University-school initiative for a career in engineering: development of self-directed learning when solving mathematics problems

Tertia Jordaan & Marietjie Havenga

North-West University
Potchefstroom, South Africa

ABSTRACT: The Science, Engineering, Technology and Health (SETH) Academy of the Faculty of Engineering at the North-West University, Potchefstroom, South Africa, is a university-school initiative with industry. SETH strives to prepare learners for studies in higher education where mathematics is a prerequisite. The intent is to assist learners in developing interdisciplinary knowledge and an array of skills for future demands. Activities take place after school hours, and involve practical sessions and teamwork. In the current study, learners were exposed to real-world mathematics problems. This article reports on the qualitative aspects of a larger mixed method study. The participants were 104 grade 8 and 9 SETH learners. Participants initially completed two open-ended questionnaires. Thereafter, 14 participants were individually interviewed. Data were analysed using ATLAS.ti™. The findings disclosed that the participating SETH learners developed self-directed learning skills as a result of their exposure to solving real-world mathematics problems.

INTRODUCTION

Irrespective of various initiatives, the performance of mathematics learners in South Africa remains unsatisfactory [1]. Due to the poor grade 12 results in the National Senior Certificate examination in mathematics, fewer learners qualify for higher education studies annually where mathematics is a prerequisite. In addition, the admission requirements for studies in engineering are challenging for many school learners. These include full matriculation exemption, with an admission point score (APS) of at least 34, a mathematics and physical science result of between 70% and 79%, and between 60% and 69% in the home or first additional language. Moreover, learners have difficulty in applying their knowledge to solve problems in unknown, sometimes unfamiliar situations and integrated scenarios. It is, therefore, imperative to expose learners to such problems, should they plan a career in science, technology, engineering, [arts] and mathematics (STE(A)M).

The Faculty of Engineering at the North-West University (NWU) in Potchefstroom, South Africa, initiated the Science, Engineering, Technology and Health (SETH) Academy at a project school to assist learners with the potential to pursue a career in engineering. SETH is a collaboration between the university, the project school community and industry.

The SETH Academy established a distinctive programme where learners are equipped to use mathematics, science and related subjects to address real-world problems. SETH learners should be able to develop as independent thinkers who are curious and motivated when they are challenged with unfamiliar problems. Hence, these learners are exposed to structured (classes, practical work, workshops), as well as unstructured (visiting the university and industry) ways to increase their interest and to introduce them to real-world engineering experiences. Further, SETH learners should be able to address complex mathematics problems from secondary school onwards, and concurrently able to engage in the development of self-directed learning (SDL).

SDL comprises an inherent drive to make decisions regarding one's own learning processes, take the initiative to determine particular learning needs, formulate learning goals, select appropriate resources, integrate and construct new knowledge and also evaluate whether the learning outcomes were achieved [2]. Savery asserts that learners should be responsible for their own learning and be knowledgeable about *what they know and what they need to learn more about* [3]. The aim of the current research was to explore the development of SDL skills where SETH learners were challenged with real-world mathematics problems.

THEORETICAL OVERVIEW

The SETH Academy, real-world mathematics problems and self-directed learning are discussed in this section.

The SETH Academy

The Faculty of Engineering at NWU initiated the SETH Academy at a project school. SETH aims to assist learners by offering extracurricular activities, promoting their interest in scientific subjects and introducing them to engineering-related challenges. The aim of SETH is to create a platform for collaboration and to support the learners to improve their achievement in mathematics and physical science to qualify for study in STE(A)M programmes, where mathematics is a prerequisite. Moreover, learners have the opportunity to develop an understanding of what the engineering discipline entails.

SETH activities involve experiments, research, practical sessions and teamwork, making it possible for learners to visit the industry, helping them interact with university lecturers and providing opportunities to participate in some workshop activities at the faculty. SETH activities are structured in such a way that learners are responsible for collaborating and solving problems together. The strength of a learner-centred approach is that each learner brings along particular knowledge, skills and competencies to enhance the team work, which enable them to achieve particular goals [4].

SETH learners are selected during grade 7 by requiring at least 80% in mathematics and science and achieving a grade average of 80% or more. The SETH Academy is committed to support the learners in developing interdisciplinary knowledge and an array of skills for future demands and innovation. Development of such skills comprises solving real-world problems, applying critical and creative thinking, investing in people skills, being self-directed and addressing new challenges constructively. Mathematics activities take place once a month on a Monday afternoon. In the current study, two mathematics teachers were involved, one for grade 8 and the other for grade 9. Initially, learners worked on routine problems. This was followed with the solving of real-world mathematics problems where learners actively collaborated in groups of four to five. Teachers selected appropriate problems themselves and facilitated the learners.

