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Student engineers optimising problem solving and research skills

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Abstract

Problem solving and researching are connected activities in the engineering profession and across education. The empirical research presented in this paper considered the effectiveness for teaching and learning of a model that was based on this connection and derived from the parameters of the Research Skill Development framework. The model, devised by students for students, is called the Optimising Problem Solving (OPS) pentagon, and was piloted in a large first-year engineering course in 2014-2015 and in another university in the first half of 2016. This article presents data from formal research conducted on the 2016 offering of the course gathered from pre (n=221) and post (n=169) surveys, and semi-structured interviews of students (n=5) and student/tutors (n=5) sixteen months after course completion. Statistically significant ($p < 0.01$) changes from pre to post in items with medium to large effect sizes provided student perspectives on which problem-solving skills improved, and the interview data provided rich detail on the nature of changes and how these changes were effected. For the 2016 cohort studied, our evidence suggests that use of the OPS pentagon was associated with improved student problem-solving skills, and tutors' capacity to teach problem solving.

Keywords

Problem solving, Optimising Problem Solving, engineering, research skills, communication

Background

Among undergraduate engineering students, written and oral communication abilities are not typically perceived as integral to problem solving, and the connection between problem solving and research skills is rarely made explicit by teachers (Willison et al. 2016). Nevertheless, this integral relationship is attested through Engineers Australia's (2011) *Stage 1 Competency Standard for Professional Engineer* and affirmed by the Australian Qualifications Framework (2013; Bachelor Honours Degree). Similarly, the expectation that undergraduate engineering students will develop problem solving and research skills has also been defined through international mechanisms that govern engineering competencies in Europe (EUR-ACE; European Network for Accreditation of Engineering Education 2015), Canada (CEAB; Engineers Canada 2014) and the USA (American Board for Engineering and Technology 2016). Three interconnected issues underlie the development and linking of these skills: defining the "problem and its salient features", developing "divergent and diverse problem-solving thinking that heeds a broadened way of perceiving problem solving processes" and clarifying the "problem through refined communication" at all stages of the process (Willison et al. 2016). What is less clear, however, is evidence for the effectiveness of specific frameworks and models which may be applied to help students develop problem-solving and research skills within an engineering context.

Development of useful frameworks for problem solving faces the difficulty of articulating problem definition processes and capturing the iterative, non-linear nature of the problem solving, including the communication elements and solution development engaged in throughout. Engineering design problems are characteristically open-ended because they are ill-structured and usually have several acceptable solutions (Dym & Little 2004). Rather than being resolvable through an algorithmic approach, these problems require expert knowledge to simply identify the existence of a problem (Dougherty & Fantaske 1996). Ill-structured problems include workplace engineering problems, frequently have unclear goals or unstated constraints, involve non-engineering success standards and typically require research processes (Jonassen et al. 2006). Ill-structured problems cannot be approached with established and formalised methods, because problem definitions and solutions evolve as understanding develops (Frederiksen 1984), as do the modes and focus of communication.

Different models of engineering problem solving have been discussed in the literature. Many of these models are related to the engineering method or the design method. The engineering method proposed by Dowling et al. (2013) provides a general sequential approach that is typical of the various engineering method morphologies. Within this conceptualisation, the engineering method is nested inside project management. Although it has many forms and interpretations, there are a few key elements which are universal to various definitions of the engineering method. Due to the limitations in information and time typically encountered when solving engineering problems, an engineering method aims to prescribe a set of heuristics which guide an engineer to an ideal solution given finite resources (Koen 2009). This approach can loosely be described as a step-by-step process or procedure "that identifies the problem and the required performance criteria and constraints, considers a range of solutions, evaluates the solutions against the criteria and constraints, and recommends one or more 'best' solutions" (Koen 2009, p. 54). Although a recursive process is suggested to encourage design iterations and successive improvements, the sequence is bound by the format to appear sequential and cyclical, and is often implemented in that way. While this sequence is important in describing and guiding the engineering design steps, it is limited in application for modelling and developing the cognitive processes involved in problem solving or in researching, including communication processes.

Research Context

In Design Graphics and Communication (DG&C), a large core first-year Mechanical Engineering course in an Australian Group of Eight University, the co-ordinator and tutors began developing approaches to address the need for greater student engagement in diverse problem solving and active research. These approaches, both pedagogical and cultural in direction, emerged in 2008 as student-centred learning and peer-led teaching (see Missingham & Matthews 2014) and evolved to include a tutor training program initiated by the peer and near- peer tutors in 2012.

