2023

Problem Solving Skills Deconstructed And Implemented In An Adaptive Learning Tool

Arne DUYVER
KU Leuven campus, Faculty of Engineering Technology, Diepenbeek campus, Belgium, Arne.Duyver@kuleuven.be

Jozefien DE KEYZER
KU Leuven campus, Faculty of Engineering Technology, Diepenbeek campus, Belgium, jozefien.dekeyzer@kuleuven.be

Els WIEERS
UHasselt, Faculty of Engineering Technology, Belgium, els.wieers@uhasselt.be

See next page for additional authors

Authors

Arne DUYVER, Jozefien DE KEYZER, Els WIEERS, Kris HENRIOULLE, and Kris AERTS

PROBLEM-SOLVING SKILLS DECONSTRUCED AND IMPLEMENTED IN AN ADAPTIVE LEARNING TOOL (PRACTICE)

A. Duyver
KU Leuven
Faculty of Engineering Technology, Diepenbeek campus, Belgium
0009-0007-1447-1611

J. De Keyzer
KU Leuven
Faculty of Engineering Technology, Diepenbeek campus, Belgium
0000-0002-2056-0174

E. Wieers
UHasselt
Faculty of Engineering Technology, Diepenbeek campus, Belgium
0000-0003-0557-3847

K. Henrioulle
KU Leuven
Faculty of Engineering Technology, Diepenbeek campus, Belgium
0000-0002-4533-822X

K. Aerts [1]
KU Leuven
Faculty of Engineering Technology, Diepenbeek campus, Belgium
0000-0001-7214-452X

[1] Kris Aerts, Kris.Aerts@kuleuven.be

Conference Key Areas: *Virtual and Remote education in a post Covid world, Innovative Teaching and Learning Methods*
Keywords: *Problem solving, building blocks, adaptive online tool*

ABSTRACT

The development of problem-solving skills is an important subject in engineering curricula. Helping novice students develop such skills can be challenging because problem solving is a complex skill in the sense that it is accompanied with an internal thinking process that many experts are even unaware of doing. From a combination of literature and a thinking-aloud exercise with the entire teaching team, a scheme with building blocks and strategies that are commonly used by engineers was constructed. In addition to commonly named steps such as Identify/Define, Plan/Choose, Carry Out/Do and Look back/Inspect the scheme refines the first step into multiple interdependent building blocks, emphasizes the need for critical reflection at each point as well as the possible need to return to previous steps at any time. Moreover, multiple correct solution paths can be followed in solving a problem. To address this and to empower the students in their divergent thinking processes when solving a problem, an innovative intra-exercise adaptive e-learning tool was created. The anywhere-anytime availability enables for virtual and remote learning in the post-COVID world. In the learning tool students can choose between different solution paths, after firstly identifying the correct context, parameters etc. This paper describes the process of defining the building blocks, resulting strategy scheme and implementation of the building blocks in the adaptive e-learning tool. Initial findings indicate that the strategy scheme consisting of building blocks and the adaptive e-learning tool help students in developing their problem-solving skills.

1 INTRODUCTION

As stated by Docktor et al., solving complex problems is an essential skill for all to possess (Docktor et al. 2016). This is especially true for engineers since problem solving plays an important role in their profession. Many higher education institutions therefore see it as an important task to help engineering students develop their problem-solving skills (Neri et al. 2010; Pavlasek 2014). However, Harshkamp and Suhre noticed that students are often taught to solve problems by using solution methods for a specific topic, e.g. in engineering mathematics or physics courses, and less time is devoted to teaching general problem-solving skills (Harskamp and Suhre 2007). The risk of this is that students see problem solving as performing a predefined number of steps dependent on the actual topic. Yet students are expected to solve ill-structured problems in a variety of domains once graduated (McNeill et al. 2016). Our contribution is that we have deconstructed problem-solving skills in more detail than previous work, and conveyed it to first year engineering students in a specific course on problem-solving skills. As problem solving is not a linear process and as multiple paths can lead to a solution, we have also implemented a number of online learning modules with intra-exercise adaptivity and multi-branched solution trees that support the divergent thinking of different types of students. This contrasts with existing tools that guide the student in a fixed, predefined path.

