick application. Adding to that a lower security culture in the civil organizations, that is why this alternative is of the 3rd rank and represents about 28% of the ideal solution, behind the alternative with jurisdiction in the defence and security departments. On the penultimate, 4th rank, there is an alternative with a private initiative that is oriented towards market opportunities and competition with about 12% of the ideal solution. However, one should not ignore the ability of private initiative to quickly respond to opportunities that may arise by calling for participation in simpler and short-term projects, such as the CatB projects of the European Defence Agency.

Conclusion, discussing and recommendations

Conducted bibliometric research and following research using the proposed analytical network procedure model provide an insight into the current state of development of quantum technologies at the national level for the Croatia, as a smaller NATO and EU country, i.e. strengths and weaknesses are observed and an optimal strategy is proposed for their further development in international, collaborative development through dual civil-military application. Looking at the surrounding countries (Table 1), we see that Croatian scientists show an interest in research in the field of quantum technologies and that they have published papers in 11 of the 17 monitored technologies, according to JCR methodology. The non-representation of works in the remaining six areas of quantum technologies is a minor weakness compared to the lack of continuity of scientific activity. Papers that appear a small number of times and do not reappear again indicate that they are not part of the comprehensive planning of scientific activity. The recommendation of this paper is to immediately begin gathering interested parties from the departments of science, economy, and defence and security in order to create a national strategy for the development of quantum technologies. This strategy would have to provide for broad international cooperation through civil and defence-security activities, supranational organizations such as the EU and NATO, and through dedicated funds. The strategy should envisage specific bearers of tasks and responsibilities for future development and the allocation of specific and regular financial support for activities.

Special attention should be paid to the sustainability of the ability to develop quantum technologies through the education of future experts and the popularization of quantum technologies in order to ensure the long-term influx of interested scientists and experts.

Bibliometric research pointed to the strength of Croatian scientists in two areas: quantum key delivery and quantum internet. In the field of quantum key delivery, the "Ruđer Bošković" Institute (IRB) from Zagreb has been continuously active since 2016, the Centre of Excellence for Advanced Materials and Sensors (CEMS, also at the same institute) has been continuously active since 2018, and the University in Zagreb from 2019. Given that QKD is one of the areas of quantum technologies with a high level and pace of development they represent a strong support for the inclusion of these organizations in dual-purpose projects, especially in short-term projects with concrete and technologically achievable results. The same is true for quantum internet technologies, despite the fact that this field is much broader in application than QKD. The same three scientific organizations have been active in recent years. IRB continuously since 2016, and CEMS and the Institute of Physics of the University of Zagreb since 2022.

The results of the third research, the quest for the best organizational form for initiation and maintaining the research and development capability of the dual purpose of quantum technologies, indicate that the best solution is the interdepartmental cooperation of all involved ministries; defence, internal affairs, economy and sustainable development, science and EU integration and funds. The second ranked alternative, placing the responsibility for the development of quantum technologies in the departments of defence and security, is more than twice as bad, and the worst alternative of maintaining the existing situation is almost 16 times worse (Table 14). Leaving the development of quantum technologies exclusively to civil departments and private initiative also resulted in a bad rating in the synthesis of the model, which is a consequence of the fact that all quantum technologies are disruptive and emerging, that is, when evaluating all the criteria in the model, the possible impact on capabilities was always considered defence and security. The situation is further complicated by our international obligations towards NATO and the EU, however, this "complication" is not in a negative context, on the contrary, it opens up great opportunities for joint acting in international projects and applying for dedicated funds. Complexity refers to more advanced organizational and administrative processes that accompany international, collaborative activities. The interdepartmental meeting does not envisage the establishment of new institutions, but primarily envisages the constant coordination of the existing and responsible units in the mentioned ministries, which is joined by the Planning Directorate (J5) of the General headquarter of the Croatian Armed Forces with its plans for the development of the Croatian Armed Forces and national obligations for the development of NATO's Capability Objectives. According to the needs of the armed forces, articulated by the J5, the directorates of the Ministry of defence; M1 “Defence policy” and M3 “Material resources” should build a framework of interministerial and international collaboration. In the ANP model, perfect organizations within the responsible ministries are assumed. In order to confirm their respective "administrative potential", which is a measurable quantity (Zoretić, 2018), it is necessary to conduct an external evaluation of the competencies of public administration officials as well as business processes developed by the relevant ministries for mutual cooperation in international projects and activities. If it turns out that the administrative potential in the responsible departments is insufficient, the only possible form of organizing activities to support the development of quantum and other high technologies would be through the establishment of a national non-profit organization, which can be the subject of future research.

Through the ministry responsible for education, it is necessary to ensure a constant interest in quantum technologies, already from the level of primary and secondary education, as well as the encouragement of higher education programs in all relevant areas with constant support for scientific research in these areas through national and international projects. Quantum technologies are specific for their great dynamism and multidisciplinary, and it is necessary to develop lively international cooperation and constant exchange of personnel in all institutions.

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NACIONALNI RAZVOJ KVANTNIH TEHNOLOGIJA, OPTIMALNA STRATEGIJA ZA REPUBLIKU HRVATSKU

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Sažetak

Ovaj članak bavi se optimalnom strategijom razvoja kvantnih tehnologija s naglaskom na njihovu dvojnu namjenu. U ovom radu nastojalo se kvantizirati koliko je u tim strategijama važno razviti nacionalnu bazu stručnjaka, s osloncem na postojeći sustav visokog obrazovanja. Specifičnost Republike Hrvatske je u tome što je ona manja država bez visoko razvijene tehnološke baze, ali kao članica NATO-a i EU ima priliku sudjelovati u suradničkim projektima koji zahtijevaju prilagodbu resornih nadležnosti i administrativnih procesa. Kašnjenje i zanemarivanje sudjelovanja u razvoju kvantnih tehnologija neizbježno dovodi do ekonomske ovisnosti, velikih izdataka, tehnološke ovisnosti i stvaranja ozbiljnih obrambenih i sigurnosnih slabosti. Imajući sve to u vidu, provedeno je bibliometrijsko istraživanje koje je ukazalo na trenutno stanje nacionalnog znanstveno-istraživačkog rada i obrazovanja u području kvantnih tehnologija te je identificiralo područja u kojima je hrvatska akademska zajednica napravila značajne pomake koji mogu biti temelj za daljnji razvoj. Drugo istraživanje koristi metodu analitičkoga mrežnog procesa (ANP) kako bi ukazalo na optimalni organizacijski okvir za strategiju pokretanja i razvoja kvantnih tehnologija na nacionalnoj razini. Analitički mrežni model ukazao je na izuzetnu važnost visokog obrazovanja u potpori obrani i sigurnosti kao i gospodarstvu. Istovremeno, u trodijelnoj sinergiji njima nadležnih resora, visoko obrazovanje će ostvariti značajan progres u visokim tehnologijama. Rezultat ovog modela je prijedlog razvijene i aktivne međuresorne suradnje, bez potrebe osnivanja novih upravnih jedinica i ustanova.

Ključne riječi: *tehnologije dvojne namjene; obrazovanje o kvantnim tehnologijama; bibliometrija; analitički mrežni proces.*