Through the training that followed, tutors were introduced in 2012 to the Research Skills Development framework (RSD: Willison & O'Regan 2006/2018; see the first article in this issue). Subsequently, the RSD framework was used idiosyncratically by tutors for the remaining weeks of the 2012 course and one full semester of 2013. In 2014, tutors were challenged with the task of making the RSD ‘speak engineering’: through a series of workshops facilitated by the second and fourth authors of this paper, the Optimising Problem Solving (OPS) pentagon was devised (Missingham et al. 2014; 2016). Modifications to the original facets of the RSD were developed to fit an engineering genre as shown in Figure 1, and the resultant changes included a change in facet names and descriptors to reflect engineering language and engineering thinking (see Willison et al. 2016). This adaptation process made the legitimate connections and overlaps between research skills, communication skills and problem-solving skills transparent to the tutors.

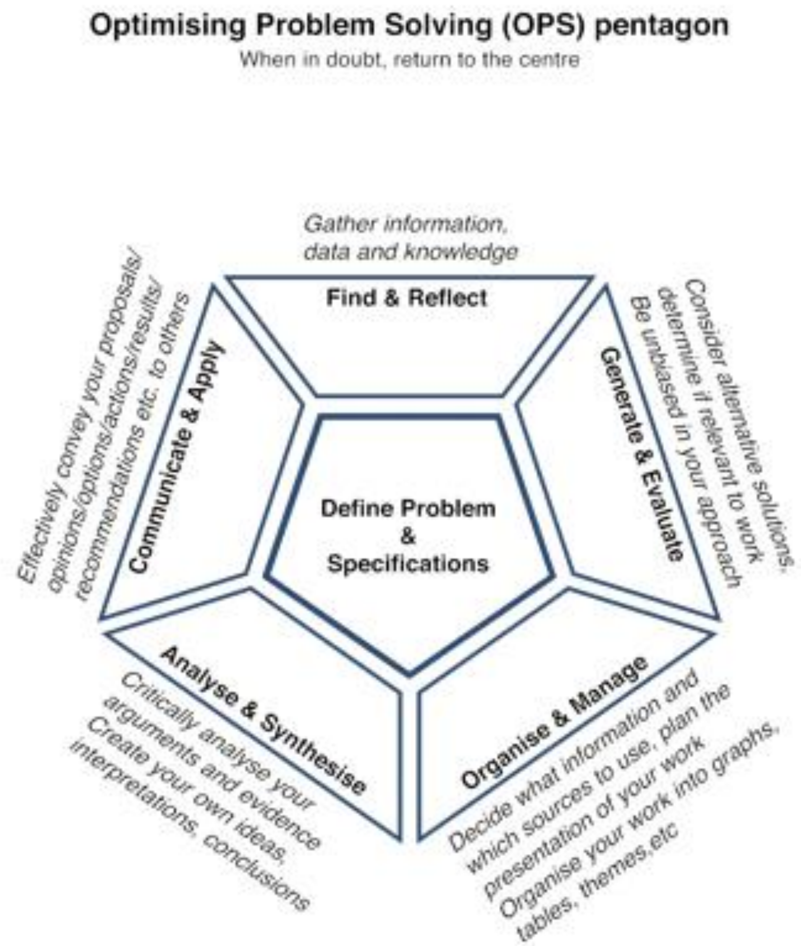

Figure 1. The Optimising Problem Solving (OPS) pentagon, designed by DG&C tutors (2014).

OPS was initially piloted in the DG&C curriculum in Semester 2, 2014. In later tutor training sessions, tutors were asked to critique the learning and teaching approaches used, from which applications were further developed and included in the 2015 course curriculum. Further piloting of OPS as a useful tool for extending student learning in engineering problem solving was conducted with an equivalent first-year engineering course at another university in early 2016 (Missingham et al. 2016). The pilots demonstrated how student engineers were able to investigate a problem and improve effectiveness of their communication within a team through the use of OPS (Missingham et al. 2016; Willison et al. 2016).

