Optimising Problem Solving: student and tutor perceptions of problem solving within mechanical engineering

John Willison, Dorothy Missingham, Mei Cheong, Tayesha Papa, Raja Baksi, Siddharth Shah and Gianni Severino
The University of Adelaide
Corresponding Author Email: *john.willison@adelaide.edu.au*

CONTEXT
Engineering programs struggle to help students understand that the explicit learning of communication is a vital aspect of developing engineering problem solving skills. More commonly students retain a perception that learning about communication processes is a peripheral and nuisance add-on to the engineering curriculum. However, employed graduates with less effective communication capacities compromise key aspects of their effective professional engineering practice such as thinking critically and creatively, making well considered and timely decisions and addressing multi-layered complex problems. Tutors of a first year Design Graphics and Communication (DG&C) course addressed this issue directly by articulating visually and in words the ways in which communication is integral to problem solving that necessarily involves a broad set of skills. Specifically the tutors devised the Optimising Problem Solving (OPS) pentagon in 2014, based on the Research Skill Development (RSD) framework (Willison & O'Regan, 2007) and used OPS in two spirals of curriculum improvement and in a current implementation being researched.

PURPOSE
The purpose of this paper is to formally introduce the Optimising Problem Solving (OPS) frame work, present findings on OPS implementation from two years of curriculum action research and preliminary findings from mixed methods research in Semester 2, 2016. This will provide an understanding of the benefits and barriers in the use of OPS in terms of the development of problem solving skills, including communication skills.

APPROACH
Action research that piloted and improved OPS use in the curriculum was undertaken in 2014 and 2015. Ongoing mixed methods research in 2016 provides triangulation of data from pre-post questionnaires, interviews with students, tutors and graduates, as well as focus groups; advantages, disadvantages and suggested improvements of OPS and its implementation will be explored.

RESULTS
The curriculum action research tentatively demonstrated that the OPS articulation changed student perceptions of the role of communication, highlighting the importance of writing, speaking and presenting as processes vital for problem solving. The current mixed methods research will provide a stronger evidence base to determine OPS effectiveness.

CONCLUSIONS
The simple yet conceptually powerful articulation of OPS, when used as a thinking routine, has the capacity to enable engineering knowledge and skills to mutually reinforce.

KEYWORDS
Student perceptions, cognitive capacity, problem solving, students as partners, action research, mixed methods research.

Context

Student learning of problem solving processes is at times stifled in university engineering programs because three interconnected, core features of problem solving are not perceived by students to be important. The first of these core features is *defining problems* and students struggle to understand, not only its salience but also its nature. For example, Ravenka *et al*. (2016) devised and evaluated a problem *finding* course in which students grappled with indeterminate problems, structured so that students would learn to define problems. At the end of the course, 33 per cent of the students responded that they 'still could not properly understand what a well defined problem is' (Ravenka *et al*., 2016, p.545) and a large percentage of students were unable to fully understand the concept of finding problems. These authors proposed that 'a proper transition from problem solving courses to problem finding course is necessary to make students more at ease' (Ravenka et al. 2016 p. 546).

The second core feature is that students often perceive communication processes as outside of, or peripheral to problem solving, rather than appreciating that teamwork, documentation and client briefs require high-level communication processes. Students from STEM backgrounds in Ravenka *et al.*'s 2016 study were 'very curious to know of the details about the technology or the problem they hypothesised. They lack the necessary skills to communicate when interviewing stakeholders' (p. 545.). This recent work by Ravenka *et al* mirrors the years of students in university courses rushing to a solution without a clear process for ensuring the suitability and effectiveness of the solution through clarification of the problem and through refined communication.

The third, interconnected core feature that is often under-appreciated by students is the initial need for divergent and diverse problem solving thinking that heeds a broadened way of perceiving problem solving processes. Initial convergent thinking and rushing are symptoms of the prioritisation of product over process, where having an answer and then moving on without reflection can be a characteristic diametrically opposite to that needed in professional practice.

The coordinator and tutors of *Design Graphics and Communication (DG&C),* a large, compulsory first-year mechanical engineering course conducted at a research-intensive university, faced difficulties with student learning of these core features of problem solving, in perhaps an escalated way, because the course was explicitly about graphical, written and spoken communication. Rather than following Ravinka *et al.*'s line of thinking of waiting to transition students to problem finding at the end of a degree, this paper reports on the front-loading of problem identification and communicating as integral components of a broadened student understanding of problem solving.

