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A Model to Assess the Impact of Computer Simulations and Photonics Demonstrations in Quantum Information Learning

Francisco Delgado[1], Alan Anaya[2], Alfonso Jaimes-Nájera[1] and Marco Enríquez-Flores[1]

[1] Tecnologico de Monterrey, School of Engineering and Sciences, Mexico.
[2] Technical University of Denmark, Physics department, Denmark.

E-mail: s222435@dtu.dk

Abstract. Quantum information Education is a growing area where professionals and students of diverse disciplines converge to develop proper solutions. The interest of those students is materialized seeking introductory approaches to this knowledge. Still, learning design for diverse backgrounds requires multiple approximations for theoretical contents, applications, calculation scaffolding, etc. Innovation oriented towards this effort becomes valuable due to students' limited time for such an experience. This work presents a proposed assessment for three technical innovation initiatives in Quantum information Education based on a mathematical model proposed to measure their impact on the research products through eight dimensions. Outcomes show an explicit sustained improvement in the quality of those products, while the model lets to identify the fingerprint of each innovation through a set of eight dimensions.

1. Introduction

Computers have transformed our world in just some decades generating improvements in all human activities and inquiring deeply in most of the knowledge areas [1]. But the amount of information regarding contemporary problems is overtaking the capacity of our current computer technology. Quantum information has appeared as a tentative solution refocusing the management of those large amounts of information into faster processing [2]. Thus, this emerging development area is continuously growing toward computer simulation necessities of almost all other disciplines.

It has implied an effervescent inclusion of Quantum information curricula in schools and universities [3, 4, 5], trying to involve students from other disciplines such as Math, Physics, and Computer sciences. Thus, chemists, biologists, data scientists, several kinds of engineers (nanotechnology, electronics), and even economists have become involved. Several of those initiatives have been documented and reported. Together, in the last decade, an increasing number of resources and technologies have emerged to approach the related topics of Quantum information.

In fact, because complex problems require detailed modeling in terms of Quantum processing, new maths, and knowledge are required to learn. Those topics, out of the main scope of those collateral disciplines should be supported by easier tools approaching them in the theoretical treatment of Quantum information. Also, as a physical development, the approximation to physical and experimental concepts is precise at least to some extent to provide a better understanding and limitations provided by their foundations.

In the institution where this report has been performed, the Quantum Information Processing Group has developed attraction efforts on different engineering and science programs for more than ten years [6]. This effort has been based on a cascade involvement of students in the area, and then possibly to post-graduate programs [5]. This effort has promoted the inclusion of technologies to scaffold those students with a slender math and physics Education [7].

The aim of this paper is to present an assessment model of educative innovation interventions for research Education, particularly applied to the Quantum information Education initiatives, thus exhibiting its utility. Section 2 depicts the description of the mentioned educative effort with the main innovative interventions in terms of development technology and experiment. The third section states the theoretical background supporting the proposed assessment model, which is depicted at the end of that section. Then, an applied analysis using such a previous model is performed in the fourth section for the last ten years of the educative initiative in Quantum information in our group. The final section provides the conclusions.

2. IMPROVING THEORETICAL CONTENT WITH TECHNOLOGY AND PHYSICS

Quantum information has a mathematical background diverse. It could be attained through introductory linear algebra concepts, together with easy physical concepts. Clearly, some topics will require more advanced maths, but in addition, the approach to valuable research problems requires extensive calculations commonly only reachable with computer simulations and/or algebraic management software. In addition, by centering on math and computer approaches, it leaves unattended the important underlying physical background.

2.1. Learning activities offered by Quantum Information Processing Group

The Quantum Information Processing Group of our institution has developed yearly workshops on Quantum information and processing since 2010 on a nationwide extent, mainly for undergraduate students in science and engineering. The attraction of those students provides them with a professional development area centered on research and post-graduate studies [7]. As a result, some of them arrived years after the masters or doctoral degrees offered by the group. The first workshops were completely based on the theoretical aspects of the Quantum information discipline. Despite this, years after, the use of technology was possible through the first innovation, the use of QUANTUM [8]. Since then, other innovations have been gradually introduced not only in such a workshop but also in other related courses and research stays around the discipline.