Real-world Mathematics Problems

Mathematics makes use of *notations and symbols for describing geometric, numerical and graphical relationships. It helps to develop the mental processes that enhance logical and critical thinking, accuracy and problem solving that will contribute to decision-making* [5]. However, solving real-world mathematics problems is a challenge for learners, as such problems do not necessarily have an obvious solution. Further, open-ended problems are related to real-life challenges and extra-curricular scenarios [6]. These problems pose a cognitive demand, as they require the application of knowledge and skills to unknown situations.

Schukajlow et al refer to the importance of constructing multiple solutions for real-world problems in mathematics. They emphasise that learners should develop different ways to solve a problem, compare solutions, reflect and make decisions regarding the given solutions [7]. Moreover, real-world problems require the use of various mathematical procedures as a result of *variations in assumptions about vague conditions* [7].

According to Jurdak *…the school and the real world have to form a network in order to work together towards a collaboratively constructed common object, which is learning real-world problem solving in school mathematics* [8]. It is mentioned that this can be done by forming partnerships between school mathematics and an activity system (according to the cultural historical activity theory), such as the Faculty of Engineering as mentioned in this research. Further, Jurdak highlights that students (learners) can be empowered by *…using appropriately developed symbolic and material tools as common spaces for interaction and cooperation*, with the aim to *…cross the boundaries between problem-solving practices in the real world and in school mathematics* [8]. The authors, therefore, used real-world examples of mathematics problems for grade 8 and 9 SETH learners. Two examples are given below. Such problems require planning, decision-making and predictions, reasoning skills, creative and logical thinking, and justification of responses [9].

Age Group: Grade 8

Problem description: a boy eats 100 cookies in five days. Each day he eats five more cookies than the previous day. How many cookies did he eat on the first day?

Age Group: Grade 9

Problem description: pump A can fill a tank with water in five hours. Pump B can fill the same tank in 8 hours. How long will it take to fill up the tank if both pumps are working simultaneously? (Round off your answer to the nearest minute).

Self-Directed Learning

Solving real-world mathematics problems also requires the concurrent development of self-directed skills. Self-directed learning (SDL) is a process where learners are in control of their own learning processes, take ownership of tasks, learn what they regard as vital, set learning goals, direct their thinking, select appropriate resources and make

justifications [2][10]. Self-directed learners demonstrate the following competencies: they are persistent and curious, identify learning gaps, manage information, consciously monitor, reflect on and regulate their learning, judge themselves critically, and evaluate others and themselves [9][11]. According to Schweder, an essential skill of self-directed learners is the ability to make analogies and associations with prior knowledge and, as a result, they are able to apply learning strategies, formulate objectives and integrate new information [12].

Management of one's own learning processes and the ability to elaborate on prior knowledge are all reflections of a self-directed learner who is responsible for and able to address new challenges and demands that may arise in the future [12]. As a result, subject knowledge and skills, as well as personal traits to direct one's own thinking are two sides of the same coin. However, school learners experience challenges in applying their mathematics knowledge and skills to solve problems in unknown and unfamiliar situations, as such problems do not necessarily have an obvious solution. In addition, learners are not necessarily used to manage their own learning processes. Such skills are seen as implicit knowledge expected from the learner. Consequently, the aim of this research was to answer the following question: how can SETH learners develop SDL skills by solving real-world mathematics problems?

RESEARCH METHODOLOGY

Although a mixed method approach was used for our research, in this article, the authors only report on the qualitative aspects.

Participants

A total of 76 grade 8 and 28 grade 9 learners (N = 104) from the SETH Academy participated. SETH learners are selected during grade 7 (last year of primary school) and should have scored at least 80% in mathematics and science, achieving a grade average of 80% or more. Ethical clearance was obtained from the University, and all ethical requirements were addressed (e.g. the learners gave informed assent).