We begin this paper with a *Rationale,* based on a *Literature Overview. "A problem"* is defined and an overview is given of methods for teaching and measuring problem-solving skills, including digital and adaptive learning tools. Next, *Developing the problem-solving building blocks*, describes the process of deconstruction and the resulting problem-solving scheme consisting of building blocks and strategies commonly used by problem solvers. In *Applying the building blocks in teaching,* we show our implementation in- and outside class. *Reported Effects* discusses the findings of a questionnaire answered by 101 out of 194 students. Points of attention and continued research are the subject of *Threats to validity and Future Work. Conclusion* summarizes the main findings.

2 RATIONALE

To be able to teach problem-solving skills, we need a definition of "a problem" and "problem-solving skills". We start with the general definition of a problem (Maloney, 2011):

> *"Whenever there is a gap between where you are now and where you want to be, and you don't know how to find a way to cross that gap, you have a problem."*

This broad definition aligns well with our own idea of a problem since it makes an implicit, but important distinction between performing a task and solving a complex problem. For us, anything that can be solved by following a straightforward procedure is to be considered a task, not a problem, i.e., it is only a problem if *'you don't know how to find a way'.* A problem solver is somebody who finds such a way. In the quote we intentionally underlined not only *find a way*, but also *you*: a task for an expert can be a very big problem for a novice: because of unfamiliarity with the subject, but also because of inexperience with problem solving. Experts are not only an expert in the domain (the *what*), but are also experts in organizing their knowledge (the *how*) in order to see the core relevant principles applicable to the problem at hand, whereas the decision-making process of novices is more narrowly context related (Docktor et al. 2016; Neri et al. 2010).
The strong link with context is prominently present in most approaches to teaching problem solving skills, tying it to a concrete subject (Docktor et al. 2016; Neri et al. 2010; Harskamp and Suhre 2007). However, others put the generic skills first (Kalyuga and Sweller 2005) and stress the uncertainty in the path to the goal and the fact that making mistakes and problem solving go hand in hand (Martinez 1998). We adhere to this vision and have deconstructed problem-solving skills into a set of thought constructs that may help in paving a path, independent of the actual problem domain. We also take care of making students comfortable with the idea that reflecting often and even backtracking, is not a failure, but a very typical instrument of the expert problem solver.
Proper support is needed for the students in this potentially uncomfortable endeavor, both inside and outside class. E-learning has been used before for problem solving, e.g. in the domain of physics (Neri et al. 2010), mathematics (Harskamp and Suhre 2007; Melis et al., 2001), or STEM (Netwong 2018), and even the concept has been mentioned, e.g. "intra-exercise adaptivity" (Göller et al. 2017). "intra-exercise branching" (Mei and Heitzer 2017) and "a branching system of programmed instruction" (Lockee, Moore, and Burton 2004), but we have not found examples of explicit support for multiple solutions paths in generic problem solving with continued feedback along each path.

3 DECONSTRUCTING PROBLEM-SOLVING INTO BUILDING BLOCKS

3.1 Context

In 2018 a specific course on problem solving skills, Basic Engineering Skills (BES), was introduced in our faculty of Engineering Technology at [university omitted for anonymity]. The course is part of the general engineering phase of three semesters, after which students choose one of seven options such as Chemistry, Construction Engineering, Electromechanics, Software Systems, … and is also part of the bridging program for students who already graduated in a related bachelor's degree, e.g. in chemistry or electronics, and seek to acquire a master in engineering technology.
Focusing on problem solving and not on the underlying subject, the problem domains of the exercises were carefully selected to match the knowledge and skill set of the incoming students, who could also use a reference sheet of basic, frequently used formulas. This ought to create a common ground and align with the practice of many courses where problem-solving exercises are used to assess students' comprehension on a certain topic (Docktor et al. 2016; Neri et al. 2010). As the difficulty of the context is reduced in our approach, we hoped to be working only on the problem-solving skills. However, depending on both the background and envisioned major of the students, the perception of the exercises ranged from a (complex) task to a real problem. E.g. an exercise with a context from chemistry, would be a task for a student with a strong chemical background, at the same time posing a challenging problem for a student orientated at computer science. To overcome this, we started an educational innovation project in 2022.