As noted above, current models are typically linear, and communication is confined to a single stage, if it features in the model at all. The OPS pentagon allows the consideration of any facet at any point, in keeping with the non-sequential McMaster Problem Solving model (Woods 2000, p.

447). While OPS necessarily focuses on the learning of problem solving, it maintains a clear relationship with research processes due to its etymological connection to the RSD framework.

OPS was operationalised in the DG&C course through scaffolded activities (see www.rsd.edu.au/smallgroups) in fortnightly three-hour workshops across the semester, designed to give students an appreciation for the individual stages of problem solving and how to navigate between them. Beyer (1984) criticises reliance on providing 'exposures' to thinking skills in place of deliberate and focused instruction for individual skills. Without smaller, targeted activities focusing on specific cognitive processes, such 'exposures' can lead to a vague understanding of the overall problem-solving process. This use of the same conceptual structure - such as OPS - under different contexts can become for students a thinking routine (Ritchhart & Perkins 2008) and, over time, may develop more general problem-solving skills outside of the disciplinary domain (Willison 2015).

This paper reports mixed methods research that was conducted to determine the effectiveness of OPS as implemented in Semester 2, 2016 following the three pilots of 2014, 2015 and Semester 1, 2016. It reports on first-year mechanical engineering students' and tutors' perceptions of the development of problem-solving skills, in order to determine the effectiveness of the use of OPS as an engineering problem-solving tool.

Methods

This paper employed a mixed methods approach (Creswell 2014) to data collection and analysis, using a pre- and post-course survey with 15 Likert scale items, and student and tutor semi-structured interviews conducted 16 months after the completion of the DG&C course. The data from the surveys was therefore complemented by the detail provided in interviews. Mixed-methods research may increase the reliability of research as well as provide a richer and fuller picture of the phenomenon under study if standards of quantitative studies and of qualitative studies are adhered to (Ary, Jacobs & Sorensen 2010). Survey designs can be effective for examining the effects of an intervention (Jagsi, Shapiro, Weissman, Dorer & Weinstein, 2006), whereas qualitative information enables a determination of reasons for those effects. The 15 Likert scale questions used in the pre and post surveys (Appendix A) were based on a study of RSD surveys (Willison 2012) with items modified to correspond to the problem-solving terminology used in OPS. Items 1-14 asked for students' ratings of their self- perceptions of specific problem-solving skills: the first item concerned problem solving 'in general' and the second in mechanical engineering contexts; and items 3 to 14 corresponded to aspects of the six OPS facets. Item 15 related to student perception of the usefulness of problem-solving skills in their future career. A seven-point Likert scale was used for the response options: Strongly disagree (-3), Moderately disagree (-2), Slightly disagree (-1), Neutral (0), Slightly agree (+1), Moderately agree (+2), Strongly agree (+3). This rating scale was used because students at the university were familiar with seven-point scales for student evaluation of courses.

Approval for the study was obtained from the University Ethics Committee. The survey gathered data from the students enrolled in Semester 2, 2016; pre survey data were gathered in the 2nd week of semester and the data for the post survey were gathered during Week 13 of the course. The web link to the survey was provided to students during workshops in both Week 2 and Week 13, and class time was allocated for survey completion. Students were given the choice to use their personal devices to participate in the online survey through Survey Monkey, complete the survey on paper, or not do the survey. Survey completion took about 10 minutes.

In-depth semi-structured interviews with a convenience sample of five students and five tutors were conducted in April 2018 to gather participants' long-term perspectives on the development of problem-solving skills in the course, 16 months after the 2016 DG&C course was completed. Such questions help the interviewer understand the beliefs and experiences of the interviewee (Ary, Jacobs & Sorensen 2010; Cohen, Manion & Morrison 2007; Rubin & Rubin 2005) and provide 'rich sources of data on people's experiences, opinions, aspirations and feelings' (Kitchin & Tate 2000, p. 213).

Method of Analysis

Pre and post survey results were tested using SPSS software for internal reliability (Cronbach's alpha), statistically significant changes (non-parametric Mann–Whitney U test) and effect sizes. A statistical cut-off level of significance ($p<0.01$) was determined a priori. This cut-off is more stringent than that which is commonly used in education and was chosen due to the large anticipated number of responses for pre and post surveys, and the corresponding increased chance of a type I error. Interview data were analysed for evidence of student and tutor attribution of factors that related to items which returned statistically significant changes and medium or high effect sizes. Interviews then provided a sense of *how* problem-solving skills were developed, to illuminate the survey data about *which* skills were developed.