Data Gathering and Analysis

During the study, participants worked in collaboration on real-world mathematics problems and extra-curricular scenarios on various levels of difficulty. Thereafter, the participants completed two open-ended questionnaires on their experiences (the SETH Academy in general, however, also commented on the mathematics interventions) ten months apart. This was followed by 14 individual interviews until data saturation was obtained. In the task-based interviews, the participants reflected on their thinking processes, problem-solving skills and strategies when solving the problems. Criteria were identified to outline the SDL skill development as a result of the mathematics interventions. The data were transcribed and coded using ATLAS.ti™, and various themes emerged.

DISCUSSION OF FINDINGS

Table 1 displays the responses of grade 8 and 9 SETH learners on the questionnaires and the task-based interviews. SDL skill development is shown in the right-hand column according to the skills outlined in the theoretical overview. Participant numbers are indicated in brackets, e.g. (P[grade]-[participant number]). Quotations are reproduced verbatim and unedited.

Table 1: SETH learners' responses on the questionnaires and the task-based interviews.

Some exemplars of learners' responses	SDL skill development
My journey with the SETH academy has been extraordinary although there are times when I feel as though the lessons are unnecessary … I have learned quite a lot. (P9-14)	Reflection
SETH gave me a new approach or outlook on matters in life, not only did it improve my marks; it changed me, Thanks, SETH, You rock! (P8-13)	Learning motivation Self-concept of learning ability
SETH has changed the way I see Maths. It has taught me to have a positive outlook on Maths. (P9-1)	Learning motivation Reflection
The interesting scenarios we are given that show the reality in all our math problems. The interesting computer-based programs we use. The interesting teacher we have and his educated insight. (P9-21)	Real-world problems Learning motivation
Challenging. Math requires determination and participation as well as interest. (P8-15)	Reflection Persistence
Well, first I read the question, and then I try to make an image for myself. Then I draw a picture for myself because it's easier for me to visualise and then write the question and then I start from there. (P8-14)	Learning strategy Learning activity

They gave the diameter, and if you calculate the area, you look for the radius. So, then I calculated the area, and I divided the area by the price of the pizza, and then you find how many square meter per rand it was. So, you can determine which pizza is more expensive or cheaper. (P9-17)	Learning strategy Learning activity
I first calculated the total volume of the cube, then I started taking different heights (5, 6 and 8) and with each height, by means of trial and error, I multiplied each height by five. I realised that it is far too small if you substitute the cube's height by five and that height, then I saw that both are too little to give a total of 80. Until I saw it became too much, then I started working with the commas. (P8-61)	Learning activity Reflection Make justifications
They say here that the stone is completely in the water. So, if some part of it stood out, then one could say there is a chance that you will miss that part of the stone, but it is completely on the bottom of the cylinder. (P9-50)	Make justifications Reflection
I sometimes do not think properly how to solve the problem, I make small mistakes, or I leave something small out, so, I see it in the wrong from what I should, and then I find a solution, but not the correct solution. (P9-12)	Reflection Identify learning gaps
The mathematics worksheets are really challenging and really push you to your limit. It is nice to think on a different spectrum from the maths we do at school. (P9-22) *…It was a struggle for me to comprehend and solve the problems, but after a while, I got used to finishing the questions on the first page without much of a hassle*. (P8-5)	Reflection Identify learning gaps Persistence
SETH academy is a wonderful programme because it helps us see what we like and what we don't like, so we can develop ourselves, the leaders of tomorrow. (P9-27)	Reflection Learning motivation
They are very challenging, I enjoy challenges; they are difficult from school papers. They are the best Math worksheets I have ever done because you see where Math is applicable in real life; they don't just ask sums and formulas. (P9-27)	Reflection Real-world problems Learning motivation
Math requires determination and participation as well as interest. (P8-15)	Persistence
Okay, soooo now I see what I did wrongly, I only added one small block and not both of them (meaning 3 cm on the one side, but not on the other side too). (P8-22)	Reflection Identify learning gaps
I actually do, I mean I like solving problems and I always find a way to connect things like something that I do, and I do enjoy solving problems. I always try to find the root cause of the actual thing that I have to find out so I would say that I am a good problem solver. (P8-24)	Reflection Self-concept of learning ability
Yes, I like it a lot. The more problems I solve, the easier … it becomes for me, and often I solve them quite quick and other times I take long. I see myself as good. (P8-101)	Reflection Self-concept of learning ability
I have more confidence to attempt a problem. (P9-26)	Self-concept of learning ability
If I reach a solution, but I'm not a 100% sure, I just quickly work it out to see if it does work, but if in the end I do get a solution and it works out I'm sort of happy that like I applied the steps right and everything. I get that moment of relief and happiness and actually got it. (P8-24)	Reflection Learning strategy Self-concept of learning ability
Yes, when I checked my question paper afterwards, this did not make sense to me. When I looked well, I saw that I said cm square per Rand [currency] *and it had to be the other way around, so I wrote this on top and reworked it*. (P8-17)	Reflection Identify learning gaps
It is a complicated subject, which needs a lot of focus and practice. … But all in all, Mathematics is a difficult subject at times. (P9-22)	Reflection Self-concept of learning ability
Due to the Math sessions always identifying current Math troubles and providing solutions, if done too frequently, there will be no more worthwhile problems to solve. (P9-21)	Real-life scenarios