Research stays for undergraduate students began to be offered in 2015. They were optional activities for one year for science and engineering students. Those activities were combined with the normal courses for students. They had open content commonly defined by the student together with a tutor. In any case, they involved learning sections with a well-defined syllabus. In 2022, due to changes in study programs, such experiences stopped, changing by a mandatory stay in the seventh semester. One option for such a stay was the scientific research stay, on which our original programmed research stays in Quantum information continued, but in this case just as one full-time semester activity (effectively just four months). An alternative for such stays was an academic minor, a full-time experience of learning focusing on a specific area. There, the Photonics and Quantum systems minor was offered, including six modules, two of them offered by us: a) Quantum information and processing, and b) Quantum interaction between light and matter. Both experiences were just implemented in August-December 2022.

In addition to the innovative media created to reach students at distance [6, 7], particularly during the COVID-19 pandemic [9], other learning innovations in the professional terrain were introduced. Thus, three different learning interventions were considered to deliver the theoretical concepts taught. In the next subsections, we depict each one of such innovative initiatives. As a preamble, Table 1 comprises the topics involved with each innovation.

Table 1. Synthetic list of software or application practices, together with experimental demonstrations or setups by innovation

	Technological/experimental innovations introduced		
Innovation	QUANTUM	QISKIT	Photonics E & D
Practices, Experiments, or other Applications	States and gates	States and registers	Light polarization
	Bell circuit	States Initialization	Beam splitters
	Inverse Bell circuit	Defining gates from simpler circuits	Interferometers
	Teleportation circuit	Bell, Teleportation and Grover circuits	Quantum eraser experiment
	Deutsch-Jozsa algorithm	Quantum simulations and Heisenberg model	Bomb tester experiment
	Grover algorithm	Adiabatic quantum computation	Polarization rotators
	Quantum Fourier Transform	Protein folding and molecular potentials simulations	BB84 cryptography protocol

2.2. Newest learning activities for research Education based on Photonics and Quantum systems

During 2022, Research stay in Quantum information together with the Photonics and Quantum systems minor began to be offered to students in the seventh semester (the last but one in their academic programs). In those two teaching activities, the first one is based on research requesting a scientific publication to students, while the second is centered on deep knowledge in several related topics, but with an applied project in photonics.

Research stay strategy was begun with a formal class, six hours by week comprising topics such as Dirac notation, Quantum states and gates, Basics of Quantum Information, and Quantum circuits. The class included the use of LaTeX and other utilities in research (ORCID, Scopus, and Research collaboration networks). That activity covered ten weeks from a total of sixteen. The last six weeks were devoted to guiding the research work of students to generate original research work. The final product was presented to one scientific committee of researchers in the group in the last week for evaluation and recommendations.

Photonics and Quantum systems had six modules, together with a directed project in photonics. Four of such modules are based on Classical light and the last two are in Quantum light and Quantum information respectively. Both are a 45-hours course taught during the last two-thirds of the semester, distributed in three weekly lectures, each lasting 1.5 hours. Two more hours per week of tutoring for each module were provided. The Quantum information module comprises the same content as the research stay class. The quantum light and matter module is concerned with the study of the interaction of light with matter. The contents were: quantum treatment of the radiation field, introductory atomic physics (ranging from the hydrogen atom to the construction of the periodic table), and the interaction of light with a two-level atom.