Results

For the pre survey, 236 student responses were collected from a total of 263 enrolled in the course (response rate: 90%). For the post survey, there were 163 responses from 240 students officially remaining in the course after the census date (response rate: 68%).

Table 1 shows the Cronbach's alpha, mean score and standard deviation for each item, for both the pre and the post survey, as well as the significance level (in bold when $p< 0.01$) and effect size for each item when pre and post scores were compared. Effect sizes were interpreted using Cohen's (1988) guidelines, whereby small = 0.1-0.29, medium = 0.3-0.49 and high >0.50.

The internal reliability of the pre survey (Cronbach's alpha = 0.93) and the post survey (Cronbach's alpha = 0.96) were both very high. Setting the significance level at 0.01 resulted in only items with medium or high effect sizes being considered. Survey items are listed in Appendix A.

The first two items concern the holistic sense of problem solving, with item 1 concerning problem solving generally and item 2 concerning problem solving as applied to mechanical engineering. For these items, there was no statistical difference in students' perceptions of their own problem-solving skills between the pre survey and the post survey.

Table 1. Pre and post survey Cronbach's alpha, mean score and standard deviation for each item.

	Pre survey		**Post survey**			
	N=229 (Cronbach's alpha = 0.93)		N=161 (Cronbach's alpha = 0.96)			
Item #	**Pre mean**	**Pre std deviation**	**Post mean**	**Pre std deviation**	**Significance level of difference between pre & post means**	**Effect size**
1	1.65	1.17	1.58	1.36	0.881	-0.05
2	1.00	1.19	1.25	1.19	0.015	0.21
3	0.99	1.09	1.31	1.19	**0.000**	**0.30**
4	1.07	1.20	1.33	1.26	0.014	0.22
5	0.87	1.21	1.37	1.25	**0.000**	**0.41**
6	1.06	1.24	1.50	1.37	**0.000**	**0.36**
7	1.03	1.17	1.64	1.20	**0.000**	**0.52**
8	0.89	1.26	1.31	1.37	**0.000**	**0.34**
9	0.76	1.32	1.25	1.38	**0.000**	**0.37**
10	1.06	1.20	1.39	1.27	**0.002**	**0.28**
11	0.79	1.20	1.22	1.28	**0.000**	**0.36**
12	0.45	1.61	1.02	1.37	**0.000**	**0.36**
13	0.55	1.47	1.21	1.34	**0.000**	**0.45**
14	0.89	1.42	1.34	1.38	**0.002**	**0.31**
15	1.97	1.45	1.95	1.45	0.997	0.01
					P< 0.010	

Two other items showed no statistically significant change: item 4 **(‘**I am good at gathering information and data for problem solving in engineering’) and item 15 (‘The ability to optimise solutions to engineering problems will be important in my career’). The pre survey score for item 15 was a very high 1.97 (max 3.0) suggesting that students were convinced already of the importance of problem solving for engineering before they started the course.

Factors Affecting Development of Specific Facets of OPS

The surveys provide a broad representation of the skills that were developed, and the interviews with five students and five tutors, sixteen months after course completion, provide an understanding of how the skills were developed. One student provided an insight into the benefits of asking for the students' perspective on OPS after a substantial period of time:

> *I think it just takes a bit of time more than anything just to get over that a bit and to be like, wow,* realise how important this is*, and I think I'm really looking forward to the third-year course. I reckon people are going to take that [OPS] far more seriously now that they've had other essays and large open-ended assignments to work on. They'll definitely realise how valuable this is now…* (Student 2).

This student knew that OPS was being used in Semester 2, year 3 in the year of the interview (2018), and saw that time without explicit OPS would enable students to appreciate the full benefits of the model.

Items 3 and 5 to 14, comprising all but one of the specific facets of problem solving, show statistically significant changes in students' perceptions of each skill represented. The items' effect sizes ranged from 0.30 to 0.52, returning a minimum of a medium level of change in students' perceptions of their own problem-solving skills across the whole semester. The statistical significance level of $p<0.01$ for the items mean the educational effects reported are unlikely to result from random variation, but rather that there was something educationally helpful going on in the curriculum, that problem-solving skills were somehow systematically developed.