3.2 The process

Because we see problem solving as a complex skill accompanied with an internal thinking process that many experts are even unaware of doing, we deemed it important to first make the unconscious problem-solving schemes and strategies explicit. The first step therefore consisted of a thinking-aloud exercise similar to a method to gauge the level of problem-solving skills of students by having them verbally explain every step in solving the problem as is described in literature (Docktor et al. 2016; Mueller et al. 2017). Each member of the BES teaching team (seven experienced lecturers from five different disciplines) was instructed to individually note every little step of their problem-solving process while solving the same problem as the other participants. Next, pairs were formed in which the approaches were discussed in depth. Finally, a group discussion took place which revealed many different paths, but also similar strategies for approaching the problem. This resulted in the identification of a set of core principles, which were refined into a set of building blocks and the interactions between them.

3.3 The building blocks

In our vision problem-solving can be deconstructed into the following elementary building blocks: Read, Analyze, Structure, Select context and formulas, Generate potential solution paths, Solve and Evaluate, and Report final result. Critical Reflection is an overarching block. Our blocks expand upon the four very basic blocks: (1) understand, (2) choose/make a plan, (3) do/carry out the plan, and (4) inspect/look back (Maloney, 2011), (Polya 2004).

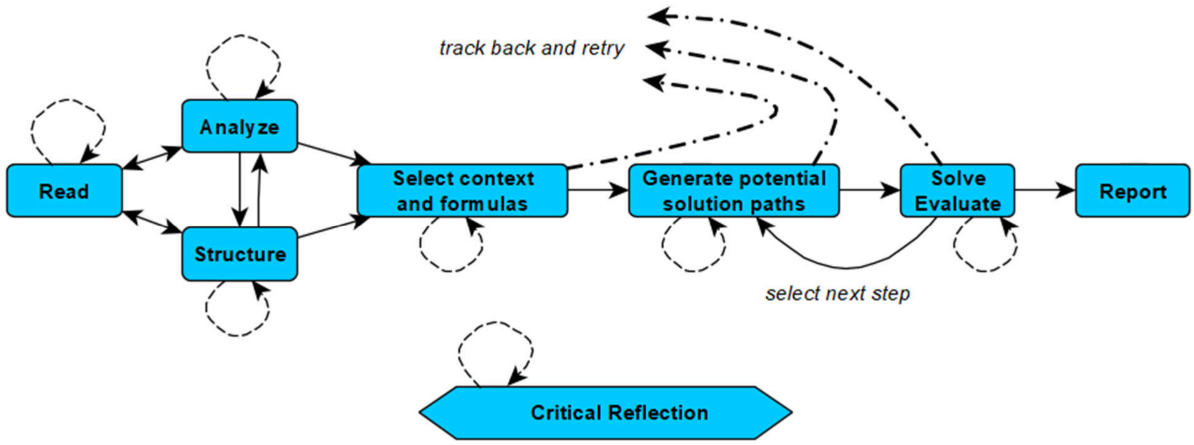

Figure 1: Problem-solving building blocks and their internal control flow.

The central idea is that the blocks do not form a step-by-step plan, but rather a toolbox that can be applied in any suitable order and that can result in a wide tree of approaches to solve the problem at hand. Therefore, the order implied by the solid arrows in Figure 1 is merely a suggestion–unless performing a task. However, when a problem must be solved, there is no direct path from reading the problem description to solving it and reporting the solution. Instead, one needs to figure out possible paths and backtrack when a previous decision turned out to be ineffective. This is denoted by the dash-dot lines.
Equally important are the dashed circles, implying critical reflection and repetition. Critical reflection entails a continuous questioning of the work done: did I read properly, is my sketch complete, is the (partial) solution meaningful, … Also, each building block is probably to be applied several times, e.g. in *Read* one can first scan the assignment to understand the major context and then return to reading when the precise input values are needed; for *Structure* a basis sketch could be made at first, and later on more details can be added. Especially after backtracking, a building block should be reconsidered, e.g. read the assignment again to verify assumptions, select a different context, generate and/or select a different solution path, …
Also notice that after solving a path, the problem solver should evaluate the outcome. When it contains the solution, report it in a proper format. If it is a step in the right direction, select the next step by generating a new path. Otherwise, track back.