The course enrolments in first year have hovered between 250 and 300 students for several years. The predominately male (90-95%) students generally indicated a desire to pass this compulsory course rather than perceiving a need to engage with learning how to communicate. Tutors of DG&C are also students in the Mechanical Engineering program.

DG&C Tutors attended a series of five facilitated workshops that were geared towards making problem solving skills explicit. Two workshops in 2012 introduced the Research Skill Development Framework (RSD: Willison and O'Regan, 2007), and tutors were left to consider the fit of the six facets of the RSD to tutoring and learning in Design Graphics and Communication course throughout 2013. Then in March 2014, eight experienced DG&C tutors attended three facilitated workshops with a brief: Make the Research Skill Development Framework (RSD) speak into first year Mechanical Engineering. The tutors found the six facets of the RSD mirror problem solving processes but fine-tuned some of the facet titles so they were more in keeping with engineering terms (Missingham *et al.* 2014).

Table 1: Facets of OPS lined up with the Facets of the RSD

Research Skill Development facet descriptions	**Optimising Problem Solving (OPS) pentagon facet descriptions**
Embark & Clarify *What is our purpose?* Students respond to or initiate research & clarify what knowledge is required, considering ethical, cultural, social and team issues.	**Define Problems and Specifications** Examine the issues, in order to define problems & specify meaning, purpose and impacts
Find & Generate *What do we need?* Students find & generate needed information/ data using appropriate methodology.	**Find & Reflect** Gather information, data & knowledge.
Evaluate & Reflect *What do we trust?* Students determine the credibility of sources, information & data, & make own research processes visible.	**Generate & Evaluate** Consider alternative solutions, determine if relevant to work. Be unbiased in your approach.
Organise & Manage *How do we arrange?* Students organise information & data to reveal patterns/themes, managing teams & processes	**Organise & Manage** Decide what information and which sources to use, plan the presentation of your work. Organise your work into graphs, tables, themes etc.
Analyse & Synthesise *What does it mean?* Students analyse information/ data critically & synthesise new knowledge to produce coherent individual/team understandings.	**Analyse & Synthesise** Critically analyse your arguments & evidence. Create your own ideas, interpretations and conclusions.
Communicate & Apply *How will we relate?* Students discuss, listen, write, respond to feedback & perform the processes, understandings & applications of the research, heeding ethical, cultural and social issues.	**Communicate & Apply** Effectively convey your proposals/ opinions/ options/ actions/ results/ recommendations etc. to others.

Tutors also changed the configuration from a matrix to a pentagon shape, resulting in the Optimising Problem Solving (OPS) pentagon shown in Figure 1.

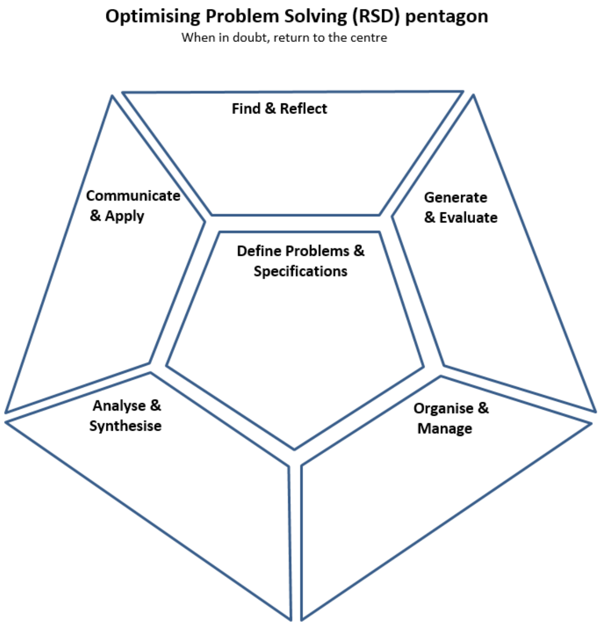

Figure 1: The Optimising Problem Solving Pentagon (Mechanical Engineering Tutors, 2014) with facets descriptions removed in keeping with the version students fill in during workshops.

