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Open-ended problem solving in chemistry during initial secondary education teacher training

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Abstract

We present a case study of the work with the Methodology of Problem-Solving as an Investigation (MPSI) in the context of the Spanish Master's in Secondary Education. Here, future physics and chemistry secondary teachers had to solve some sequences of school open-ended problems, in order to promote reflection on its characteristics and favour its later use. The objectives of this research consist of describing how the problem *"What might happen when a substance is heated up?"* was introduced, and analysing preservice teachers' achievement levels in the competence dimensions of the MPSI. In addition, the article justifies the suitability of the above-mentioned problem to work on most of the curricular requirements about physical and chemical changes in a single problem. The results from the future teachers' written reports can be considered as positive, and appear to be best for the "formulation of hypotheses" and worst for the "design of resolution strategies". Moreover, these results do not seem to depend to any great degree on the preservice teachers' previous studies. Finally, we call for the provision of more inquiry-based learning opportunities for future teachers, in order to promote improvement in these scientific competencies and favour a later inclusion of the Inquiry-Based Science Education at school levels.

Keywords: Problem-Based Learning (PBL), Methodology of Problem-Solving as an Investigation (MPSI), preservice secondary education science teachers, physical and chemical changes.

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1. Introduction

Over the last few years, there has been a concern at an international level about the necessity of improving the quality of science education at school level. In this sense, there is a consensus about considering the students' development of *scientific competencies* as a main goal (OECD, 2013) and, in addition, that the problem of an increasing lack of motivation towards science should be solved (OECD, 2006). Taking into account a variety of pieces of research in this field, it has been concluded that one of the key aspects for achieving the aforementioned improvement consists of incorporating inquiry-based methodologies in teaching and learning processes (European Commission, 2007). But what does "inquiry" mean? In order to clarify its meaning, we will provide a definition by Crawford (2007) which is consistent with a view about this approach commonly held in the science education community: *«inquiry involves appreciating the diverse ways in which scientists conduct their work; knowledge of and ability to ask testable questions, make hypotheses; use various forms of data to search for patterns, confirm or reject hypotheses; construct and defend a model or argument; consider alternate explanations, and gain an understanding of the tentativeness of science, including the human aspects of science, such as subjectivity and societal influences»* (page 614).

The *Inquiry-Based Science Education* (IBSE) methods provide students with some problems or dilemmas which they must overcome by learning the necessary content without being given previous explanations. Therefore, the differences between these methodologies lie in the degree of challenge for students, and the level of scaffolding provided by the teacher to guide them (Hmelo-Silver, Duncan & Chinn, 2007). Among these IBSE methodologies, problem solving-based teaching models (PBL, *Problem-Based Learning*) have shown a great potential to favour inquiry in science classrooms. These approaches provide opportunities for students to develop investigations, integrate theory and practice, and construct knowledge in order to find feasible solutions for problems which do not have "a single solution" (Savery, 2006). In other words, these learner-centred methodologies emphasize students' responsibility for their learning.

As suggested before, the IBSE approach **–**and PBL in particular**–** is supported by extensive research which has shown its success in improving students' academic performance in terms of conceptual, procedural and attitudinal contents (Ibáñez & Martínez-Aznar, 2007; Minner, Levy & Century, 2010). Furthermore, these methodologies have proven their effectiveness in promoting persistent learning in science and fostering students' motivation in different contexts (European Commission, 2007; Martínez-Aznar & Bárcena, 2013; Pavón & Martínez-Aznar, 2014).

On the other hand, applying these methodologies involves some important challenges, such as a change in the roles of students and teachers – in the last case, from being "knowledge *transmitters*" to being "knowledge *activators*"– (Hmelo-Silver et al., 2007). The latter requires organizing sequences of learning activities so that the students, starting from their alternative conceptions, can properly revise and change their ideas in order to give meaning to new knowledge. Therefore, in spite of being a student-centred approach, PBL requires greater teacher involvement than is usual in traditional methodologies. In addition, there are some teachers' beliefs that might limit the use of these methods at school, such as the thought that they require a lot of time in the classroom, the presumed difficulty for students to learn by using them, and a supposed lack of teaching materials (Colburn, 2000; Dabbagh & Williams Blijd, 2010).

Because of this change of paradigm, we believe that these inquiry-based methods should form an active part of preservice science teacher education programs. As such, in accordance with other authors (*e.g.*, Etherington, 2011; Crujeiras & Jiménez-Aleixandre, 2015), we stand up for the need for these training programs which provide learning opportunities through IBSE methods, in order to promote reflection on their nature and benefits for science education (Rodríguez-Arteche & Martínez-Aznar, 2016). Otherwise, IBSE methodologies are unlikely to be developed in classrooms.