The research question aimed to determine how SETH learners can develop self-directed skills through the solving of real-world mathematics problems. This is followed by an integrated view on various SDL skills that SETH learners developed.

Table 1 displays several examples of experiences of SETH learners as emerged from the data. It was an extraordinary journey with interesting scenarios and real-world problems where they learned much. Some participants indicated that they improved on their mathematics scores and developed a positive outlook on mathematics. Furthermore, learners used particular strategies to visualise and solve problems. Learners made justifications and had the courage to adapt their thinking where required, they reflected on their problem-solving processes and made connections between concepts.

Others experienced mathematics as a complicated subject, where problems were seen as challenging, mistakes were made and important steps were left out. Although the learners identified various gaps, they persisted in solving the

problems and eventually got it right. Reflection was especially mentioned as an important skill in mathematics, for example, *I checked my question paper …I saw that I said cm square per Rand and it had to be the other way around, so I wrote this on top and reworked it* (P8-17); *I always try to find the root cause of the actual thing that I have to find out so I would say that I am a good problem solver* (P8-24). It is, therefore, of the utmost importance to reflect not only on the correctness of the solution, but also on the effectiveness of the problem-solving procedure.

The same skills mentioned above are also essential for solving real-world problems as these skills characterise self-directed learning. SETH learners actively participated in solving the problems, they were curious and persistent, and many enjoyed working on challenging and real-world problems. Solving such problems poses a high cognitive demand to learners, because of the *unfamiliarity* of the problem. Participants were intrinsically motivated to attempt the problem knowing that they could solve it. In addition, solving these problems also enhanced the self-concept of SETH learners regarding their learning ability in mathematics.

The qualitative findings revealed that SETH learners developed a variety of SDL skills during their exposure to real-world mathematics problems. Participants developed the following: they learned vital aspects; managed information; monitored and reflected on their learning; became knowledgeable, persistent and curious; controlled their learning processes; made justifications; evaluated themselves; and identified some learning gaps. Learners identified *what they know and what they need to learn more about* as mentioned by Savery [3]. Consequently, developing self-directed skills plays a vital role in preparing learners for higher education and future demands and becoming responsible learners.

Figure 1 outlines the themes that emerged with relationships between the key concepts involved in the solving of real-world mathematics problems, which are also essential for the development of SDL skills, as discussed in the theoretical overview.