Item 3**:** One of the changes frequently mentioned in the interviews was around the central facet of OPS, reflected in item 3. *I am good at specifying clear problems in engineering* (effect size = 0.30).

> *I think the biggest light bulb moment of me using this [OPS] was the define problem and specifications, because it's something that I had never really done much of before* (Student 2).

For this student, 'Define Problem and Specifications' filled an essential skill gap, and it could have been that the mere statement made the difference. However, this student went on to state:

> *I think OPS makes an incredible difference because you're always coming back to that definition of your problem and your specifications of that problem. You can't really solve an open-ended question without continuously defining your problem, otherwise, you know, everything's got a sort of timeline on it* (Student 2).

The placing of 'Define Problem and Specifications' in the centre of OPS original design by the tutors in 2014, and the motto 'when in doubt, go to the centre' prompted this student to return to that centre when stuck or lost or in doubt of any kind. Enabling students to realise the absolute essential role of 'continuously defining your problem' had been one of the largest challenges students and tutors had faced in previous iterations of DG&C.

Items 5 and 7 dealt with evaluation and reflection:

> 5. I am good at reflecting on the relevance of information for the engineering problem at hand (effect size = 0.42).
> 7. I am good at evaluating the effectiveness of alternative ideas for engineering problems (effect size = 0.52).

The sense of checking, refining and challenging was evident in the interviews:

> *So to give you a framework where you would think about …* is this the right thing *that I'm designing, instead of just going ahead and doing it* (Student 3).

Students saw the vital connection between idea generation and refinement, with evaluative processes at the heart of refinement:

> *I think it's really easy to generate lots and lots of different ideas, but it's always hard to refine them…* (Student 5).

Reflection in the interviews pertained not just to relevance of information but also the ability to use OPS to evaluate where an individual or a team was operating in the whole problem-solving process:

> *[OPS] … provides a* platform *where you can* look at *and you can be, like, okay, well* where are we*, what have we done? You can kind of like summarise everything that you've kind of worked on so far and then you can identify what you are missing or lacking in your work or solution* (Student 4).

This use of OPS as a reflective surface was a major aspect evident across the interviews, where students found that the *explicit* articulation of problem-solving skills was, in itself, helpful, and enabled them to be more metacognitive while solving problems:

> *Before studying the OPS pentagon, I never really* thought *about my problem solving methodology. Although it was very close to the OPS methodology, it's really important to actually* stop *and* think about it*, and break it down and articulate it* (Student 5).

For this student, OPS was in keeping with his idea of problem solving, but also provided a way of understanding the process more deeply through its explicit articulation. All five of the interviewed students highlighted not only the important role of OPS in developing their problem-solving skills, but also how the learning process unfolded for each of them:

> *It's very like systematic, and OPS actually provides more of a breakdown of different ideas to focus on, and that actually helps with the discussion and the kind of final design of anything, really... It helps students that lack a little bit with the* critical mindset *to develop that… the single defining feature of an engineer, and many other traits of an engineer come from the critical mindset* (Student 1).

The development of this *critical mindset* was enabled, according to Student 1, by the explicit use of OPS to break down the problem-solving process. Even though the processes in OPS may for some students be intuitive, as per Student 5 above, a systematic and explicit approach is frequently beneficial.

Item 9: states ‘I am good at managing resources and teams during the problem-solving process’ (Effect size = 0.37). Students interviewed spoke frequently about how OPS helped with the complexities of team management:

> *… during the group project which we were working on, we really had to think about how we would problem solve as a team. OPS made us more aware of the importance of … organising team work, you know, delegation of workload and stuff like that. So in that sense it was useful in the communication aspect of the group work* (Student 5).

In the above statement, students naturally connected team management processes and communication, knowing that these are interwoven to a large extent.