1.1. Methodology of Problem-Solving as an Investigation (MPSI) as an inquiry-based method

Within the PBL methods, the *Methodology of Problem-Solving as an Investigation* (MPSI) has been proven as an effective approach for science teaching and learning. As such, the MPSI has achieved good results at both primary and secondary education levels (Martínez-Aznar & Bárcena, 2013; Bárcena, 2015; Rodríguez-Arteche, Martínez-Aznar & Garitagoitia, 2016), and in primary school teacher training programs (Martínez-Aznar & Varela, 2009). The MPSI consists of a group of five stages that reflect not only the way in which scientists work, but also the dimensions of scientific competencies included in school curricula. The stages and characteristics of the MPSI are described in

Figure 1. They correspond to a cyclical problem-solving process that must be organized in *cooperative groups* in order to promote an exchange of ideas between students. Moreover, the teacher is expected to provide *scaffolding* when required (Hmelo-Silver et al., 2007), for example by posing questions to the students in order to guide their resolution.

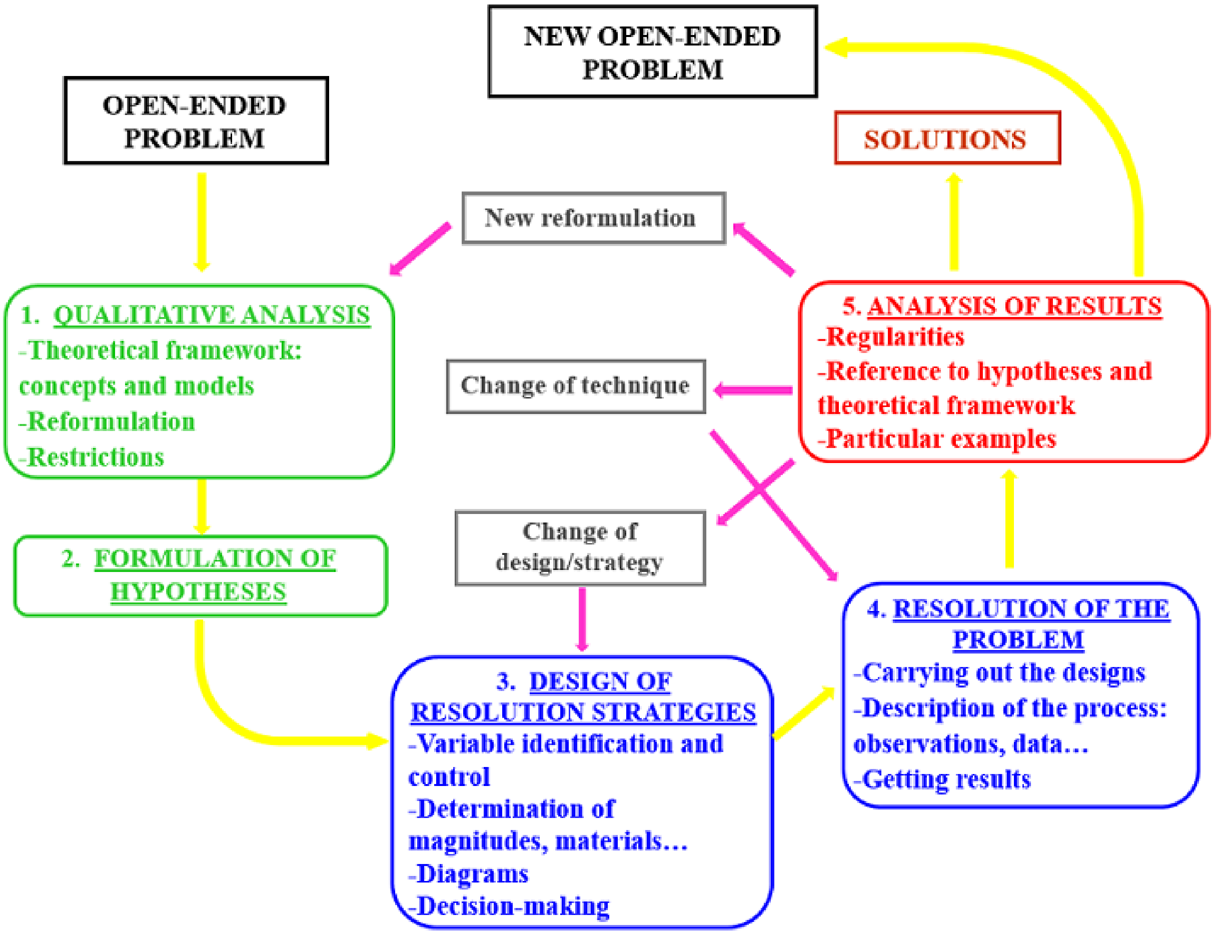

Figure 1: Stages and characteristics of the Methodology of Problem-Solving as an Investigation (MPSI)

The MPSI is designed to solve "authentic problems", both theoretical and practical, which do not incorporate data and have various possible solutions –they are open-ended statements–. The main characteristics of this method are (Martínez-Aznar & Ibáñez, 2005):

1. *Qualitative analysis of the problem.* Here, an appropriate theoretical framework should be described, including the concepts and models that are implied, and later the open-problem should be reformulated in operative terms. As such, this is a creative step as different proposals stemming from an original question or statement could be made according to the students' interests.