3.4 The reported solution does not represent the problem-solving process.

An eye opener to us was the sudden understanding that handing out model solutions for the various exercises did not help students in becoming better problem solvers. The first obvious reason is the absence of different solutions paths, unless many model solutions would be prepared, but more important is the fact that in a model solution the different steps are presented linearly, whereas problem solving is always a back-and-forth process trying out different solutions paths. This simply cannot be made visible in a model solution. We still stress the importance of writing down the final solution in a structured manner, but explicitly position it as a distinct and final phase.

4 APPLYING THE BUILDING BLOCKS IN TEACHING

Although we hinted earlier that uniformly paced on-campus lectures are not perfect, they still are important for introducing the concept and for elucidating it by giving a few examples of different paths that are derived from the same set of building blocks and that lead to the same solution. Next, students solve some problems in class with guidance by the lecturer who always refers to the building blocks as they are applied. We consider the explicit reflection on the concrete stage in the problem-solving process by referring to the building blocks an innovative approach on teaching problem solving skills.

To support the students outside of the classroom, online learning modules were developed for a variety of exercises and contexts. The idea is that students first try to solve the problem without the online module. When the student provides the correct answer, a model solution is presented as an example of how to properly structure a solution. In the case of a wrong answer, feedback is shown and options are given. Just as in the on-campus lectures, we explicitly mention the building block they are currently handling to make the thought process explicit. We thus target a consistent learning experience in respect to the building blocks regardless of the learning lieu (online or on-campus), while at the same time taking care that on-campus and online complement each other. As the covid-era learnt that online teaching simply cannot serve as a full substitute for the social experience of co-learning with fellow students, with our approach we combine the social benefits of on-campus teaching with the benefits of independence and self-pacedness of online learning.

Figure 2 shows a simplified example of a solution tree with different paths. After selecting a path, the learning module continues with options only related to the chosen branch, even if the branch finally would not lead to a final solution, e.g. because of missing data. At the end of the (partial) solution path, the students must evaluate their solution by entering it into the online module. The process of confirming and continuing versus refining or backtracking continues until the student finds a correct solution. Regardless of their position in the module, students can always enter a new attempt for the final solution, to prevent them from having to wade through the rest of the module as soon as they experience the “aha”-moment.

We consider our concept a fine example of intra-exercise adaptivity as depending on the answers and progress of the student, other solution paths are presented that might explore completely different parts of the solution space or that progress at a smaller or faster pace through a similar part with the solution tree.