The OPS pentagon is striking for its simplicity, its graphical representation and its emphasis. Simplicity due to the removal of much of the detail of the origin RSD Framework, providing a version immediately useful with first-year students. The graphical representation is a pentagon within a pentagon which gives a specific centre. This inspired its motto: *When in doubt, return to the centre,* providing an emphasis of the process of defining problems and specifications. This is like sagely advice from a more experienced student rather than a rule or algorithm to follow. There is, indeed, no linearity, sequence or even circularity in OPS. For example, much movement back and forth between problem definition and communication to determine what a client wants or even what an academic wants is typical before other facets come into play. Likewise, there is strong interaction between organise and manage, and analysis and synthesis, as information or data needs to be organised in ways where the analysis can take place in a very effective fashion; often the analysis leads to reorganisation of data. Recursive movements between two or three facets is typical, and particularly common between any of the facets and evaluation. The OPS pentagon captures the messy, recursive nature of problem solving in a way that is learnable and teachable.

Approach

Action research 2012-2015

After exposure to the RSD in 2012, tutors had free scope to use explicitly, implicitly or ignore the framework for tutoring in DG&C in 2013. With the facilitated workshops in 2014, there was broad agreement that the RSD general parameters were sound for DG&C, but the framework was too complex and terminology did not match Engineering. After drafting and redrafting, the pentagon, as described above, emerged and experienced tutors introduced OPS to new tutors in June 2014. Following an initial teaching introduction of OPS in a large lecture at the beginning of DG&C the tutors primarily kept OPS in the background to support each Communication workshop with the first-year students throughout semester 2, 2014. In this action research mode, tutors ultimately recognised the need to make their use of OPS and student learning of OPS more explicit. Tutors themselves reformulated the 2015 introductory lecture to the 300 DG&C students in Semester 2 and devised ways to make the use of OPS more directly explicit in each workshop.

By the end of 2015, action research suggested to tutors to once again to increase the explicit use of OPS. This laid the groundwork for the 2016 implementation and the adoption of mixed methods research being used currently to determine OPS effectiveness. With tutors as action co-researchers, they were necessarily co-writers of this paper, and epitomise the role of ‘students as partners’ (Levy, 2011; Healey, 2014) in the development of the conceptual model, in its implementation in the curriculum, in action research for improvement and in the communication of outcomes. Tutors’ initiative resulted in the creation of OPS as a conceptual framework for the DG&C course and their drive saw ongoing improvement in the implementation of it. Tutor-author narrative accounts are provided below to provide a deep sense of the action research and begin with a tutor who was part of the original OPS design team, then move to tutors with differing type of experience with the use of OPS, and finish with an account of OPS experienced as a student.

Mixed methods research for the 2016 implementation.

Questionnaires were administered in week 2 and in week 13 of the DG&C course (semester 2, 2016). Fourteen Likert scale questions elicit student self-assessment of their problem solving skills in mechanical engineering, one Likert scale question seek student attitudes to problem solving in engineering working contexts, and three open-response questions ask about student perspectives on problem solving. The pre-post questionnaire Likert scale items are in Appendix 1 and the scale used ranged from strongly disagree (-3), neutral (0) and strongly agree (+3). Analysis will focus on statistically and educationally significant differences between pre- and post- Likert scale items, as well as the differences in emphases in the open field questions.

Interviews will be run after Semester 2 exams and seek student perspectives on advantages, disadvantages and potential improvements to OPS and its implementation, and include: first-year students and their experiences with OPS in DG&C; Third-year students and their experiences with OPS in 2014 as First-year students and 2016; new tutors; experienced tutors; and graduates.

Results.

Data presented here focuses on tutor perspectives on involvement in the curriculum action research 2014 to 2015, and presents preliminary data from the pre-questionnaire 2016.

Curriculum action research 2014 and 2015

This section reports on the action research with tutors and students as co-authors of this paper who reflect back on their experiences of change.

Tutor leading the design of OPS: Mei

Mei, a PhD student at the time, led the tutors in the initiative in 2014 to create a version of the RSD that would be useful in first year engineering.

