SECONDARY SCHOOL STUDENTS' KNOWLEDGE OF STOICHIOMETRY

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Abstract
The purpose of this investigation was to evaluate the success and to determine the difficulties faced by Slovene secondary school students (age 19) in solving stoichiometry problems. The data were collected at the Matura exam over a five-year period (1995–1999). A general model for stoichiometry problem-solving was formed. On average, 46 % of students correctly solved the task, while almost 4 % of students did not even attempt to solve it. The most common mistakes in solving stoichiometry problems were in using symbolic chemical language and in calculating the amount ratio. Guidelines for teachers are given on how to improve students´ chemical problem-solving strategies, in order to diminish the range of such mistakes in solving stoichiometry problems.

Introduction
An important part of chemistry learning is the development of chemical language, i.e. learning the symbols of chemical elements, writing formulae and chemical equations and using them at the qualitative and quantitative level.[1] In order to solve tasks on stoichiometry one has to understand the relation between the mass (m), the amount of substance (n) and the molar mass (M): $n = m / M$. From a balanced equation, students can determine the amount of substance ratio which is needed for calculating unknown quantities.

For successful solving of stoichiometry problems, the solver must be familiar with some general and specific problem solving strategies. The most general problem-solving model is Poyla´s model[2]. It is based on four steps: (1) understanding the problem; (2) designing the plan; (3) carrying out the plan and (4) looking back. Bransford and Stein[3] developed an IDEAL general model for problem–solving. They anticipated a five–step approach to solving a problem: (1) **I**dentify problems and opportunities; (2) **D**efine goals; (3) **E**xplore possible strategies; (4) **A**nticipate outcomes and act, and at the end (5) **L**ook back and learn.

After reviewing research on problem solving in chemistry, Frazer[4] listed the following points as general strategies or advice to problem solvers: (1) Work backwards from the goal not forwards from the given information; (2) Break down the problem into sub-goals and work at each separately, do not try to cope with too much information at any one time; (3) Convert an unfamiliar problem into a familiar problem and then apply an already learnt procedure; (4) Make a guess at the solution and work backwards to see if the guessed solution is consistent with all the information available; (5) Check that all information stated in the problem has been used and that all other sources of information (memory, literature, experts, experiment etc.) have been exhausted; (6) Check that all the stages of problem solving (recognising, solving, checking and implementing) have been used; (7) Check whether there are any guidelines or algorithms applicable to this problem; (8) Try to see the problem as a whole; (9) Draw diagrams, verbalise the problem, convert a statement into a question, convert statements into mathematical expressions; (10) "Brainstorm"; that is, write down all the ideas that come to you, however foolish or irrelevant they seem; (11) Rest to allow time for "incubation" of the problem. Herron[2] suggested another, for him more logical, sequence of steps to solve a problem formed by Frazer. He changed the steps in the following order: 1, 4, 2, 8, 3, 9, 6, 10, 5, 7 and 11. The numbers mean Frazer´s original steps.

In *Figure 1* the general step-by-step strategy for solving chemical problems using PAM (**P**rogram of **A**ctions and **M**ethods) and SAP (**S**ystematic **A**pproach to solving **P**roblems) models by Mettes et al.[5] and Kramers–Pals, Pilot,[6] is presented.

The research in problem-solving strategies has detected the most common difficulties of students at different levels of schooling regarding solving quantitative problems in stoichiometry.[1,7–19] These strategies help students to realise the essential stoichiometry problem-solving actions and to give feedback when mistakes occur. Gabel et al.[11] conducted a study to determine the general problem–solving skills that students use in solving problems involving moles, stoichiometry, the gas laws and molarity. They have shown that successful high school students and students with high proportional reasoning ability tend to employ algorithmic strategies more than their less successful and low proportional reasoning counterparts. According to Staver and Lumpe[18] misunderstanding of the mole concept is a major block in the ability of college freshman to solve stoichiometry problems.