Items 12 & 13*:* The DG&C course focus, as suggested by its name, was written, oral and graphic communication. OPS use showed evidence of addressing a major problem with the first-year course, which was that engineering students preferred to jump immediately into solving a problem, without learning problem solving as a process and with communication throughout. A notable feature of the research reported here was that in the pre survey, oral (item 12) and written communication skills (item 13) were given the lowest scores by students: item 12. *I am good at communicating orally what I understand when solving problems in engineering* (pre survey mean of 0.45); item 13: *I am good at communicating in writing what I understand when solving problems in engineering* (pre survey mean of 0.55). These low starting perceptions about oral and written communication provided a powerful justification for the focus of the course. The learning shifts evident in item 12 (effect size 0.36) and Item 13 (effect size 0.41) were amplified in the interviews, where students articulated how important these communication skills were to develop:

> *If, say, you’re half done with a project and you don’t communicate effectively, or data has been lost as you give it to another person, or another company, then that project is put to a halt. You wasted all that time developing because you can’t communicate properly. So I think, yes, that’s how vital it [communication] is. It holds everything together* (Student 1).

For this student, communication holds all the other problem-solving processes together. Very commonly, students coupled management of teams with communication.

> *If you’re working in a team, then it can refer to how you communicate within your team members to make sure that everybody’s on the same page, and everybody understands what their jobs are, and you know, how the project is running and that they’re all working towards the same end goal…* (Student 3).

However, students recognised that communication comprises even more than collaborating with one's team, as the above student continued:

> *…But it can be communicating with your client about back to the centre, basically, what the problem is and what the specifications are, what you actually need to do* (Student 3).

For some, communication outside of the team was even more complex than team communication:

> *…communicate exactly what you want to the client, I think that takes more practice* (Student 5).

Tutor Perspectives

DG & C tutors worked with a large number of students (35 to 60) during a whole semester, and their perspectives provide a broader and different consideration of the use of OPS. Interviews conducted with the tutors show the way OPS may be used to develop student problem-solving skills from their perspective as teachers, as well as the ways tutors found OPS useful in developing their own problem-solving skills. For tutors' teaching, OPS provided a diagnostic teaching tool to sharpen what they may focus on with each student:

> *We can use OPS to see [student] strengths or weaknesses with their design. So maybe we can see from OPS that they haven't researched enough, or their research is really good but they've only generated one design, when they should be generating a whole bunch more. So that was fantastic for having a* look for the weak points, *I guess, or improvements that the students could be doing throughout their design process* (Tutor 2).

Even more powerfully, OPS was seen by tutors as a tool that students could learn to use directly themselves, for students' own learning:

> *I think OPS is just useful to* help *students break down problems that they can't really see the end goal, and then they can use OPS to break it down and then solve problems along the way* (Tutor 1).

Once students learn to use OPS, the tutors also need to assist them to go through processes that lead to improvement:

> *So by having a look at OPS,* students go back *and they might start to get it all in together, all their information, and maybe that might spur a better solution, like a more optimal solution. I guess that comes from the name* (Tutor 2).

'Better solution' speaks to an endemic problem for tutors of students not being willing or able to improve designs. This tutor found that through the OPS' revelation of the processes involved, students could first improve their processes and then their products. This idea was amplified by another tutor, where student exposure to OPS:

> *… early on in their university careers really starts to get them* thinking about how *they go about solving problems rather than* just delving straight into solving *a problem without*

> *actually properly … I guess really just to get them thinking about* how *they solve problems is probably the biggest part* (Tutor 3).

Tutors used OPS to get students back to considering how they problem solve, and especially to help them return to the centre of problem definition and specification, time and again, rather than just focussing on the solution or product itself. They tried to help students to *see* that the problem-solving process was perceived as a task that requires time for students to appreciate:

> *… as a tutor, I think the role that OPS has for students is more than most of them realise. For one, I think they don't quite realise how useful it is until they get to practically apply it. They* learn to see *how having a framework for a problem-solving method that is flexible enough that, when they hit a problem, the problem can be redefined and have five different avenues about which they can come to the problem again,* each time they get stuck (Tutor 4).

This aspect of what to do when stuck is salient for tutors who are frequently fielding questions about what to do next. This also related to tutors' personal sense of difficulties when solving problems themselves. Tutors' identification of how OPS was helpful in their own learning principally related to the importance of using the facets to ensure the rigour of their approach to problem solving, especially when things were conceptually difficult:

> *When you're half-way through, when you're in the middle, when* you're in the heat of the moment, *you forget what stage you're at, and that's where OPS really helps… The general pattern of thinking just sort of* evaporates *when you actually have a problem in front of you, and that's when I realised I had to keep coming back to the OPS framework. That's where it has changed my way of problem solving now. It stays in your head. It's sort of a reference every time you face a problem* (Tutor 1).