As well as in the Research stay as in the minor, the use of collaborative activities based first on conceptual understanding, and then on procedural developments (problems requiring mathematical calculations). It promoted the discussion of concepts and the finding of solutions to the learning objects through peer interaction. Some activities are required to be solved using software such as Mathematica and particularly QUANTUM, as will be explained below, thus improving the learning process. The use of Mathematica was very useful to teach the second part of the Quantum light and matter module (quantum orbitals in hydrogen-like atoms). By using it, dynamic images of related functions were plotted, so the orbitals could be visualized.

2.3. QUANTUM: an Add-on of Mathematica

QUANTUM [8] is an Add-on of Mathematica software implementing Dirac Notation and many other features of Quantum information. Aided by the algebraic management of Mathematica, it lets reproduce since easy to complex discrete quantum states calculations. After a proper introduction to Bras, Kets, and operator concepts, together with operations among them and their meanings, QUANTUM is introduced as a guide for students in the calculations that emerged from the contents. Despite, after, it becomes a notable tool to perform complex calculations comprising several quantum systems. Thus, QUANTUM is used to first reinforce the algebraic ability through the contents, after, to perform more complex calculations upon a well-stated ability of critical scrutiny on the outcomes.

Thus, after to be introduced the main operations (inner product, operators, qubit notation, outer product, tensor product, probabilities, mean values, etc.), parallel developments are included in the syllabus: Bell, Teleportation, Deutsch-Josza, Grover, and Quantum Fourier transform (see Table 1). It lets the fluid use of QUANTUM in research products (poster conference presentations, research articles, etc.) with more complex and novel problems. This tool began to be introduced in 2015 in the workshops and research stays, which both had a common theoretical content. During 2022, a minor in Photonics and Quantum systems began to be offered, including a module on Quantum information and processing, there, QUANTUM was used.

2.4. QISKIT: a quantum programming interface with real quantum computers

QISKIT is an open-source software development implementing basic gate operations on two-level systems or qubits, also combining classical registers [10, 11]. Since simple developments such as quantum circuits through its composer tool, QUISKIT let to acquire the ability to implement more sophisticated code to set quantum and classical systems together, to set processing tasks. This language lets to interact with real quantum computers through circuits and algorithms. Also, it provides well-stated algorithms and procedures already implemented by the community to develop more complex problems, which can be run on the prototypical quantum devices on the IBM Quantum Experience or also computer simulators on a local classical computer.

QISKIT was first introduced in the 2019 nationwide workshop on Quantum information through a couple of talks implementing quantum circuits, visualization, and noise. The Quantum phase estimation problem was implemented with the students. Finally, an introduction to the Ising model was presented, and the adiabatic way with some of QISKIT algorithms could be constructed. In 2021 the experience was repeated in the 2021 nationwide workshop. In this case, the Teleportation algorithm was first constructed, to then move the attention to adiabatic processing, particularly the variational algorithm to find molecular potentials. Since 2022, it became a mandatory tool implemented in this case during the research stay in the group of nine undergraduate students and for all students in the minor of Photonics and Quantum systems. Topics involved are reported in Table 1. Some research articles on those groups of students implemented QISKIT applications on them, particularly in quantum cryptography.

2.5. Photonics: experimental demonstrations supporting meaningful learning
Since 2015, it was common to present during the nationwide workshop the Stern-Gerlach experiment using light polarization. This experiment is a key piece in the understanding of Quantum information operations. Then, such a demonstration was converted into an experimental practice performed by the participants. Other brief practices by 2018-2021 were added to observe: a) the hydrogen, mercury, and sunlight spectrum; b) the two-slit experiment; and c) the Michelson and Mach-Zehnder spectrometers configuration. For 2022, through the research stay and the minor courses, a complete set of demonstrations were included (see Table 1).

Despite being limited, some research articles developed by undergraduate students involved simulations based on a better comprehension of physical principles and noisy effects, being mainly related to Quantum communication topics. Graduate students have also worked with structured light, thus reaching a clearer approach to experimental research. This is a desired goal in the group around the research stays and alternative educative initiatives to combine theoretical and experimental knowledge in the student's development.