Frazer[4] developed guidelines for solving stoichiometry problems. He anticipated a five-step way: (1) Write balanced equations for all the processes; (2) Hence find the stoichiometric ratio of the unknown to the known species; (3) Convert all the given quantities (masses, volumes, concentrations etc.) into moles of specified chemical species; (4) Find the moles of the specified unknown species, and (5) Convert moles of unknown species into the required quantity (masses, volumes, concentrations etc.).

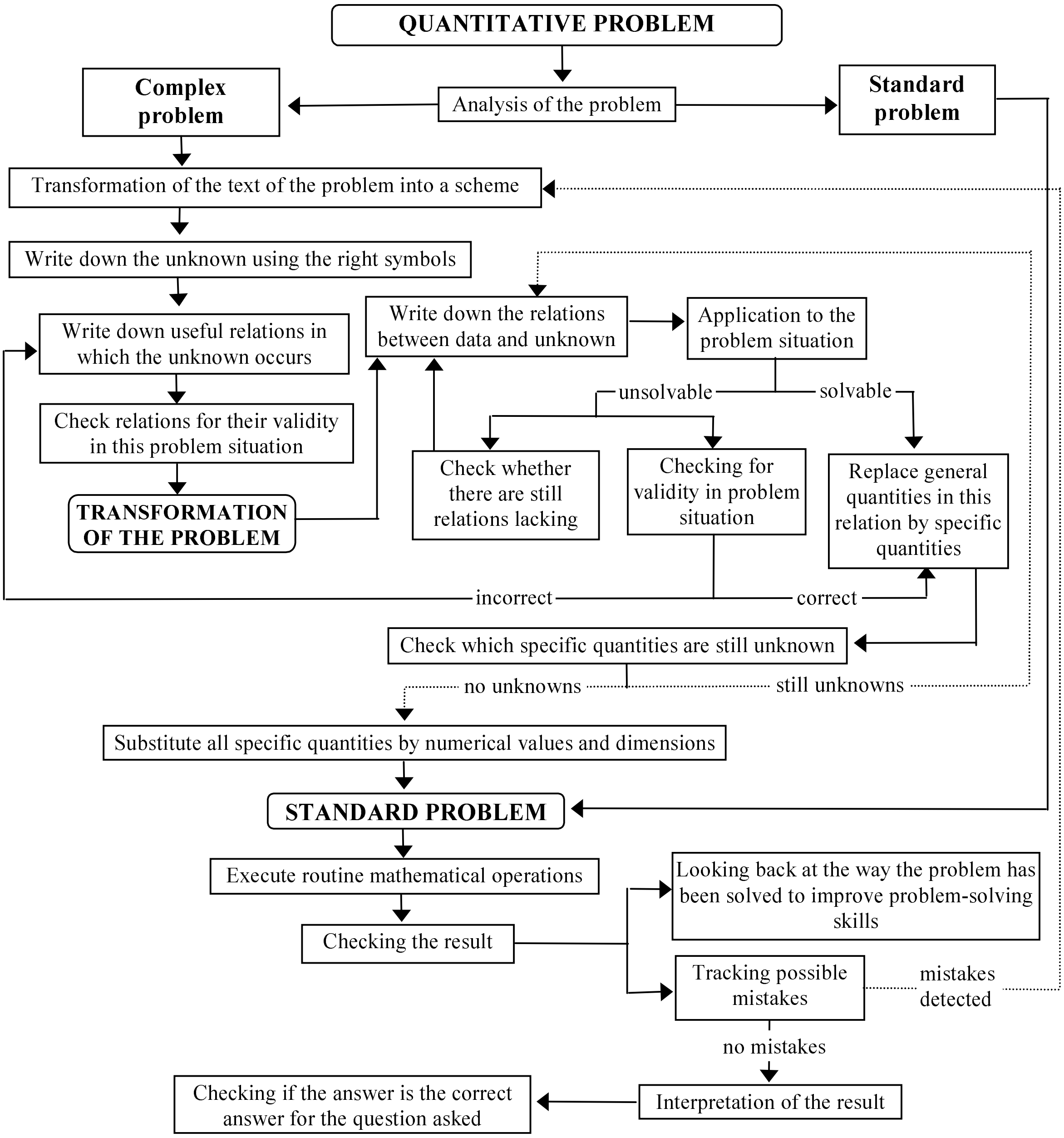

Figure 1. General step-by-step strategy for solving chemical problems integrating PAM and SAP approaches.