This use of OPS for their own learning was practical:

> *The advantage…for me is that when you get stuck, you always have six different places you can look at to try and get past your writer's block* (Tutor 4).

Tutor improvement in OPS processes for their own learning was also perceived to result in improved teaching:

> *Actually, I do a fair amount of tutoring outside of school as well…After a whole bunch of conversations, talking about OPS, design and stuff like that, it was really good to sort of build upon my own communication skills and it (OPS) made it [tutoring] easier for me* (Tutor 2).

This is a complex process of improving their own tutoring communication skills through awareness and personal use of OPS for problem solving, with mutually reinforcing loops with their tutoring. Moreover, in keeping with the students interviewed, tutors saw that OPS enabled the focus of the DG&C course on communication to be absolutely central to problem-solving processes, not something done after the effect:

> *I think quite often in engineering at university,* communication gets put on the backburner a little bit *whereas perhaps not—if you talk to any engineer or senior engineer I think, and then you got them to list their most important aspect of being a good engineer, a lot of the time they'd come up with communicate with other staff members … so being able to work out what's the best way of communicating with a completely diverse range of individuals is very important* (Tutor 3).

As noted earlier, communication was often perceived by cohorts previous to OPS use as peripheral to problem solving, or as something which succeeded it. OPS helped tutors to explain the integral nature of communication for problem solving.

Transferability

One aspect of OPS that was not asked about in the survey was the other side of the coin of the 'communicate' facet: 'apply'. However, the sense of application of skills from OPS emerged without prompting in the interviews for both students and tutors, with one student noting that in:

> *… my design summit, we integrated—even though we didn't focus on OPS, I did use areas of it. So OPS could easily branch off into other methods and work in parallel with them* (Student 1).

Application of learning from OPS was shown by transfer of the explicit awareness of problem-solving skills to other areas not explicitly using OPS:

> *I've found that when I've been using OPS, I use it lots. I've used it in* my other courses as well*, and it's definitely best in group situations. So obviously in management it's a really important role in problem solving* … (Student 2).

Specific features of OPS were highlighted by one tutor as having a broader range of application when compared to other approaches or models tutors had encountered:

> *The biggest advantage of OPS* over other templates *of solving problems is that it can be applied to almost any situation, and I think that's really good. I think that's probably why it's been developed* (Tutor 3).

There are plenty of engineering problem-solving frameworks, but this tutor saw, in the comparison, that OPS had a broader range of applications. This was amplified by another tutor:

> *I would think that the intended purpose has changed a little bit in that I think the original tutors had intended for it to be mostly for engineers, still, but as time went on, … (we) realised more and more that it can be used for applications outside engineering* (Tutor 4).

Discussion

The explicit representation of the often non-sequential but recursive processes of problem solving in OPS helped students to be more aware of the way they could and did solve problems. The sense of ‘a platform’ for checking each component and ‘doing a better job’ shows a process for improvement in evaluation and reflection skills.

Students in the high-response surveys perceived that numerous specific skills required in mechanical engineering problem solving improved over the semester. Students and tutors interviewed understood the role that OPS played in the development of these skills, and it was the framework’s explication of skills, and how these were represented, that was highlighted as being influential on skill development. Of particular note were the central representation of problem definition and specification being a place to turn to and return to; the way that OPS made communication integral to the problem-solving process, including, but not limited to, team management; and that the whole pentagon, as well as specific facets, induced reflective and evaluative thinking by students as individuals and as teams.

A crucial element of this study was that the OPS pentagon was devised within the broad parameters of the RSD framework, which led over a 12-year period to the recognition of general parameters for the Models of Engaged Learning and Teaching (MELT; Willison 2017), of which OPS is one. This is early evidence that MELT may broadly represent the cognitive, affective and social dimension of complex learning, whatever it may be called (Willison 2017), as long as that learning is represented with terminology in keeping with the domain of use. It is possible that a recognition of connections between problem-solving skills and research skills in engineering provides an opportunity to prompt the development of cognitive, affective and social skills that are broadly useful, if such development occurs in multiple contexts and over multiple semesters of a degree. The Mechanical Engineering degree is currently piloting OPS use in third year, and the Electrical Engineering program in the same faculty has been using the RSD in the fourth project-based year for a decade. Over time, there is a need to consider what will happen to student learning if the dots are joined between students’ problem-solving experiences and their research experiences.