> When I did Level 1 Communication - it was a 'communication' course in that we learned how to analyse reports critically, generate postulations and conclusions based on our analysis of various sources, structure and present engineering reports, and give effective presentations. However, there was a disconnect between the skills taught and how they fit in the engineering world. Inexperience to the 'real engineering' field contributed to a premature conclusion that since this course did not 'speak' engineering, it was therefore an English/non-engineering course that must be done to 'tick a box'.
>
> Upon completion of my engineering degree - through the various projects and team work - there was a hazy almost muddled revelation on where 'the communication course' fit in the engineering profession. It was only when I started tutoring in DG&C through my PhD years that I truly appreciated the importance of communication. My tutoring in engineering courses was where it was most evident when students struggled to problem solve ill-defined problems/open ended problems. I thought the issue was that they were used to high school where problems were well defined for them and that there was 'a solution'. It took many conversations on teaching and its frustrations over cups of tea that highlighted an underlying issue - students are missing that 'step 1' in engineering i.e. defining the problem. We tend to be excited with the solution - maybe because it is more concrete and tangible, that we forget that we needed to define the problem first - which would be the more abstract part of the engineering problem. I did not get an 'eureka!' moment but as I was learning how to teach my students, I realised that I was teaching my students how to learn an abstract, non-tangible skill we label as 'problem solving' ... a task I still find extremely challenging.
>
> It was when I attended the session on RSD that I realised it wasn't just me with these teaching issues with students and that there were two problems - 1) how to get students to treat the communication course seriously and 2) how to teach students the abstract skill of problem solving. I perceived that the first problem was because the communication course did not speak engineering - there was a disconnect on how important it is, and where it fit in the engineering world. The second problem was that students tend to disregard/skip that vital step in engineering of defining the problem.
>
> To address these problems, we needed to demonstrate explicitly that communication is part of the problem solving process, we needed to give students a tool that reminded them

to 'go back to the main step in problem solving' i.e. defining the problem. Once we got RSD reconfigured to speak engineering visually and verbally - OPS was born.

Tutor experienced with training new tutors on the use of OPS: Tayesha

The senior tutor, and most experienced of the current tutors, Tayesha was mentored by Mei to help introduce OPS to the larger tutor team. Tayesha provides the ‘compass’ for training and development with junior tutors.

> Teaching tutors how to teach OPS is an interesting process revolving around testing methods on new tutors and gauging their response. For me this meant the senior tutors who developed OPS initially tested methods on me and other newer tutors of 2014, to teach me OPS as a framework for learning and teaching. This I feel worked out just fine and is a testament to the methods used. I now use similar methods to train new tutors before supporting them in workshops as a senior tutor.
>
> By testing teaching methods on new tutors it both reacquaints them with the content of DG&C, and introduces a teaching perspective. An important part is including the new tutors in the discussion of the effectiveness of the method and the process of defining the curriculum and how it is taught. There is a level of autonomy that is expected of the tutors during workshops, but they still need to be observed to ensure appropriateness and consistency. For this purpose, a senior tutor is also present to observe the class as a whole. I enjoy supporting junior tutors' autonomy as they develop their own nuances to teaching OPS. I believe it is important to support their growth in this way so that they can input into the future development of OPS.

Experienced tutor on the use of OPS with tutors and students: Raja

Now in his honours year of Engineering Raja was a member of the tutor team to first introduced OPS to students in DG&C in 2014. Raja, together with Sid (see below), is currently involved in devising new approaches for helping students to develop skills in using OPS.

> The OPS tool is useful for tutor to student interaction and articulation of thinking processes and problem solving principles. Specific principles of problem solving are second nature to higher level student tutors, and this makes the translation of those principles to first year students challenging. Similarly, students are often unaware of where their thinking process is lacking, or are unable to articulate their difficulty in finding a solution. The OPS pentagon provides a visual tool through which each facet of critical thinking is identified and discussed between student and tutor. Currently, most learning activities are coupled with students documenting their application of each facet on a print out of the pentagon. As the students’ thinking process is slowed down and becomes more accessible and visible, the tutors can interrogate students further on each facet and directly assess and give feedback. Thus, students are actively engaged in reflecting on their own strength and weakness, where weaknesses are easily identified where the student has left the facet blank. Early identification of weaknesses allows individuals to begin building their skills throughout the degree. Students can take away a visual representation of their thinking process in solving the problem, rather than the conclusion of their thinking. The OPS pentagon is therefore an effective teaching tool in engaging and accessing students’ minds, which is otherwise a major challenge when trying to provide them with subjective feedback and support. It is also advantageous in training junior tutors and equipping them with a tool that opens interaction with younger peers.