Problem

In Slovenian primary school the fundamentals of the quantitative level of chemical language (chemical symbols and the simple formulae of mainly binary compounds, and simple chemical equations) are first taught at the age of 13–14. Applications of chemical equations at the quantitative level are further developed in the first year of secondary school (16 yrs.).

The previous results of the *Matura* exams in chemistry at the end of secondary school show that students have difficulties in writing symbols, formulae and balanced equations, which results in their inability to solve stoichiometry problems.

The purpose of this investigation was to determine the most common strategies used by students in Slovenia in solving stoichiometry problems and to show how a knowledge of chemical language exerts an influence on success in solving stoichiometry problems.

Method

1. Sample

The data were collected at the end of secondary school at the Matura exam. During a five year period (1995–1999), altogether 1070 secondary school students at the age of 19 participated in the study. In Slovenia all students who choose chemistry as a Matura subject follow a six-year course of chemistry (two years in primary school – students aged between 13 and 15 years, and four years in secondary school – students aged between 15 and 19 years) with two periods (45 minutes) a week. Additionally, in the fourth year, the students have to follow a special course of lab work.

2. Description of the quantitative problems

We analysed the course of solving four different stoichiometric tasks, and found that the students approached the tasks in different ways.

The chosen tasks have two main steps. The first step was writing down the equation and balancing it, and the second step was calculation of: (1) the volume of ammonia used in chemical reaction with sulphuric(VI) acid, if a known mass of ammonium sulphate(VI) is formed (J 95 /2/, J 97 /2/); (2) the volume of the phosphoric(V) acid solution of a known molarity used for neutralisation of the potassium hydroxide solution of a known volume and molarity (J 98 /7/); (3) the volume of the oxygen produced after heating the known mass of potassium chlorate(V) with manganese(IV) oxide as a catalyst (J 96 /2/); and (4) the mass of chlorine used for obtaining a known mass of bromine from sea water (J 99 /3/).

Students were required to follow six steps in the problem-solving procedure: (1) writing down the equation and balancing it; (2) writing down the data and useful relations; (3) calculating the molar mass of the known and unknown substances; (4) calculating the amount of the known substance; (5) using the amount ratio to calculate the amount of the unknown substance; and (6) calculating the volume of the gas or liquid or the mass of a substance required in the task.

3. Procedure

A 15-item (one or two items are stoichiometry problems) paper-and-pencil test was assigned to the students. The time required to complete the test was 90 minutes. Students used the enclosed periodic table of elements and a calculator. In our study only one stoichiometry problem from the test each year was analysed. The main steps needed to solve the problem were identified. For each step, the proportion of correct answers was calculated and the most common mistakes were established.

Results and discussion

From the results obtained in analysis of chosen stoichiometry problems, we can conclude that Slovene secondary school students were the most successful in solving the neutralisation stoichiometry problem J 98 /7/ in school year 1997/98 (65 % of correct results) (*Chart 1*). The task was quite easy for students because they came across such types of tasks quite often in their secondary school chemical education (the neutralisation of the acid with the base) – 77 % of the students correctly wrote the chemical equation for this reaction. The highest percentage of wrong answers was detected at the Matura exam in school year 1994/95 and 1996/97, when only 34 % (J 95 /2/) and 28 % (J 97 /2/) of students correctly solved the same problem. The most frequent mistake was in calculating the amount of reactant from the amount ratio (27 %

of incorrect calculations). Only 16 % of the students correctly calculated the volume of ammonia in given conditions at the end of the problem-solving process.