Those three innovative interventions have provided, for the research stays and the minor, a higher level of learning through the four months of each experience. But the most important aspect is to assess the impact of them on the research products delivered by the students through time, particularly in the last ten years, comprising the events where the innovations were introduced. Commonly, the research products were initially posters to be presented in some national or still international conferences (2013-2019), but with the experience gained in the workshop and the research stays, they moved on to research articles (2017-2022). In the next section, we present a model to perform a such assessment based on the analysis of such research products.

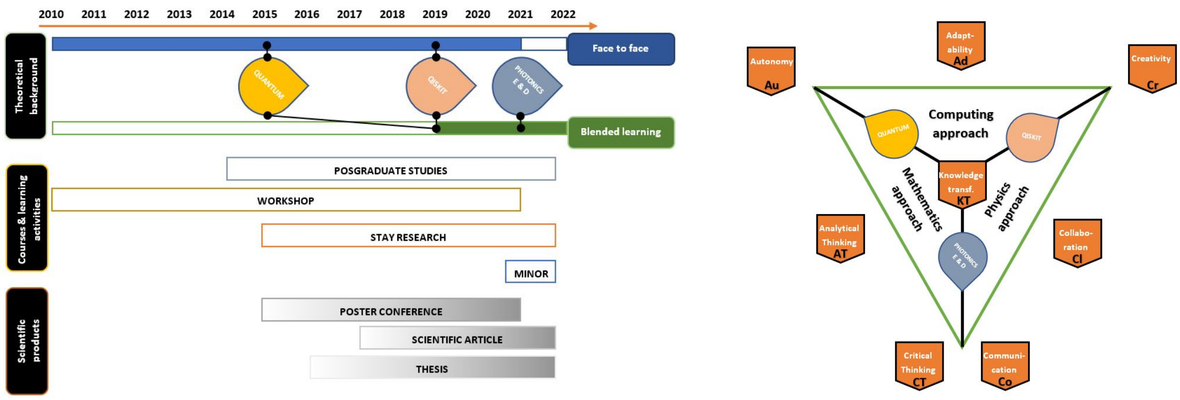
3. A model to assess the impact of innovations in research education
Motivation for learning innovation, particularly in sciences, should be centered on the effort to explain their relevance. Innovations typically exploit computer simulations or use computers to guide the practice of science skills, but also introduce experiments to deepen the understanding of concepts [12]. The impact of such innovations on learning should be based on measurements used to understand the relationship between them and educational outcomes. A positive association should be expected across time [13].

3.1. Implementation of learning innovations and their chronology
Thus, innovation in Education is understood as the application of certain interventions producing planned changes through the entire or at least some parts of the learning process [14] being detected by specific measurements. Such measurements should be indexes based on the perceived changes for specific questions. They are constructed with standardized measures to detect those changes and particularly as they are observed consistently through time. It is expected they show sustained growth [13].

A guide to implementing educative innovation is provided in the MAIN methodology [14] by isolating the learning scenario to be improved. In our case, the research product was initially in the form of a conference poster for the short workshops, but also for the research articles in the more extended experiences (research stays and the minor). Such products become more complex, innovative, and oriented to applications. But it is difficult to pursue in little time and only based on the main theoretical concepts developed traditionally in the learning interactions. Tools to boost complexity, such as QUANTUM, let students develop more complex problems than those based on direct calculations performed by students. For that reason, the QUANTUM implementation was the first promoted.

But another recommendation provided by the MAIN methodology is to apply multiple strategies. Despite QUANTUM boosts the calculation ability of students, other initiatives could provide accumulated experience and improved scientific dissemination [14]. Thus, because QISKIT is a tool that lets to interact with real quantum computers, it was almost mandatory, particularly in the most recent years, to introduce it to the students. Then, QISKIT naturally shifted the research proposed by the students into applications involving it. Also, as Quantum information is a discipline supported by Physics, it naturally pushes tutors to improve the experimental segment that already began years ago.