2. *Formulation of hypotheses.* The proposition of conjectures which turn into hypotheses has a central role in the MPSI. Therefore, hypotheses will orientate the whole resolution, indicating the parameters and data to keep in mind, and allowing analysis of the results. In this way, testing the hypotheses becomes a tool for conceptual change.

3. *Design of resolution strategies.* It consists of developing one or more strategies to check the validity of the hypotheses and the theoretical framework. For this purpose, independent, dependent and control variables have to be identified, together with the necessary materials and magnitudes to be measured. Finally, a number of decisions have to be made in order to solve the problem.

4. *Resolution of the problem / development of the experiments.* Once the resolution is planned the designs proposed in the stage 3 should be put into practice, taking note of the

observations and measurements carried out, recording the data and verbalizing the entire process.

5. *Analysis of results.* This is the last but not least important step, where results should be analysed with reference to the emitted hypotheses and the initial qualitative analysis. Therefore, this phase goes further than revising the mistakes that have been made, and consists of testing the internal validity of the whole resolution. Furthermore, the obtained results can give rise to new questions and problems.

Because of the newness of a constructivist method like this for most future teachers, we argue for the need to ask preservice teachers to solve sequences of open-ended school problems using the MPSI. In this way, they will take the role of their future secondary school students and reflect on the potentials of the MPSI, the difficulties that arise when implementing the method, or the 'new' role of the teacher (Rodríguez-Arteche & Martínez-Aznar, 2016). Therefore, this study will focus on the explicit use of the MPSI in an initial physics and chemistry teacher training program, in the Spanish context.

2. Research objectives

The study is guided by the following objectives which cover a double perspective.

1. With regard to the class methodology in the Chemistry Education subject and the curricular contents of the proposed open-ended problems:
   - 1.1 Describe a preservice teacher-training proposal for inclusion of the Methodology of Problem-Solving as an Investigation (MPSI) into the teaching and learning of secondary school chemistry.
   - 1.2 Show that well designed open-ended problems allow for the adequate development of the competencies in the school curricula.
2. With regard to the students' performance in the problem-solving process:
   - 2.1 Analyse how future physics and chemistry teachers solve the open-ended problem "What might happen when a substance is heated up?", in terms of the MPSI dimensions of scientific competencies.
   - 2.2 Look for statistical differences dependent on the future teachers' previous studies.

3. Methods

The case study was done with a class-group made up of 24 students from the «Chemistry Education» subject of the Spanish one-year *Master's in Secondary Education* (MSE) –a necessary requirement for working as a teacher with students age 12-18–. The research was carried out in the Universidad Complutense de Madrid. There were 13 female and 11 male preservice teachers; 10 chemistry graduates, 8 physics graduates and 6 with other degrees, mainly engineering. Physics and chemistry are taught together in secondary education, and this is why people from different backgrounds study the same "physics & chemistry" Master's specialization.

In order to develop the *first objective* of this work, we considered the question that follows as a guide: "How did we work with the MPSI in the Chemistry Education subject?" In addition, we examined the Spanish *physics and chemistry* curriculum for students aged 14-15. This has the purpose of showing the connection between the assessment indicators of the curriculum and the design of the open-ended problem "What might happen when a substance is heated up?"

Concerning the *second objective* of the study, the data was obtained from the individual reports that the future teachers wrote after ending the experiments, in terms of the 5 MPSI stages –they had a week to do so–. In order to facilitate the analysis, the phases 1 and 3 from Figure 1 were divided into the following competence dimensions (CD): *CD1.1*, Qualitative representation of the problem (theoretical framework); *CD1.2*, Reformulation of the problem; *CD3.1*, Variable identification and control; *CD3.2*, Decision-making for the problem.

Then, we established achievement levels for the competence dimensions involved in the MPSI, according to what is expectable for MSE students. The definition of the levels for this problem about heating a substance is shown in the Appendix –for each CD–, but all of them follow the general criteria shown in Table 1. Then, the reports were coded –with the requirement of a consensus of the two researchers–, and the average resolution levels between 0-4 and standard deviations were calculated for each CD, as has been done in other similar studies (Martínez-Aznar & Ibáñez, 2005; Rodríguez-Arteche et al., 2016). Finally, the Mann-Whitney *U* test was carried out in order to look for possible meaningful differences between the results of preservice teachers with different previous studies.

Table 1: Achievement levels for the competence dimensions (stages) of the MPSI

Levels	Criteria
0	Irrelevant / Does not answer
1	Poor. Lacks important information *or* with important mistakes
2	Average. Lacks some information *or* with small mistakes
3	Good, even though some information is missing
4	Very good

4. First objective: Our proposal for introducing an inquiry-based method during initial secondary education teacher training

4.1. How did we work with the MPSI in the Chemistry Education subject?

The Chemistry Education subject is based on the resolution of professional problems such as content selection, design and implementation of learning activities and assessment of the teaching and learning process. In this sense, the MPSI was introduced as an inquiry-based methodology in order to face the challenges related to experimental activities.