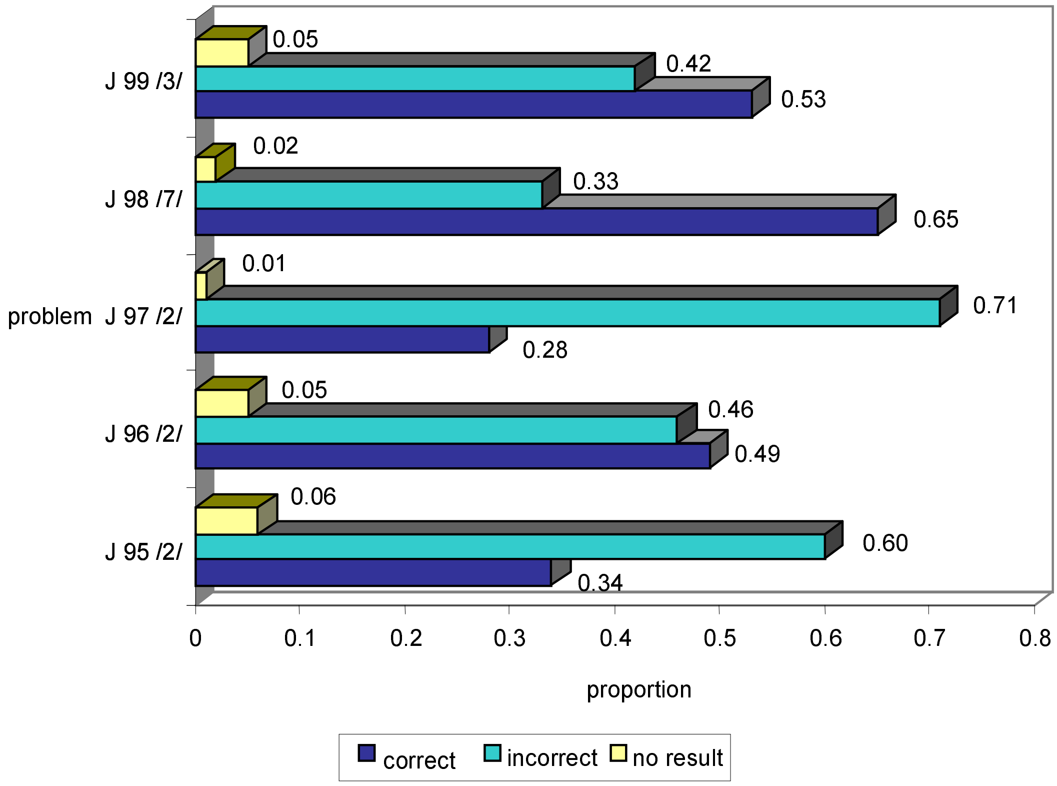

Chart 1. Comparative review of success in solving chosen stoichiometry problems in years 1994/95 - 1998/99

The average score of correct answers obtained by using the stoichiometry model are given in *Figure 2*. On average, 46 % of the students correctly solved the task, but 3.8 % of students did not even attempt to solve it. 51 % of students correctly wrote the chemical equation, and 32 % of students correctly solved the unknown amount of substance from the amount ratio. On average, 26 % of students solved the items using the step-by-step model, and 20 % of students used other strategies (chunking of steps in the problem–solving procedure, and by using the rule of proportion).