Only during 2021-2022, such a three-folded picture of innovation become complete. Figure 1a mainly depicts the chronology involving the activities, together with differentiated approaches based on face-to-face implementations (workshops, research stays) and after moving to blended learning (workshops, research stays, minor). This movement was due to maintaining the nationwide scope of our learning activities, and then mandatory because of the COVID-19 pandemic. Note particularly how the conference poster was moving into research articles when the workshop became transformed into a minor.



(a) (b)

Figure 1. (a) Chronology of educative activities, research products, delivering methodology, and innovative interventions. (b) Learning approaches to Quantum information, the main impact of innovative interventions, and their global dimension of them.

3.2. A criterion to guide the assessment of the success of educative innovation

In this subsection, we discuss which criteria could be considered in assessing the different aspects regarding the relation among innovations and the impact on the main objective: improve the research products developed by the students. Proposed for educative innovations based on software inclusion, [15] has stated a group of dimensions to be fulfilled by the intervention regarding how they enable, transform, or support the learning process. Those dimensions concern drivers leading innovation together with indicators measuring the fostering of innovations on the skills needed in our contemporary world as observed in the final learning products. Then, an index is suggested to be constructed departing from the evaluation of those dimensions based on a criterion. Those eight dimensions, as proposed in [15] and paraphrased for our own interest are:

1) Analytical thinking: the ability to analyze information to address research problems.
2) Critical thinking: the ability for accessing, analyzing, and synthesizing information to discriminate alternatives to make decisions.

3) Autonomy: the ability to learn how to learn, thus setting learning goals, planning and monitoring them without the formal support of tutors.
4) Adaptability: the ability to adapt the several ways to learn the contents and then apply the associated knowledge in research problems.
5) Creativity: the ability to manage the ideas being used to address a research problem, then choosing that best fitting into the context.
6) Collaboration: the ability to interact effectively with partners participating in a collective process to learn, share, and apply knowledge in research problems.
7) Communication: the ability to communicate with partners the understanding of acquired knowledge for research.
8) Knowledge transformation: the ability to perform transformations between tacit and explicit knowledge.

The last dimensions pursued by educative innovations are not only valuable for software, such as QUANTUM and QISKIT, but in fact for experimental practices and demonstrations fostering learning and widening the scope of research. Figure 1b shows a diagram allocating the eight dimensions together to the main approaches being present in Quantum information: Math, Physics, and Computation. Thus, Autonomy (Au), Analytical Thinking (AT), and Critical Thinking are mainly present in the intersection between Math and Physics, being better fostered by QUANTUM and Photonics experiments. Creativity (Cr), Collaboration (Cl), and Communication are all deeply developed by the set-up of experimental activities and by the programming practice, thus mainly involving Photonics experiments and QISKIT. Finally, Adaptability (Ad) is mainly promoted by QUANTUM and QISKIT as compared and complemented with the introductory theoretical handmade calculations. The last one, Knowledge Transformation (KT), is considered to be fostered for the three innovations, unifying foundations, theory, and applications.

The last dimensions should be evaluated and identified on the research products, as a result of the learning process given in the workshop, research stay, or minor. A criterion should be aligned with the previous definitions. Table 2 states the criteria observed or not on each research product presented through the time (poster conference or research article). A criterion is provided for each dimension. Note that dimensions could be present still with the original structure of the theoretical presentation (without innovations introduced). Alternatively, the explicit presence of some innovation in the research product account as evidence to be considered fulfilled.

