33rd Annual Conference of the Australasian Association for Engineering Education (AAEE 2022)
4 - 7 December 2022 – Sydney, NSW
WESTERN SYDNEY UNIVERSITY

Discipline-wide Study of Threshold Concepts and Capabilities

Paul N. Beuchat, Glenn J. Bradford, and Gavin Buskes
University of Melbourne
Corresponding Author Email: paul.beuchat@unimelb.edu.au

ABSTRACT

CONTEXT

The notion of threshold concepts has gained traction across many academic disciplines due to an intuitive language and description easily grasped by academics and students alike. A significant body of engineering education literature has focused on identifying technical threshold concepts within a single subject or subdiscipline at the bachelor's level. Numerous publications also investigate threshold concepts and capabilities for the learning and practice of general professional skills; however, studies of threshold concepts at the discipline-wide and post-graduate levels are much less common.

PURPOSE OR GOAL

The purpose of this study is to investigate threshold concepts and capabilities, both technical and professional in nature, that exist across the breadth of an electrical engineering master's program. While each subdiscipline within electrical engineering warrants an in-depth study of threshold concepts itself, the goal of this study is to identify and understand the relationship between threshold concepts and capabilities spanning multiple subjects and subdisciplines within a degree, with the intention of using the results to inform a curriculum review and renewal process.

APPROACH OR METHODOLOGY/METHODS

The research methodology is modelled on previous studies and employs a mixture of semi-structured interviews and focus groups with instructors, demonstrators, and students. Recorded audio from the interviews is transcribed and textually analysed to extract evidence supporting the identification of threshold concepts and capabilities. Instructors of core and advanced subjects within a single Australian electrical engineering master's program were interviewed.

ACTUAL OR ANTICIPATED OUTCOMES

Analysis of collected data is still on-going but some initial observations are possible. Several foundational technical concepts identified in earlier studies, including frequency domain analysis and reactive power, appeared in advanced subjects across multiple subdisciplines. Multiple interviews provided evidence for thresholds that are general but still technical in nature, including abstraction, approximation, associating real-world meaning to mathematical analytical tools, and systems-level thinking. This paper will also reflect on the efficacy of the adopted methodology and the observed impact on academics who participated in the study.

CONCLUSIONS/RECOMMENDATIONS/SUMMARY

Threshold concept interviews are recommended as a valuable tool for discipline-wide teaching and learning renewal. Further interviews are required to refine the notion of general technical skills as threshold capabilities and should explore whether overcoming such thresholds is transferrable across subdisciplines.

KEYWORDS

Threshold concepts, threshold capabilities, electrical engineering.

Introduction

In forming future graduates, engineering educators face a constant challenge to effectively prepare students for their future careers by selecting a subset of technical topics from an ever-expanding base of disciplinary knowledge. At the same time, there is an increasing demand from industry that graduates develop professional skills to a proficient level such that they can enter practice with confidence (Crosthwaite, 2021). These competing demands on the scarce space available within existing engineering programs necessitate tools to support continuous curriculum review, revision, and renewal. In this paper we report initial findings of a department-wide investigation of *threshold concepts and capabilities* across the breadth of a master's level electrical engineering program carried out to support such a curriculum renewal effort.

Threshold concepts were first described by Meyer and Land (2003) as "core learning outcomes that represent 'seeing things in a new way'" in the sense that they can be compared to "a portal, opening up a new and previously inaccessible way of thinking about something." Such concepts require a *transformation* in student thinking to grasp fully and thus may be both troublesome to master and are often identified with a given discipline's "way of thinking." Their usefulness as a tool to support curriculum renewal (Male & Baillie, 2014) is motivated by an intuitive language accessible to both academics and students and a promise to inform efficient curriculum design by focusing precious time on the topics students most need support to learn, such as in the modular approach reported in Parker & McGill (2016). In this line of thinking, important but less transformative concepts within a discipline may be better left for graduates to master through self-directed learning as the need arises.

Studies have looked at threshold concepts within engineering and electrical engineering specifically, typically focusing on technical concepts in specific subjects within the discipline. Results also exist for thresholds in the practice of professional engineering skills (Male, 2012). In this paper we discuss conducting a department-wide study of threshold concepts and capabilities at a master's level, encompassing both technical and professional skills. A key motivation for taking this department-wide view is to better understand where thresholds may be reoccurring throughout the program with an eye towards providing better scaffolding for student learning. The project has led to a greater appreciation of the threshold concept study as a useful tool for curriculum renewal even if many identified thresholds align with existing literature. There are significant benefits to understanding the unique patterns of threshold recurrence and persistence across an individual institution's curriculum. The identification process, particularly when conducted by means of academic interviews, is also an excellent way to promote self-reflection among academics and implicitly promote alignment of content across a program.