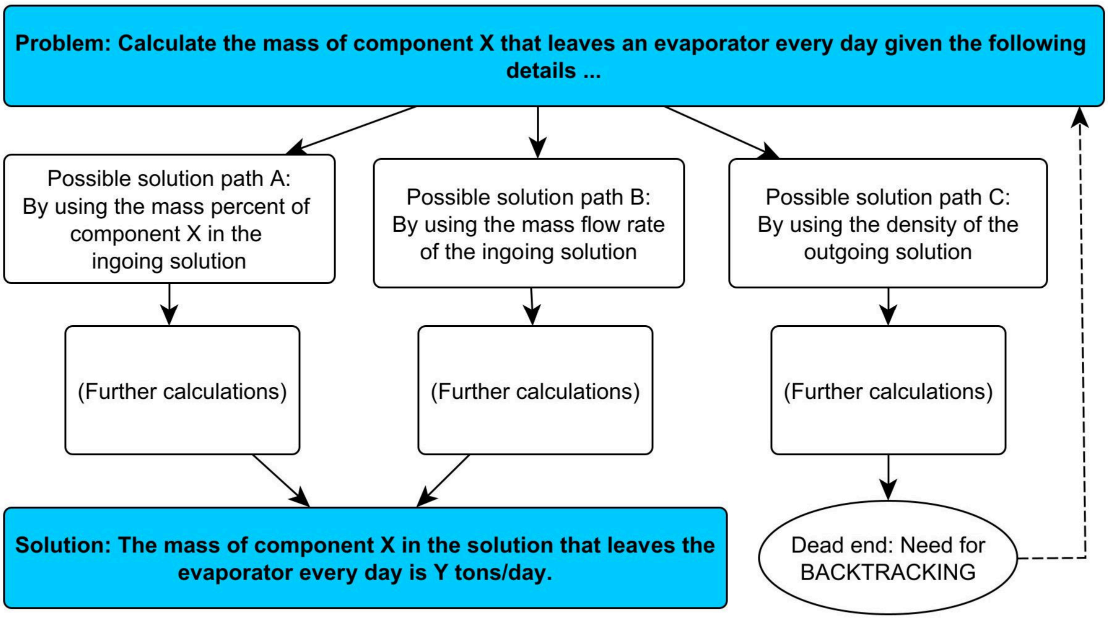

Figure 2: Simplified example of an adaptive solution tree

5 REPORTED EFFECTS

To determine the effectiveness of the online learning modules, we asked all students of the first bachelor year (n = 194) to voluntarily fill in a questionnaire. Most questions used a likert scale, four questions were multiple-choice and two open-ended. Because usage of the modules was also voluntary, some questions were different depending on the number of modules used. 101 students responded, resulting in an overall error margin of 8,90% with a confidence level of 99%. We categorized three groups: no modules used (*zeroMod* group, 41 respondents), one module used (*oneMod* group, 13 students) and two or more modules (*moreMod* group, 47 students). Because the oneMod group consisted of only 13 students, we decided not to withhold this group. In a lot of the domains the students in *zeroMod* and *moreMod* answered similarly, except for the questions in Figure 3. The chances of failing the exam, and being dissatisfied with the results are almost double In the *zeroMod* group compared to the *moreMod* group. This can probably not be solely attributed to using the online modules as students in *zeroMod* probably also practice less when off-line. However two facts at least give an indication of the perceived value of the modules: 1) that 17% of the *zeroMod* group regrets not having used more learning modules and 2) that 34% of the *moreMod* group is convinced that they got a better grade thanks to the modules.

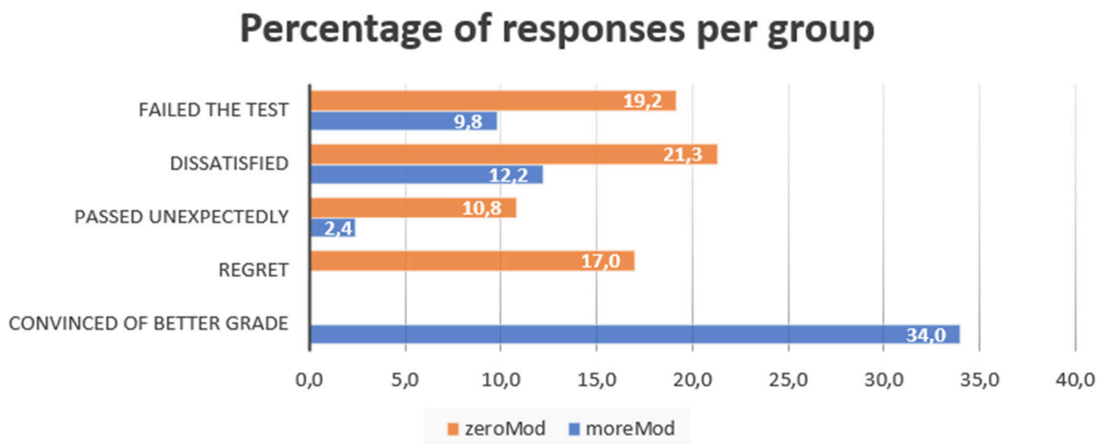

Figure 3: Different answers between zeroMod and moreMod group

We also asked questions similar to Göller et al. (Göller et al. 2017), where 80% of their users found the tool with multiple solution paths helpful in understanding the mathematical concepts, and 40% stated that without the tool they would not have passed the exam. Table 1 shows distinctly lower figures for *moreMod*: 46,3% resp. 4,8%. Looking at the students who barely passed the test and thus need to learn more, this rises to 60% resp. 20%.