3.3. A quantitative model to define a global index for the three innovative interventions

By assessing each research product being presented yearly since 2013, we first classify them by type (poster conference, research article). A total of c_j products of type j is considered in each year ($j = 1$ for posters, $j = 2$ for articles). In addition, we assign a weight w_j for each type j, by instance, as a function of their complexity. Thus, scoring each dimension $i = 1, ..., 8$ with one if the dimension is fulfilled based on the respective criterion, we get a series of scores by type of product j, $d_{i,j}$. In fact, $d_{i,j}$ is the average score given to each dimension i in the innovation impact assessment for each type j of product. The score is estimated given one point for each product during the year barely fulfilling the dimension criterion (otherwise zero). Despite the sum of the dimensions scores $d_{i,j}$ working as a global index (each one weighted by w_j), such quantity considers the impact of innovations but does not reflect the number of authors. Then, we introduce p_j as the number of products per author (P/A) for each type of product j. Thus, we propose the innovation impact index I as:

Table 2. Dimensions regarding skills being effectively developed by the inclusion of learning innovations [15] and criteria considered to assess the research products

Dimension	Criteria based on evidence observed on the research product
Analytical thinking	The product required the use of analysis performed by several approaches
Critical thinking	The product demanded decision-making to be developed or presented
Autonomy	The product involved the use of the software introduced as innovation
Adaptability	The product involved several approaches: mathematical, physical, or computational
Creativity	The product required to develop new knowledge to then get complex outcomes
Collaboration	The product required effective interaction among students to take decisions
Communication	The product exhibits communication with others the acquired knowledge
Knowledge transformation	The product integrated several types of approaches to discover new knowledge

$$\begin{aligned} I &= \sum_{j=1}^{C} w_j p_j \sum_{i=1}^{D} d_{i,j} \\ & \text{with :} \quad c_j \geq d_{i,j} \end{aligned} \tag{1}$$

such index becomes quadratic with respect to the number of products but reduced by the number of authors participating in each product or some of them not fulfilling the corresponding dimension criterion.

4. A brief assessment for the introduction of innovations

In our further analysis, by simplicity, we have simplified the last formula considering the same weight w_j for each type of research product j (more complete implementations could discriminate products by value or complexity: conference products, conference articles, indexed articles, etc.). Together, the number of products by the author p_j was obtained by gathering the total of products (with distinction on j), as well as the innovation scores $d_{i,j}$. The historical outcomes are reported in Table 3, and the last column reports the innovation impact index by each year.

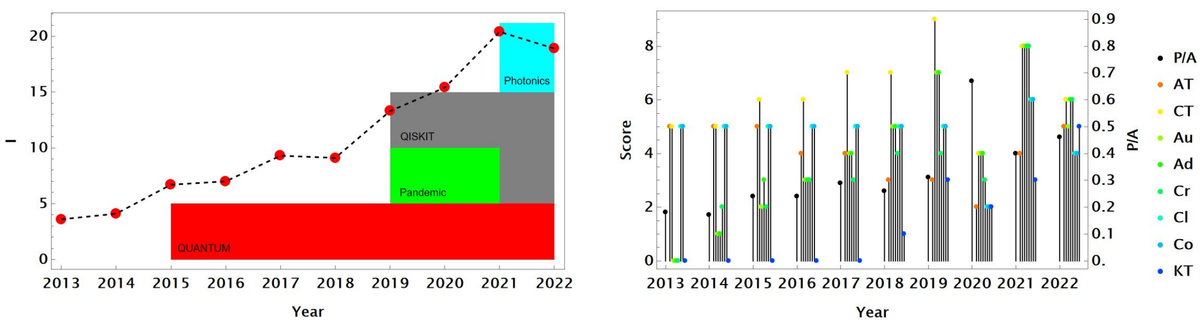
Thus, we can compare globally the innovation impact index I through time, or also, observe the score of each dimension. Figure 2a shows the evolution of I in each year clearly exhibiting its increase. Colored shaded regions there exhibit several periods through the implementation: use of QUANTUM (red), QISKIT (grey), Photonics experiments (cyan), and COVID-19 pandemics (green). The peak observed in 2021 is mainly explained because during 2020 there was effervescent work in publishing due to the work conditions as it was reported in [9].