Implications and Recommendations

The study suggests the potential for OPS to be used as a thinking routine (Ritchhart & Perkins 2008) in many contexts, where multiple exposures may, over time, lead to greater generalisability and transfer of skills. That tutors noted improvements in their teaching and improvements in their problem solving through the use of OPS suggests a mutually reinforcing feedback loop, where this use and re-use of OPS in different contexts, with different roles and perspectives, lifted all aspects of problem solving. Students too, looking back on 16 months since DG&C ended, saw many places where they themselves applied OPS and perceived their problem-solving skills to have improved because of its explicit use. One tentative assertion from this research is that OPS, as a conceptual framework for learning and teaching, may effectively convey complex problem-solving skill sets in domain-rich contexts. Its use in many subsequent contexts may be a better way of developing student problem-solving skills than employing generic introductory courses that try to address many disciplines. The comments highlight the flexibility of OPS as a problem-solving tool in matching the iterative and non-sequential nature of real-life problem solving.

Survey data provides a representation of the cohort, with high response rates pre (90%) and post (68%). However, these results are not generalizable to other cohorts or to other programs and contexts. Pre and post survey data from the majority of students, interview data from five students and five tutors together provide a data source triangulation. Surveys at the beginning and end of semester and interviews 16 months later provided a time triangulation of data, in order to minimise the potential skewing of perspective of a recent intervention. Nevertheless, the interview data on how the skills were developed only provides some examples of the experiences of those interviewed and is not representative of the cohort. Perspectives provided may be restricted to those students and tutors willing to be interviewed. Further research is needed to determine whether the advantages evident for this cohort hold across multiple cohorts in Mechanical Engineering, in other engineering and non-engineering courses and in other universities. Moreover, research is needed to determine efficacy of OPS use across degree programs in multiple courses, as well as OPS connecting with other Models of Engaged Learning and Teaching, such as the Research Skill Development framework, and the Work Skill Development framework (Bandaranaike 2018: this issue) in engineering contexts and more broadly.

Tutor perspectives were vital, because they provide a broad perspective about students and tutors' opinions and are potentially more objective than student self-assessments. However, biases may be introduced by tutors wanting to confirm that an initiative that they are integrally involved in implementing is effective. Future research could seek for anonymous tutor surveys, to gain a broader and more immediate sense of their perspective on student improvement over the semester.

Conclusion

Students perceived that all but one of the problem-solving skills identified in the OPS pentagon improved from beginning to the end of the semester, and interviewed students and tutors attributed many of those improvements to the DG&C use of OPS. The explication of problem-solving skills in OPS, in discipline-oriented terminology and in a configuration that placed problem definition and specification at the centre, was seen to promote student metacognition of problem-solving skills and enhance students' capacity to articulate and self-develop these skills. Tutors in particular related transferring OPS-mediated understanding of problem-solving processes to learning in other courses as well as improving their teaching.

It may be that the use of OPS as a conceptual framework that is revisited in numerous courses across a degree allows students to make connections between different contexts in a way that explicitly reinforces problem-solving skills. If the connection between problem-solving skills and research skills is made explicit, there is opportunity for otherwise separate conceptualisations to work together as thinking routines for students over time, where they become increasingly metacognitive. OPS use provided tutors and students with a powerful and practical conceptualisation that communication in its various forms is not peripheral or after the effect, but absolutely integral to optimal problem solving.

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Appendix A

Pre & Post Survey Questions

1. I am good at solving problems generally

2. I am good at solving problems in mechanical engineering

3. I am good at specifying clear problems in engineering

4. I am good at gathering information and data for problem solving in engineering

5. I am good at reflecting on the relevance of information for the engineering problem at hand

6. I can generate alternative ideas for engineering problems

7. I am good at evaluating the effectiveness of alternative ideas for engineering problems

8. I am good at organising information/data from multiple sources in engineering

9. I am good at managing resources and teams during the problem solving process

10. I am good at analysing information and data when solving engineering problems

11. I am good at synthesising information and data for the problem solving process

12. I am good at communicating orally what I understand when solving problems in engineering

13. I am good at communicating in writing what I understand when solving problems in engineering

14. I am good at communicating graphically what I understand when solving problems in engineering

15. The ability to optimise solutions to engineering problems will be important in my career