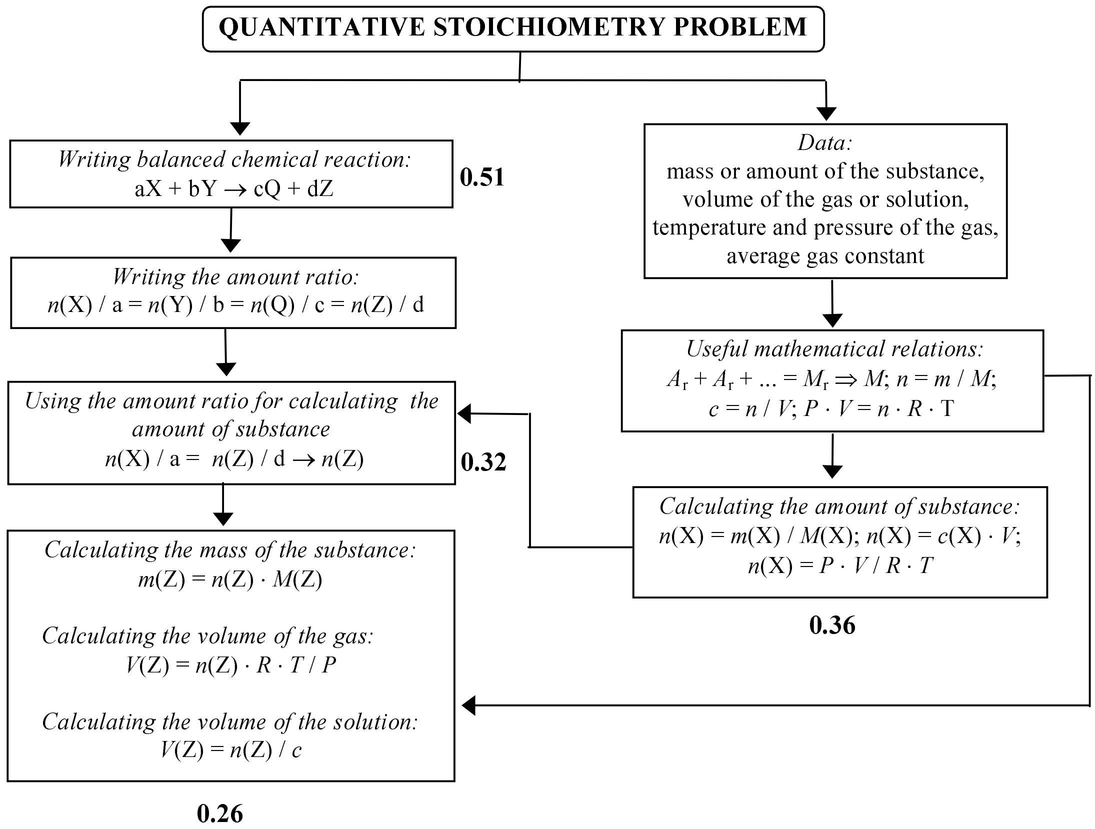

Figure 2. Model of solving stoichiometry problems, including the average proportion of correct answers

The use of other strategies increased from the year 1995, when 14 % of students used other strategies, to 17 % in year 1999. These results may show different aspects in teaching problem-solving strategies, but the average success in solving stoichiometry problems was not improved. The symbolic chemical language is the first barrier in solving stoichiometric problems. On average, 76 % of students correctly wrote the formulae of reactants and 63 % formulae of products, and 51 % of students correctly wrote the balanced chemical equation.

The most common mistakes in writing chemical equations were: (1) wrong symbol for elements forming a compound; (2) wrong anion or cation in the formula for salt; (3) wrong charge of ions in the salt; (4) not understanding the role of the oxidation number in the compound name, and (5) not understanding prefixes (di-, tri-,...) in the names of compounds.

The results of the analyses conducted on tests from Matura exam in the years 1995 and 1997 show that students do not have difficulties in writing down the formula of sulphuric(VI) acid, but they do have problems with the formula of its salt with ammonia (60 % of the students correctly wrote the formula of the salt in 1995, J 95 /2/; and fewer than 70 % in 1997, J 97 /2/). The most common mistake was connected to the formula of the ammonium ion. On testing in 1995, this mistake was made by 26 % of the students, and in 1997 by 21 % of the students, out of all students who incorrectly wrote the chemical formula of the ammonium sulphate(VI). The students wrote down some quite confused formulae of the ammonium ion, such as NH_3, NH_2, NH, N_2 or just N. The most frequent mistake is the confusion of the ammonium ion with ammonia (1995 – 12 % and 1997 – 11 % out of detected mistakes relating to the ammonium ion). Students know the formula of sulphuric acid, because they have learned about it in primary and secondary school as an example of a strong acid. Writing down the chemical formulae of the salts of alkali and alkaline earth metals with sulphuric acid also does not pose a great difficulty to the students, but they do have troubles writing the formula of a salt with ammonia. The mistakes could be the consequence of a lack of knowledge about how ammonia forms an ammonium ion in water solutions, what its charge is, and how its alkali characteristics could be explained.

The understanding of the amount ratio is, beside the symbolic chemical language, the most difficult step in the stoichiometry problem-solving procedure. This could show the lack of proportional reasoning ability of our nineteen-year-old secondary school students. Gabel et al.[10, 11] found similar results in their research on American secondary school students.