Before introducing the MPSI, preservice teachers were asked to solve an open-ended problem of low conceptual difficulty –*"Which piece of paper absorbs more?"* (Rodríguez-Arteche et al., 2016)– without any scaffolding. Their resolutions focused on the solving strategies –with a low achievement level in the control of variables–, and they didn't qualitatively analyse the problem. Therefore, the professor presented the educational justification of the MPSI, and proposed two teaching units which included sequences of open-ended problems to tackle physical and chemical changes, in accordance with curricular requirements for 14-15 year-old students. In order to favour a reflection about this methodology, preservice teachers were asked to solve these activities by themselves. In this paper, we will look at the problem *"What might happen when a substance is heated up?"* corresponding to the teaching unit «Change and diversity in nature», which is solved after the complete development of other open-ended problems.

In this way, preservice teachers were asked to carry out the first three stages of the MPSI for the open-ended problem as homework. Later, they did some laboratory experiments working in heterogeneous cooperative groups –containing at least one chemistry graduate and one physics graduate– in a class session of 90 minutes. However, first of all they reached an agreement about the reformulation of the problem and the design of resolution strategies in order to test their hypotheses. The strategies they developed for homework considered the possibilities of solid, liquid and gaseous initial substances. Therefore, once they knew that the initial substance was solid, they revised and finalized their strategies. These procedures focused on identifying the physical and chemical changes which occurred when the proposed solid was heated up.

In this case, a white and crystalline unknown solid "C" was provided, which was $KClO_3$. The MSE students had to heat the sample and determine whether changes in states of matter or in the nature of the substance occurred. This activity presents great opportunities from an educational point of view, and allows for looking into the students' alternative conceptions. As such, initially the substance melts –a reversible change– and later, if heating goes on, a chemical decomposition occurs. This chemical reaction implies the emission of a gas –oxygen, which could be determined in the laboratory–.

All the previous chemical concepts will now be described in relation to the curricular requirements for physical and chemical changes –for students aged 14-15–. At this point, it is convenient to highlight the importance of making future teachers aware of the potentialities of an inquiry-based method such as the MPSI in order to promote the development of these scientific competencies. Furthermore, we believe that the fact that preservice teachers were able to observe how the professor provided scaffolding to assist them will prompt reflection on their future role in secondary education.

4.2. Connection of the open-ended problem with the school curriculum

Here we will justify the suitability of the problem "What might happen when a substance is heated up?" in order to develop the curricular requirements about physical and chemical changes. In particular, this problem is related to 4 out of the 7 assessment indicators included in the Spanish contents block about «physical and chemical changes», for students aged 14-15. These indicators are shown in Table 2.

Table 2: Assessment indicators of the Spanish curriculum (14-15 year-old students) that are related to the problem "What might happen when a substance is heated up?"

Indicator	Criterion
i	Distinguish between physical and chemical changes, by carrying out simple experiments to test if new substances are formed or not.
ii	Characterize chemical reactions as changes of some substances into others.
iii	Describe the process by which reagents are transformed into products, considering a molecular level of representation.
iv	Deduce the law of conservation of mass and recognize reagents and products by means of laboratory activities.

With regard to the *indicator i*, the design of our problem incorporates two types of changes which are related to the process of heating, a feature we consider as helpful for an appropriate chemistry knowledge construction. At around 350 ^{o}C, potassium chlorate –$KClO_3$– melts, which can be confirmed as a physical change because of the reversibility of the process. As such, by repeatedly heating and cooling this substance, it melts and solidifies.

At higher temperatures, although the sample's boiling could be expected, after a bubbling and crackling process what remains in the test tube is a solid substance. Moreover, the liquid cannot be recovered in spite of cooling down the sample. How can it be explained? If the latter heating process is carefully observed, the emission of a gas can be detected –at around 400 ^{o}C–. For all these reasons, this last change can be confirmed as a chemical reaction of decomposition. Therefore, this inquiry-based activity puts together the two different types of changes, these are, physical and chemical changes.

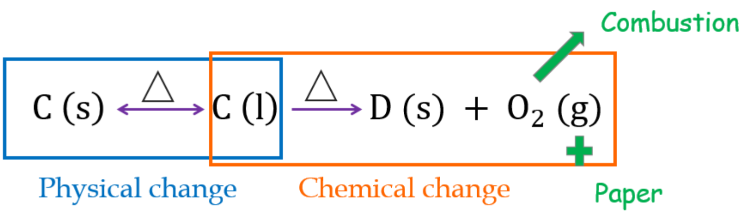

Figure 2: Symbolic representation of the changes that occur throughout the activity (the triangles represent heating processes)

Concerning the assessment *indicator ii*, it should be said that the second of the previous changes involves the change of a substance into others. In this sense, this problem enables the practical determining of the gas which is emitted as oxygen. To do this, the teacher –as part of the scaffolding task– could indirectly suggest introducing a small piece of paper into the test tube when the sample starts to bubble and crackle, for example. In that way, the paper would burn without direct contact with the flame –a combustion reaction–, and this implies the presence of an oxygen-rich atmosphere. All these processes that occur when heating up the sample are summarised in Figure 2.