	moreMod	*moreMod* barely passing	Göller et al.
Found the tool helpful	46%	60%	80%
Not passing test without tool	5%	20%	40%

Table 1: Reported effect on learning

Further qualitative support could be found in the open-ended questions. The students praised the format in comments as '*Step-by-step guidance'* and '*You can get help and informative feedback when stuck'*. One student put it this way:

> *"I find the online modules very useful because I can clearly see the steps here and I also learn a lot from them."*

The immediate feedback and the proposed proactive approach with hints ensure a good pace in practicing and solves challenges commonly associated with remote learning, where students might drop out of frustration when struggling and void of help or feedback.

Regarding the concept they wrote: '*You are encouraged to search for solutions yourselves'* and '*It encourages logical thinking'.* This fits well in a blended context where you can subsequently challenge the students in-class. The free flow is also appreciated: '*You can skip the feedback steps and just enter the final solution'*. Despite our observation earlier that *only* handing out model solutions does not help students in becoming better problem solvers, students still value them: '*The structured example reports at the end.'*

6 THREATS TO VALIDITY AND FUTURE WORK

A first threat is the socially desired behavior with students unconsciously giving the answers that please their tutors. More important is that we asked about their opinion without really measuring the effect, e.g. whether they think their problem-solving skills improved. To tackle this we will look at the rubrics presented by Docktor et al. (Docktor et al. 2016) and the quantitative measurement of Voskoglou and Perdikaris (Voskoglou and Perdikaris 1993). Another threat is that we tried to let all students participate whereas the central idea of the modules and adaptivity in general, is that only the students who really need it, would use the modules. It is however more likely that the results will only improve when only the correct target groups use the modules. Complaints such as "*It takes too long", "I don't need the modules"* would then disappear.
We also plan further improvements, notably adding more intra-exercise paths, particularly in applying backward thinking, i.e. recoiling from the desired end point to the start; in tracking progress throughout the solution tree and in giving timed hints. The idea is to make estimations of the time needed to progress to a certain state, and to pop up a hint box (with spoiler alert) "*Do you want a hint on topic X".* This somehow resembles the approach by Harskamp and Suhre where students can ask for hints (Harskamp and Suhre 2007), but our approach is proactive instead of waiting on the initiative of the student.

7 CONCLUSION

This paper presented a deconstruction of problem-solving into a non-linear schema consisting of a toolbox of eight building blocks that expands upon previous work with typically four of five basic blocks. The scheme was introduced in a complementary approach for on-campus exercise classes and online learning modules with a focus on consistent reflection on the usage of the building blocks and targeted at blended learning. The intra-exercise adaptivity and multi-path solution trees support divergent thinking and provide the right level of feedback to ensure that students are able to reach a solution.

A survey with 101 respondents out of 194 invites shows that the chances of failing for the tests decreased strongly for students who used at least two modules compared to students who didn't use any modules. The open questions gave further qualitative evidence on the effectiveness of the approach, supporting the claims of the authors to expand the approach. Follow-up research focuses on optimizing the existing modules, developing more developing more modules. Assessing more formally the long-term effects, i.e. the actual increase in problem-solving skills, is also still needed.

8 ACKNOWLEDGEMENTS

Thanks to the students, the team of BES, and the support of KU Leuven Learning Lab, for granting and financially supporting the ZIP-MIPSi-project under the call *Innovatief Digitaal Leren 2021*.