Experienced tutors on the use of OPS with students: Sid

Sid has been involved with the tutor program in DG&C for three years and has tutored for two of these years, having taken time away to pursue a University exchange. Sid is currently in the third year of his undergraduate studies in engineering and in finance.

Initially, the introduction of OPS to first year students is often met with a high level of scepticism or disregard. At first, it is perceived as another depiction of common sense through the use of academic buzzwords in shapes. Although the content is not entirely new to students, the structure and phrasing is deliberate and the impact on their problem solving is obvious. While OPS is designed to help students interrogate a problem and improve the effectiveness of their communication, the exercises used in workshops showed how the tool can broaden problem solving approaches and inspire more holistic thinking. For many tasks, students were forced to plan their approach using OPS and the common reaction was to question the relevance of certain facets to the situation. It was evident through student presentations that aspects of the problem, initially unconsidered, were ultimately addressed when brainstorming with the framework. In a task involving the description of a hidden object to a team of illustrators, some students questioned the relevance of "Communicate and Apply" in the planning stage. After acknowledging the facet, they soon realised they could devise a co-ordinate system or agree upon certain phrasing to aid their communication. Although the tool can be viewed as ordinary intuition inside a pentagon, many students will tend to approach problems in a narrow manner without it. OPS assists students by providing alternative pathways to consider a problem when one line of thought is exhausted and can ultimately guide them towards a broader, more complete solution.

First Year student perspective: Gianni

Gianni was introduced to OPS in his first year of Engineering in 2015. Now in his second year of undergraduate studies Gianni is a junior tutor in DG&C.

When first exposed to the OPS pentagon, its purpose was not so clear to me. My problem solving techniques were rather intuitive and most of my thinking was done internally without a clear direction. After using OPS through my Communications course, I've found that it is a great tool to combat open-ended problems with. The OPS pentagon provides an extensive and elegant structure which clearly identifies the problem and covers the main facets of problem solving. Not only was it used in first year Design Graphics & Communications, but now as a second year student, I find OPS helpful when encountering design problems with no clear direction. The WARMAN robotics competition is an example of this. It has also been my pleasure to be on board the Communications tutoring team and conveying concepts and ideas about OPS to first years has been a real treat.

Pre-course Questionnaire Results

We did not plan to provide the pre-questionnaire results here, as the post-questionnaire, interviews and focus groups are not yet completed at the time of submission of this paper. However, the pre-questionnaire provided unanticipated results which became vital to share back with the students. This data was provided to the students in week 5 as part of a feedback loop, and anecdotal evidence is that students worked much more seriously on oral presentations in their week 6 workshop than in the presentation before getting that feedback, a possibility that will be investigated once the complete set of data is available.

Table 2. Results: pre-questionnaire mean scores for each item (n=198). Min score -3, Max score +3.

Item	1.	2.	3.	4.	5.	6.	7.	8.	9.	10.	11.	12.	13.	14.	15.
Av score	1.63	1.02	0.93	1.06	0.85	0.98	1.01	0.87	0.73	1.06	0.82	0.4	0.55	0.8	1.9

The Items are in Appendix 1. The four lowest self-rated scores were for the following items:

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

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

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

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

Discussion

The approach by the engineering tutors to use the same learning processes articulated in OPS time and again is in keeping with findings that effective teachers use *thinking routines* (Richhart and Perkins 2008). *Thinking routines* are simple ways for students to structure their thinking, internalised over time, focused on process, and enacted and re-enacted in varied contexts where the processes are appropriate to content covered. In DG&C as an early course in the degree, OPS as a thinking routine is highly appropriate because problem solving is a core conceptual skill of the entire Mechanical Engineering undergraduate program. OPS as a thinking routine emphasises that problem solving comprises communication, problem definition and a broad array of skills, not a narrowed orientation to devising a solution.