Finally, with regard to the *indicators iii* and *iv*, our design of scaffolding for the problem promotes microscopic representations of the changes (Bridle & Yezierski, 2012) once the substances involved have been identified –potassium chlorate, potassium chlorite and oxygen–. Our proposal starts from "practical" microscopic situations that can be represented by using Dalton's model, but all these situations give rise to a unique chemical equation with stoichiometric proportions when considering the law of conservation of mass, as can be seen in Figure 3. Therefore, this is a procedure for balancing chemical equations which focuses on its chemical interpretation, instead of on the algebraic process.

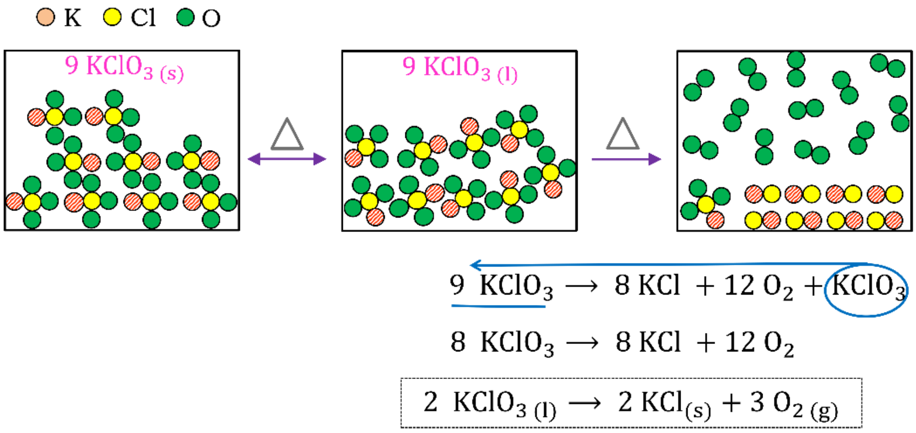

Figure 3: Microscopic and symbolic representations of the changes; obtaining the balanced chemical equation for the thermal decomposition by considering the law of conservation of mass

5. Second objective: Preservice teachers' performance in the problem-solving process

5.1. Results from the future teachers' written productions

We analysed how a group of future teachers wrote their reports about the previously described open-ended problem, concerning the heating of a substance. Table 3 shows the frequencies of the achievement levels and their mean values for each competence dimension. In addition, detailed descriptions of these achievement levels are shown in the Appendix, for a better understanding of the results.

Table 3: Frequencies of the achievement levels (between 0 and 4), mean values and standard deviations (SD)

	Dimension	Frequencies (n = 24)					Scores	
		L0	L1	L2	L3	L4	Mean	SD
CD1.1	Qualitative representation	0	2	8	8	6	2.75	0.92
CD1.2	Reformulation of the problem	0	1	13	3	7	2.67	0.94
CD2	Formulation of hypotheses	0	0	7	3	14	3.29	0.89
CD3.1	Variable identification and control	0	5	11	4	4	2.29	0.98
CD3.2	Decision-making for the problem	0	5	8	7	4	2.42	1.00
CD4	Resolution of the problem	0	3	6	10	5	2.71	0.93
CD5	Analysis of results	0	2	7	8	7	2.83	0.94

The best results correspond to the formulation of hypotheses (CD2, $\bar{x}$ = 3.29), which may have happened because the main content of the problem –physical and chemical changes– is fundamental to the university degrees involved. Equally, other research projects with secondary school students have demonstrated that the performance in this procedure strongly depends on the context of the problems, and on the students' familiarisation with them (Martínez-Aznar & Ibáñez, 2005; Bárcena, 2015).

In contrast, the worst results are for the design of resolution strategies (CD3, $\bar{x}$ = 2.36), both in the variable identification and control (CD3.1), and with respect to the decision-making for testing the hypotheses (CD3.2). These results –similar to the ones found in other studies with IBSE methods (Martínez-Aznar & Varela, 2009; Ferrés, Marbà & Sanmartí, 2015; Rodríguez-Arteche et al., 2016)– might be considered as predictable, taking into account the type of methodologies that the future teachers frequently used in their previous experiences as students. In these cases, the development of "recipe-type activities" prevails over the work about open-ended situations where students have to make their own decisions about the strategies (Dillon, 2008). Moreover, in the field of school chemistry it is quite rare to analyse the variables that take part in the processes, which may increase the difficulty of developing these stages with the MPSI. Instead, the results for the description of the problem resolution (CD4, $\bar{x}$ = 2.71) and the final analysis of results (CD5, $\bar{x}$ = 2.83) are better, possibly due to the inclusion of these procedures in the usual laboratory activities. In addition, the revision and discussion of the previous open-ended problems solved by the MSE students with the professor may have helped to improve these competence dimensions.

Regarding the initial qualitative analysis of the problem (CD1, $\bar{x}$ = 2.71), a significant number of the participants omitted reference to possible types of chemical reaction in the context of the problem when developing their theoretical frameworks (CD1.1). In this way, 75% of the MSE students considered a framework that was limited to the distinction between physical and chemical changes, without explaining particular examples which are relevant to the problem –and without achieving a Level 4–. However, other authors have suggested that one of the most difficult aspects of open-ended problem-solving is to 'connect' the variety of intervening contents (Reid & Yang, 2002). Finally, the process of making the problem operative (CD1.2, reformulation), which involves the transition from an open-ended situation to a specific question for investigation, presented a number of difficulties.