One fifth of the students made a mistake in calculation in part of the problem-solving procedure. The most probable reason is negligence. With proper integration of the chemical and mathematical knowledge the students would be aware of the magnitude of the numerical result and its units.

We detected some misconceptions regarding: (1) understanding the role of a catalyst in chemical reactions J 96 /2/ (13 % of students think that a catalyst is a reactant from which the products are formed); (2) the concept of particles in solutions of ionic compounds; J 99 /3/ (20 % of students consider sea water as a solution in which "molecules of bromine compounds" are present); (3) the meaning of balanced chemical equations and amount ratio, and (4) some students confuse some physical quantities such as density, mass, amount and volume of the substance.

Conclusion and application

The chemical equations should be derived from the experimental work. With systematic observation of the chemical change and its proper step-by-step illustration using symbolic chemical language, the ability of abstraction, anticipation of possible products and reasonable conclusions could be developed in students, even when the real chemical reaction is not performed. Yet we do not teach chemistry in such a way in our schools, since usually teachers just demand from students chemical equations learned by heart. The consequences of such teaching of chemistry are often misconceptions about chemical reactions, which can be reflected in writing down some meaningless and wrong chemical compounds as a result of the students' guessing.

The overall conclusion is that students – even after six years of chemistry education – do not adequately master the chemical language which is fundamental for stoichiometry, the reason being that not enough emphasis is given to teaching and consolidating the use of the proper symbolic language of chemistry. Students do not understand the correlation between the name of a substance and its formula**.** They do not master the meaning of suffixes in naming chemical substances. Students do not correlate the oxidation number of elements with the name of the substance. In some cases they also confuse the symbols for elements. They do not pay attention to the positions of the elements in the periodic table and their common oxidation number.

Beside very weak knowledge of chemical language, students do not have adequately developed proportional reasoning, but they just follow the algorithms learnt, using mathematical operations in solving stoichiometry problems. They do not think chemically about the obtained result in the problem-solving process.

In the chemistry curriculum in Slovenian secondary schools more stress should be given to chemical language and its application in stoichiometry. The quantitative level of chemical reaction should be an essential part of teaching chemistry, and not only a part of the curriculum in the first year. The teachers should make a greater effort to:

(1) understand chemical concepts regarding the quantitative problem, and not just apply mathematical relations in the problem-solving procedure;

(2) present quantitative relations between substances in the chemical reaction through experiments, and develop the skill of exact observation and meaningful use of symbolic chemical language;

(3) introduce and practice the problem-solving strategies in pairs or small groups, so that students will be able to solve stoichiometric problems step-by-step and to evaluate the solutions for each step;

(4) develop exactness in reading the text of the problem and in performing the solution process;

(5) deal with problems as specific situations – and students must be aware that, for problem-solving, critical and logical reasoning is necessary;

(6) encourage students in seeking suitable information to solve a problem from other sources (books, articles, internet, CD–ROMs...);

(7) explain the step-by-step problem-solving procedure, so that students could incode the process in long-term memory for later application to similar situations;

(8) develop proportional reasoning, and

(9) evaluate the problem-solving process and the end result (its magnitude and units).

All these points require from the teacher greater knowledge in leading the educational process, detection of misconceptions and their elimination.

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Povzetek

Namen raziskave je oceniti uspešnost in ugotoviti težave slovenskih srednješolcev (starih 19 let) pri reševanju stehiometrijskih problemov. Podatki so bili zbrani na maturitetnih preizkusih znanja v zadnjem petletnem obdobju maturitetnih preizkusov (1995–1999). Postavljen je bil splošni model reševanja stehiometrijskih problemov. Ugotovljeno je bilo, da je povprečno 46 % maturantov pravilno rešilo naloge, skoraj 4 % dijakov pa nalog ni reševalo. Najpogostejše napake pri reševanju tovrstnih problemov so napake v uporabi simbolnega kemijskega jezika in uporabi množinskega razmerja. Na koncu so podane smernice poučevanja te vsebine, v upanju na zmanjšanje tovrstnih napak.