In all the DG&C workshops OPS use and reuse provides students with a chance to increase their confidence in how to act, even when working in areas of uncertainty. This use of OPS as a thinking routine has the scope to make a substantial difference in a one-course timeframe, and as OPS is being escalated in its use into the third year of the program, then the opportunities for conceptual broadening and deepening become pronounced. Tutors role-model the same development of cognition expected of the first year students. Moreover, tutors have a strong sense of ownership of the teaching and learning environment with First Year students, and this may have a knock-on effect to other courses in which they ultimately tutor. The ownership of the learning process by tutors and then students shows scope for a culture shift that values the learning of communication and problem defining to advance problem solving skills.

The results in Table 1 show that the mean score from 198 students responses to the survey at the start of the course was 0.4 out of 3 for Item 12, which strongly suggested that students were under-confident, under-skilled or both for Oral Communication, There was a similar low perception for Written Communication (mean score of 0.55 out of 3) and only slightly higher for Graphic Communication (mean score of 0.82 out of 3). While the questionnaires were set up to look at change in perception of students' own problem solving skills pre to post questionnaire, these low communication-oriented results underscored the importance of student learning of communication in DG&C. This precipitated the provision of results in the Week 5 lecture, so that all students would see that many students perceived their communication skills to be underdeveloped. However, interviews will be needed to tease out if students do connect communication skills and problem solving skills.

The data gathered to date has had a dynamic influence on the running of the course. Action research from 2014 and 2015, as well as research data into the present-time running of the course also has the potential to greatly influence student performance in terms of DG&C content and problem solving skills. The mixed methods research that is ongoing relies on triangulation of data, focussing on statistically significant changes in pre-post questionnaire scores, changes in the open field answers, and interviews with students, tutors and graduates. In particular we will search for evidence of the problems with OPS implementation and all data will be subject to considerations of credibility, limitations and biases.

Conclusion

The OPS pentagon created by student tutors for first-year students has provided an ownership of the learning environment for the tutors, including the design of that learning environment. Through the use of OPS, the Design Graphics and Communication course highlights the role of visual, written and spoken communication in the problem solving process, emphasises the absolute need for problem definition and specification, and keeps a broadened sense of problem solving also by necessity including evaluation, analysis and synthesis, finding information, generation of ideas, all vital facets of problem solving. Other educators outside of the Mechanical Engineering context are examining the use of OPS, and beginning to explore their own adaptations for different contexts.

As first-year students engage in OPS when writing, speaking, designing and building, they have opportunities to see their skills mature in context-specific and diverse contexts. As the mixed methods research data collection includes student revisitation of OPS in third year, a strong notion of the advantages and disadvantages of OPS in multiple contexts will emerge. This will provide useful information and strong potential to inform and improve the coherence of the degree to facilitate the development of graduates who are optimal problem solvers.

References

Levy, P., & Petrulis, R. (2012). How do first-year university students experience inquiry and research, and what are the implications for the practice of inquiry-based learning? *Studies in Higher Education*, *37*(1), 85-101.

Mechanical Engineering Tutors (2014). *Optimising Problem Solving pentagon.* Retrieved September 30, 2016, from http://www.adelaide.edu.au/rsd/framework/frameworks/ops_rev4.pdf

Missingham, D., Cheong, M., Tonkin, M., Matulessya, S., Lowe, S., Cook, T., & Ashby, R. (2014). Workshop: Thinking like an engineer. In *25th Annual Conference of the Australasian Association for Engineering Education: Engineering the Knowledge Economy: Collaboration, Engagement & Employability* (p. 646-647). School of Engineering & Advanced Technology, Massey University.

Ravankar, A. A., Imai, S., Shimamura, M., Chiba, G., Takasuka, T., & Yamanaka, Y. (2016). Nurturing Problem-Finding Skills in Graduate Students through Problem Based Learning Approaches. In *Advanced Applied Informatics (IIAI-AAI), 2016 5th IIAI International Congress on* (pp. 542-546). IEEE.

Ritchhart, R., & Perkins, D. (2008). Making thinking visible. *Educational Leadership,* 57-61.

Willison, J., & O'Regan, K. (2007). Commonly known, commonly not known, totally unknown: a framework for students becoming researchers. *Higher Education Research & Development*, *26*(4), 393-409.

Acknowledgements

Mechanical Engineering tutors and students past and present brought this research to life.

Appendix 1: Likert scale questions from the pre-post questionnaire

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