5.2. Dependence of the results on the future teachers' previous studies

The data obtained also allow for enquiry into the relationship between the preservice teachers' results in problem-solving and their previous university studies. Table 4 shows the mean achievement levels for the MPSI procedures, organised according to the participants' university degrees. These results appear to be quite similar to each other, although they are a bit better for physicists. However, when carrying out the statistical Mann-Whitney test (*U*), only one meaningful difference was found, which corresponds to the decision-making (CD3.2). In this case, the physics graduates' performance is significantly better than that of the chemistry graduates ($U = 17.00$; $p < 0.05$).

Table 4: Mean achievement levels for the MPSI competence dimensions, organised according to the participants' previous studies; *: statistically meaningful difference ($p < 0.05$)

Competence dimension	Chemistry graduates (n = 10)	Physics graduates (n = 8)	Others –mainly engineers– (n = 6)
CD1.1, Qualitative representation	2.70	3.00	2.50
CD1.2, Reformulation of the problem	2.70	2.63	2.67
CD2, Formulation of hypotheses	3.20	3.63	3.00
CD3.1, Variable identification and control	2.10	2.75	2.00
CD3.2, Decision-making for the problem	2.00*	3.00*	2.33
CD4, Resolution of the problem	2.60	2.75	2.83
CD5, Analysis of results	2.80	2.88	2.83

6. Conclusions and final reflections

From our point of view, any educational change implies the involvement of teachers in their classrooms. As such, the improvement of the quality of chemical education in secondary levels requires the inclusion of IBSE-type methodologies in initial teacher training programs (Rodríguez-Arteche & Martínez-Aznar, 2016). In order to collaborate on achieving this purpose, we have presented a proposal for the Spanish Master's in Secondary Education which includes the MPSI. In this sense, we have supported the need that future teachers should participate in inquiry-based learning processes, in order to become aware of their benefits for science education –development of scientific competencies, motivation…–. In addition, this fact could help to combat a traditional –and transmissive– school culture.

One of the main contributions of this article –*first objective*– is the description provided about the design of a chemistry open-ended problem through the MPSI. This scheme allows for working on most of the required contents about physical and chemical changes in a single problem, and also promotes a view about the way of working of a scientist. Therefore, this fact rebuts a common teachers' belief which indicates that the work with inquiry-based methods implies a lot of teaching time, making it difficult to complete the school curricula (Colburn, 2000).

The analysis of results for the *second objective* reveals an adequate performance in the scientific competencies involved in the problem-solving process –overall, 53.6% of the responses achieved Levels 3 and 4, 35.7% were classified at Level 2, and 10.7% of the productions obtained Levels 0 and 1–. On the other hand, the order of the scientific procedures from best to worst results was the following one: CD2 ($\bar{x}$ = 3.29) > CD5 ($\bar{x}$ = 2.83) > CD1 ($\bar{x}$ = 2.71) = CD4 ($\bar{x}$ = 2.71) > CD3 ($\bar{x}$ = 2.36). These data, together with the analysis of the relationship between the participants' university degrees and their problem-solving results, enable reflection on the influence of the classical closed-ended practical activities that are usually developed in physics, chemistry and engineering studies –"recipes"– (Dillon, 2008). As such, the procedures which are less frequently considered have obtained the worst results: the variable identification, the students' decision-making process and the problem reformulation. To overcome these difficulties, we call for the provision of more learning opportunities in order to improve in the competencies that are involved in the resolution of open-ended and ill-structured problems.

Finally, we want to highlight that at present we are carrying out research on future teachers' views about the strengths and weaknesses of the MPSI, once they have completed the Physics & Chemistry Education courses (Rodríguez-Arteche & Martínez-Aznar, in press). In addition, it is our intention to develop further research with regard to the practical teaching phase of the Master's program. This analysis would help to improve the teacher training programs and support the use of inquiry-based methodologies in secondary school classes.

References

Bárcena, A.I. (2015). *A study of the influence of Problem-Solving Methodology as an Investigation (PSMI) on learning chemistry in high-school students*. PhD Thesis, Universidad Complutense de Madrid. Retrieved September 1, 2016, from: http://eprints.ucm.es/30524/1/T36151.pdf (English summary provided on pages 545-551)

Bridle, C.A. & Yezierski, E.J. (2012). Evidence for the Effectiveness of Inquiry-Based, Particulate-Level Instruction on Conceptions of the Particulate Nature of Matter. *Journal of Chemical Education*, *89*(2), 192-198.

Colburn, A. (2000). An inquiry primer. *Science Scope*, *23*(6), 42-44.

Crawford, B.A. (2007). Learning to teach science as inquiry in the rough and tumble of practice. *Journal of Research in Science Teaching*, *44*(4), 613-642.