Alternatively, by observing and comparing the detail for each dimension $d_{i,j}$, we note interesting facts. Figure 2b exhibits those outcomes by year. The number of products per author is reported there on the right scale (black dots) showing a clear increase. Scores of remaining dimensions are reported on the left scale. The Collaboration dropped in 2020 mainly

Table 3. Synthetic report of research products (considering the same weight for both $w_j, j = 1, 2; w_1 = w_2$) together with the Products by Author index ($p_j, j = 1, 2; p_1 = p_2$) and the global points for dimension ($d_j, j = 1, ..., 8 = D$). The last column reports the impact index (I)

Year	Poster	Article	P/A	AT	CT	Au	Ad	Cr	Cl	Co	KT	I
2013	5	0	0.18	5	5	0	0	0	5	5	0	3.6
2014	5	0	0.17	5	5	1	1	2	5	5	0	4.1
2015	5	1	0.24	5	6	2	3	2	5	5	0	6.7
2016	5	1	0.24	4	6	3	3	3	5	5	0	7.0
2017	5	2	0.29	4	7	4	4	3	5	5	0	9.3
2018	5	2	0.26	3	7	5	5	4	5	5	1	9.1
2019	5	4	0.31	3	9	7	7	4	5	5	3	13.3
2020	0	4	0.67	2	4	4	4	3	2	2	2	15.4
2021	5	5	0.40	4	8	8	8	8	6	6	3	20.4
2022	0	6	0.46	5	6	5	6	6	4	4	5	18.9

due to the absence of a workshop that year because of the COVID-19 pandemic (previously, the workshop was blended, despite the second part was always mandatory face-to-face). Inversely, the number of products per author (P/A) peaked in 2020. Knowledge transformation has grown through time. Analytical Thinking (AT) decreased due to a lower number of theoretical articles mainly due to the introduction of QUANTUM, being preferred those products based on simulations due to this tool. Other dimension scores barely increase through time. In any case, the innovation impact index I shows a clear improvement in the quality of research products. Despite we are not differentiating the impact of each innovation introduced, it could be assessed through main relations remarked in Figure 1b and evolution observed in Figure 2b. Thus, QUANTUM impact is expected to be observed in Au, Ad, AT dimensions; QISKIT in Ad, Cr, Cl dimensions. Photonics experiments in AT, Cl, Co, CT. Consistently with I, KT dimension exhibits a coordinated effort between the three innovations to improve the research product quality.



(a) (b)

Figure 2. (a) Innovation index through time regarding different periods of implementation. (b) Innovation dimensions (colors) through time together with the innovation index (black).

5. Conclusion

Research Education is mandatory in our institution. As part of one of the strategic research groups there, the inclusion of students in such activities since the early stages of undergraduate studies is mandatory as a function of their academic interests. Academic spaces to scaffold such interests when they are related to our research areas have been provided by our university, thus, strategic innovation in those academic activities should be efficient and effective.

In our research group, the improvement of quality and maturity of research projects emerging from learning spaces in our research area for undergraduate students is notorious, it should be properly measured and assessed consistently through time to provide advancement and improvement. The three innovations mentioned and included in all learning spaces (workshop, research stay, minor) have produced changes in the research developments presented by students as an outcome, promoting collaboration and extending the topics proposed by them.

The model to assess the innovation impact is an easy model evaluating each research product under eight dimensions that can maintain the unity of the mathematical, physical, and computing approaches in the learning of Quantum information. The usefulness of the innovation impact index clearly lets to advise an improvement in this research Education effort. The index lets in addition to assess such improvement in the quality of research products. While groups of individualized dimensions are involved in the model let to assess the value of each innovation. In the future, a following based on research products generated in those spaces and being sustained by the eight dimensions proposed in [15] through the synthetic index introduced, is mandatory. It should let to guide the efforts of our inclusion model for undergraduate students in research.

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