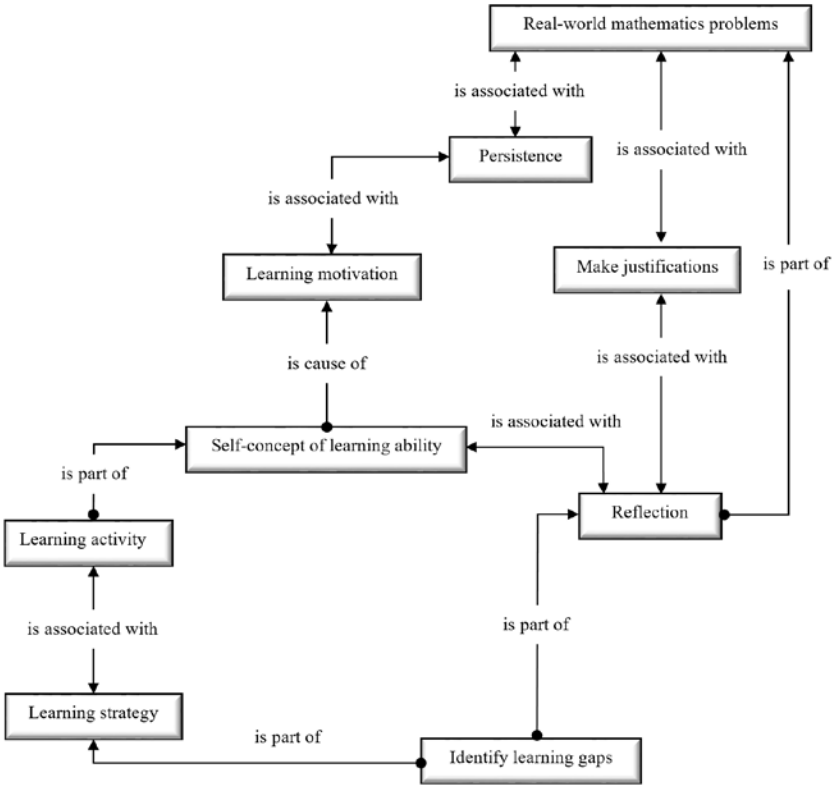

Figure 1: Development of self-directed learning in SETH learners when solving real-world mathematics problems.

CONCLUSIONS

Solving real-world problems forms part of everyday life. The grade 8 and 9 SETH learners were exposed to solving real-world problems, with the aim of preparing learners who want to pursue a career in engineering. Despite the fact that they were initially resistant to this *new and unfamiliar* way of doing mathematics, they gradually accepted the challenges posed to them, became excited about the challenges and motivated to solve such problems. As a result, they obtained a variety of integrated knowledge and self-directed skills over time.

Finally, the use of real-world mathematics problems seemed to have made a noteworthy contribution, not only to the development of a variety of self-directed skills among the SETH learners, but also in terms of their problem-solving abilities. The development of SDL skills over time ought to prepare learners more effectively for a career in engineering.

ACKNOWLEDGEMENTS

The authors acknowledge the Faculty of Engineering of the North-West University, Potchefstroom, South Africa, for their financial support of the study.

REFERENCES

1. DBE, Report on the Annual National Assessments of 2014 Grades 1-6 and 9. Pretoria: Department of Basic Education (2014).
2. Knowles, M.S., *Self-Directed Learning: A Guide for Learners and Teachers*. New York: Cambridge (1975).
3. Savery, J. R., *Overview of Problem-based Learning: Definitions and Distinctions*. In: Walker, A., Leary, H., Hmelo-Silver, C.E. and Ertmer, P.A. (Eds), Essential readings in problem-based learning: exploring and extending the legacy of Howard S. Barrows. Purdue: Purdue University Press, 5-15 (2015).
4. Johnson, D.W. and Johnson, F.P., *Joining Together: Group Theory and Group Skills*. (11th Edn), Harlow: Pearson Education, 637 (2014).
5. DBE, Curriculum and Assessment Policy Statement: Grades 7–9 Mathematics. Pretoria (2011).
6. Smith, C. and Morgan, C., Curricular orientations to real-world contexts in mathematics, *The Curriculum J.*, 27, **1**, 24-45 (2016).
7. Schukajlow, S., Achmetli, K. and Rakoczy, K., Does constructing multiple solutions for real-world problems affect self-efficacy?, *Educational Studies in Mathematics*, 100, **1**, 43-60 (2019).
8. Jurdak, M., Learning and Teaching Real World Problem Solving in School Mathematics (2016), 28 April 2020, https://scholar.google.com/citations?user=ZYPX3r8AAAAJ&hl=en#d=gs_md_cita-d&u=%2Fcitations%3Fview_op%3Dview_citation%26hl%3Den%26user%3DZYPX3r8AAAAJ%26citation_for_view%3DZYPX3r8AAAAJ%3ABqipwSGYUEgC%26tzom%3D-120.
9. Van de Walle, J.A., Karp, K. and Bay-Williams, J., *Elementary and Middle School Mathematics: Teaching Developmentally*. Boston: Pearson (2015).
10. du Toit-Brits, C. and van Zyl, C.-M., Self-directed learning characteristics: making learning personal, empowering and successful, *Africa Educ. Review*, 14, **3-4**, 122-141 (2017).
11. Guglielmino, L.M., The case for promoting self-directed learning in formal educational institutions, *SA-eDUC*, 10, **2**, 1-18 (2013).
12. Schweder, S., Mastery goals, positive emotions and learning behavior in self-directed vs. teacher-directed learning, *European J. of Psychology of Educ*., 35, **1**, 205-223 (2020).