Crujeiras, B. & Jiménez-Aleixandre, M.P. (2015). Desafíos planteados por las actividades abiertas de indagación en el laboratorio: Articulación de conocimientos teóricos y prácticos en las prácticas científicas. *Enseñanza de las Ciencias*, *33*(1), 63-84. (English summary provided on pages 83-84)

Dabbagh, N.Dr. & Williams Blijd, C. (2010). Students' perception of their learning experiences in an authentic instructional design context. *Interdisciplinary Journal of Problem-Based Learning*, *4*(1), 6-29.

Dillon, J. (2008). *A review of the Research on Practical Work in School Science*. London: King's College. Retrieved September 1, 2016, from: http://www.score-education.org/media/3671/review_of_research.pdf

Etherington, M.B. (2011). Investigative primary science: a Problem-Based Learning approach. *Australian Journal of Teacher Education. 36*(9), 53-74.

European Commission (2007). *Science Education Now: A Renewed Pedagogy for the Future of Europe*. Brussels. Retrieved September 1, 2016, from: http://ec.europa.eu/research/science-society/document_library/pdf_06/report-rocard-on-science-education_en.pdf

Ferrés, C., Marbà, A. & Sanmartí, N. (2015). Trabajos de indagación de los alumnos: instrumentos de evaluación e identificación de dificultades. *Revista Eureka sobre Enseñanza y Divulgación de las Ciencias*, *12*(1), 22-37. (Abstract in English is included)

Hmelo-Silver, C., Golan, R. & Chinn C.A. (2007). Scaffolding and achievement in problem-based and inquiry learning. A response to Kirschner, Sweller and Clark (2006). *Educational Psychologist*, *42*(2), 99-107.

Ibáñez, M.T. & Martínez-Aznar, M.M. (2007). Solving problems in genetics (III): Change in the view of the nature of science. *International Journal of Science Education*, *29*(6), 747-769.

Martínez-Aznar, M.M. & Ibáñez, M.T. (2005). Solving problems in genetics. *International Journal of Science Education*, *27*(1), 101-121.

Martínez-Aznar, M.M. & Varela, M.P. (2009). La resolución de problemas de energía en la formación inicial de maestros. *Enseñanza de las Ciencias*, *27*(3), 343-360. (English summary provided on page 359)

Martínez-Aznar, M.M. & Bárcena, A.I. (2013). ¿Es beneficioso masticar bien para realizar una buena digestión? Una actividad de indagación en un aula de diversificación. *Educació Química, EduQ*, *14*, 19-28. (Abstract in English is included)

Minner, D.D., Levy, A.J. & Century, J. (2010). Inquiry-based science instruction. What is it and does it matter? Results from a research synthesis years 1984 to 2002. *Journal of Research in Science Teaching*, *47*(4), 474-496.

OECD. (2006). *Evolution of student interest in Science and Technology studies*. Retrieved September 1, 2016, from: http://www.oecd.org/science/sci-tech/36645825.pdf

OECD. (2013). *PISA 2015 Draft Science Framework*. Retrieved September 1, 2016, from: http://www.oecd.org/pisa/pisaproducts/pisa2015draftframeworks.htm

Pavón, F. & Martínez-Aznar, M.M. (2014). La metodología de resolución de problemas como investigación (MRPI): una propuesta indagativa para desarrollar la competencia científica en alumnos que cursan un programa de diversificación. *Enseñanza de las Ciencias*, *32*(3), 469-492. (English summary provided on pages 491-492)

Reid, N. & Yang, M-J. (2002). Open-ended problem solving in school chemistry: A preliminary investigation. *International Journal of Science Education*, *24*(12), 1313-1332.

Rodríguez-Arteche, I. & Martínez-Aznar, M.M. (2016). Introducing inquiry-based methodologies during initial secondary education teacher training using an open-ended problem about chemical change. *Journal of Chemical Education*, *93*(9), 1528-1535.

Rodríguez-Arteche, I., Martínez-Aznar, M.M. & Garitagoitia-Cid, A. (2016). La competencia sobre planificación de investigaciones en 4º de ESO: un estudio de caso. *Revista Complutense de Educación*, *27*(1), 329-351. (Abstract in English is included)

Rodríguez-Arteche, I. & Martínez-Aznar, M.M. (in press). Indagación y modelos didácticos: La reflexión de cuatro profesores de física y química en formación inicial. *Campo Abierto*. (Abstract in English is included)

Savery, J.R. (2006). Overview of problem-based learning: Definitions and distinctions. *Interdisciplinary Journal of Problem-Based Learning*, *1*(1), 9-20.

APPENDIX

The following Tables A.1–A.7 show the precise definition of the achievement levels for each competence dimension (CD), corresponding to the problem "What might happen when a substance is heated up?" These levels were defined between 0 (irrelevant response, or students do not answer) and 4 (very good answer), as has been described in the «Methods» section. For this analysis, a consensus between the researchers was required.