References

Docktor, Jennifer L., Jay Dornfeld, Evan Frodermann, Kenneth Heller, Leonardo Hsu, Koblar Alan Jackson, Andrew Mason, Qing X. Ryan, and Jie Yang. 2016. "Assessing Student Written Problem Solutions: A Problem-Solving Rubric with Application to Introductory Physics." *Physical Review Physics Education Research* 12 (1): 010130. https://doi.org/10.1103/PhysRevPhysEducRes.12.010130.

Göller, Robin, Rolf Biehler, Reinhard Hochmuth, and Hans-Georg Rück. 2017. *Didactics of Mathematics in Higher Education as a Scientific Discipline: Conference Proceedings*.

Harskamp, E., and C. Suhre. 2007. "Schoenfeld's Problem Solving Theory in a Student Controlled Learning Environment." *Computers & Education* 49 (3): 822–39. https://doi.org/10.1016/j.compedu.2005.11.024.

Kalyuga, Slava, and John Sweller. 2005. "Rapid Dynamic Assessment of Expertise to Improve the Efficiency of Adaptive E-Learning." *Educational Technology Research and Development* 53 (3): 83–93. https://doi.org/10.1007/BF02504800.

Lockee, Barbara, David (Mike) Moore, and John Burton. 2004. "Foundations of Programmed Instruction." In *Handbook of Research on Educational Communications and Technology*, 2nd ed., 545–69. Mahwah, New Jersey: Lawrence Erlbaum.

Maloney, David P. 2011. "An Overview of Physics Education Research on Problem Solving." *Getting Started in PER*, 1–33.

Martinez, Michael E. 1998. "What Is Problem Solving?" *The Phi Delta Kappan* 79 (8): 605–9.

McNeill, Nathan J., Elliot P. Douglas, Mirka Koro-Ljungberg, David J. Therriault, and Ilana Krause. 2016. "Undergraduate Students' Beliefs about Engineering Problem Solving." *Journal of Engineering Education* 105 (4): 560–84. https://doi.org/10.1002/jee.20150.

Mei, Robert Ivo, and Johanna Heitzer. 2017. "Didactics of Mathematics in Higher Education, a Service to Science or a Science in Itself? Experiences Made with Tree--Structured Online Exercises." In *Didactics of Mathematics in Higher Education as a Scientific Discipline Conference Proceedings*, 486.

Melis, Erica, Eric Andres, Jochen Budenbender, Adrian Frischauf, George Goduadze, Paul Libbrecht, Martin Pollet, and Carsten Ullrich. 2001. "ActiveMath: A Generic and Adaptive Web-Based Learning Environment." *International Journal of Artificial Intelligence in Education*, no. 12: 385–407.

Mueller, Julie, Danielle Beckett, Eden Hennessey, and Hasan Shodiev. 2017. "Assessing Computational Thinking Across the Curriculum." In *Emerging Research, Practice, and Policy on Computational Thinking*, edited by Peter J. Rich and Charles B. Hodges, 251–67. Educational Communications and Technology: Issues and Innovations. Cham: Springer International Publishing. https://doi.org/10.1007/978-3-319-52691-1_16.

Neri, Luis, Julieta Noguez, and Víctor Robledo-Rella. 2010. "Improving Problem-Solving Skills Using Adaptive On-Line Training and Learning Environments." *International Journal of Engineering Education* 26 (January): 1316–26.

Netwong, Titiya. 2018. "Development of Problem Solving Skills by Integration Learning Following STEM Education for Higher Education." *International Journal of Information and Education Technology* 8 (9): 639–43. https://doi.org/10.18178/ijiet.2018.8.9.1114.

Pavlasek, P. 2014. "ADAPTIVE EDUCATIONAL ENVIRONMENT: CREATING A CULTURE OF INNOVATION TO SUPPORT STUDENTS' PRACTICAL KEY COMPETENCES DEVELOPMENT." *INTED2014 Proceedings*, 7488–97.

Polya, G. 2004. *How to Solve It: A New Aspect of Mathematical Method*. Princeton University Press.

Voskoglou, Michael G., and Steve C. Perdikaris. 1993. "Measuring Problem-solving Skills." *International Journal of Mathematical Education in Science and Technology* 24 (3): 443–47. https://doi.org/10.1080/0020739930240315.