Table A.1: Achievement levels for the "qualitative representation of the problem – theoretical framework (CD1.1)"

Level	Description
1	*a)* Explaining basic concepts like substance (elements/compounds) or heat, but this stage is not focused on the intervening physical and chemical changes. *b)* They make important mistakes when explaining concepts like chemical reaction or heat & temperature.
2	In addition to the concepts involved in *Level 1*, they briefly introduce the idea of physical and chemical changes, although this is done in generic terms.
3	*a)* Properly explaining the chemical concepts involved in the problem (*see Level 4* *); however, the possibilities of physical and chemical changes that could happen in this problem are not fully developed. *b)* Providing explanations of the concepts that are relevant to the problem (*), but in a disorganised way.
4	Adequate explanations of the intervening concepts (*): substance (elements/compounds), states of matter, physical and chemical changes (describing possibilities in the context of the activity), heat and temperature.

Table A.2: Achievement levels for the "reformulation of the problem (CD1.2)"

Level	Description
1	A mere change of some words in the initial question; the statement is not yet operative.
2	Using operative terms to change the initial statement; however, the reformulation does not allow for completing an investigation about heating a substance (*e.g.*, they just consider the possibility of an *only* change in state / chemical reaction).
3	Using operative terms to restate the problem and complete an investigation into it; nevertheless, there are some mistakes in this formulation.
4	Appropriate reformulation: the research will consist of analysing both the physical (reversible) and chemical (irreversible) changes which occur when heating a substance.

Table A.3: Achievement levels for the "formulation of hypotheses (CD2)"

Level	Description
1	The hypotheses do not match the objectives of the problem.
2	*a)* The hypotheses just focus on changes in state / chemical reactions starting from the substance in the solid state (*i.e.*, a complete heating process is not considered). *b)* The hypotheses anticipate some aspects that arise during the problem-solving.
3	Writing coherent statements with the problem, but not expressed in terms of testable hypotheses.
4	The hypotheses are coherent with the problem and properly written.

Table A.4: Achievement levels for the "variable identification and control (CD3.1)"

Level	Description
1	The identification is incoherent with the problem's objectives, or the variables are not assigned as independent, dependent and control ones (although they might be considered in the later research planning).
2	Correct identification of the *dependent variable* (type of change, physical or chemical), in agreement with their hypotheses.
3	Adequate identification of both *dependent* and *independent* (temperature) variables, although in an imprecise way (*e.g.*, they consider a dependence of the results on the particular substance chosen and the possibility of changing the temperature, but the latter is not explicitly identified as the independent variable).
4	Correct identification of both dependent and independent variables. Moreover, they include properly some *control variables* (*e.g.*, pressure).

Table A.5: Achievement levels for the "decision-making for the problem (CD3.2)"

Level	Description
1	The resolution criteria are not well specified. The decision-making simply focuses on how to heat the substance in the laboratory.
2	*a)* They focus on how the substance is heated, and include only a single criterion to classify the changes (reversibility / emission of gases / change in colour or appearance). *b) A part* of the decision-making is incorrect, and may imply some difficulties for the practical resolution of the problem.
3	The strategies include a complete explanation about (ir)reversibility as an indicator of (chemical)/physical change. Furthermore, they properly describe *one* of the following two observations to make in the investigation: 1) emission of gases as a sign of chemical change, 2) change in characteristic properties or in colour/odour/appearance as chemical change indicators.
4	Appropriate explanations of all the contents that appeared in *Level 3*. They can also describe different criteria regarding the states of matter of the substance(s) involved.

Table A.6: Achievement levels for the "resolution of the problem (CD4)"

Level	Description
1	*a)* Wrong resolution of the problem (*e.g.*, they mix up the decomposition reaction with a combustion reaction –both of them are involved in the open-ended problem–). *b)* The problem-solving steps described are clearly insufficient (*e.g.*, they just focus on the initial –physical change– or final –chemical change– part of the heating process).
2	Adequate but incomplete description of the resolution. *One* of the three key ideas shown in Figure 2 is missing: physical change / chemical change / combustion reaction. In several cases, they make some mistakes in their descriptions (*e.g.*, they don't realise that after decomposition, potassium chloride –a product– is in solid-state and not in liquid-state).
3	The description made is correct, although there is a lack of supporting evidence (pictures, explanations…) for *one* of the previous basic aspects of the problem. For example, they don't include a proof in terms of reversibility for the initial physical change.
4	Appropriate explanations of the resolution processes, taking into account the three basic ideas described for *Level 2* and providing complete experimental evidence.

Table A.7: Achievement levels for the "analysis of results (CD5)"

Level	Description
1	*a)* Incorrect analysis: there are several important mistakes in the explanations. *b)* Incomplete final analysis of results. In addition, they don't make any reference to their hypotheses based on practical criteria.
2	*a)* They explain whether their hypotheses have been tested or not. Nevertheless, they don't specify in this section which are the basic experimental criteria that allow for testing the hypotheses. *b)* The analysis is adequate but incomplete. For example, they describe the occurring change on a microscopic and symbolic level (chemical equation), but they don't make reference to their hypotheses and experimental observations.
3	Their analysis is good, although either the microscopic and symbolic representations *or* the experimental evidence to support their explanations are missing (the latter could have been explained in the resolution stage).
4	Complete analysis of results. The aspects that were missing in the *Level 3*–responses are properly explained.