Background

As mentioned, threshold concepts and capabilities are distinguished by the fact they require a transformation in a student's way of thinking, which can make them troublesome to learn. Importantly, they are not synonymous with *core concepts* in that not all core concepts in a discipline will require a change in thinking (Male & Baillie, 2014). Some additional key characteristics generally associated with thresholds include: being unlikely to be unlearned (irreversible); being limited to a specific discipline (bounded); connecting seemingly disparate topics (integrative); leading to a change in the use of language (discursive); and reconstituting a learner's subjectivity, such as a counterintuitive concept (reconstitutive). Mastery of a threshold requires a passing through a *liminal space,* in which a given concept or capability is encountered but not fully understood. A student may then spend an indeterminate time within this liminal space with only a partial understanding of the topic. Ideally, at some point the student passes through the threshold (portal) to a more complete understanding of the concept or, less desirably, may stay stuck being only able to mimic understanding.

Threshold concept and capability theory is not without criticisms of both the theory and its utility (Nicola-Richmond et al., 2018). Critiques often focus on whether student mastery of a threshold can be truly measured, or whether the difficulty associated with a threshold is inherent to the concept itself or attributable to a student's existing knowledge structure. More fundamentally, there is a question of whether the threshold definition is precise enough to allow reasonable discernment of which concepts and capabilities are truly thresholds. Such criticisms all have merit, but threshold theory has also proved to be a fruitful framework for engaging academics in discussing and designing curriculum renewal (Male & Baillie, 2014).

Studies have identified thresholds within the discipline of electrical and electronic engineering, with specific subjects explored including circuit theory (Carstensen & Bernhard, 2008), transmission lines and fields (Flanagan et al., 2010), electronics (Scott & Harlow, 2012), and signal processing (Male, et al., 2021). Reeping et al. (2017) initially sought input to their electrical and computer engineering program restructure via a Delphi method study on threshold concepts. Ultimately, they elected to conduct academic self-reflections and focus groups to identify "big ideas" within the program, which were then cross-referenced against existing threshold concept literature as part of their analysis. This semi-structured input from the department was considered a key benefit over the Delphi approach as it better captured the values of the department. Some threshold concepts and capabilities applicable to multiple engineering disciplines were identified by Scott and Harlow (2012) and Male (2012). A detailed bibliography of threshold theory literature, including for electrical engineering, can be found at on Flanagan's website (Flanagan, 2022).

Methodology

The review of Barradell (2013) describes a range of methodologies that have been employed across the literature to identify threshold concepts and capabilities, including: informal, semi-structured, phenomenographic interviews; questionnaires, surveys, short answer problems; review of old examination papers; and observation of classroom behaviour. A number of studies have used the Delphi method to identify threshold concepts (Townsend et al., 2016; Nicola-Richmond et al. 2016; Kilgour et al., 2019), which requires a sizable panel of experts for each topic of interest and is hence considered intractable for an initial department-wide curriculum review.

The methodology that we followed for investigating threshold concepts across our electrical engineering curriculum is modelled upon that used in the work of Male et al. (2021). This involves semi-structured interviews and focus groups for which the audio is recorded and subsequently transcribed for performing textual analysis to extract evidence of threshold concepts. Semi-structured interviews were chosen because they afford the participant full freedom of expression, and they afford the researcher an immediacy for adjusting the interview questions and focus. We consider this freedom of semi-structured interviews to be important because the seven characteristics for a candidate threshold concept are challenging to succinctly describe. Moreover, semi-structured interviews provide the researcher with rich data from which to draw connections across participants that may be using different phrasings, allowing connections to be made that may remain hidden when using a survey tool. These aspects are particularly relevant for our study because we are reviewing across all topics within the curriculum.

An important aspect influencing the selection of methodology is that we assume the participants to have no prior engagement with threshold concept theory, nor do we have time to bring all participants to a baseline level of detailed exposure and understanding of the theory. Hence, the semi-structured interviews can be adapted to spend more or less time discussing threshold concept theory as appropriate for each participant.

We conduct individual interviews with academics and tutors/demonstrators who teach into the subjects of interest for our study, namely, the core subjects across the electrical engineering master's program. Individual interviews are considered most appropriate here as they allow the academic to express their opinions without being affected by ideological, political, or personality conflicts that may exist for a variety of reasons. Due to the small class sizes of tutorial and workshop sessions, the tutors/demonstrators can offer a complementary viewpoint to the academics, one that is often more informed by direct conversations with students in the liminal space of battling with a threshold concept.

Student focus groups are conducted with current students and recent graduates. It is generally difficult for students to distinguish and articulate the transformative and other characteristics of a potential threshold concept because they may still be moving around within the liminal space. Hence a focus group, of four to six students allows for comments and discussions to prompt follow-on comments that provide a richer data set.

The methodology we follow includes second round interviews of the academics, i.e. the subject matter experts. The first round of interviews and focus groups is seen as a divergent and exploratory phase to garner as much breadth of expression and topics as possible across our whole curriculum. A textual analysis of the first round of interviews and focus group transcripts is used to extract evidence in support of any one of the seven threshold characteristics, i.e. the phenomenological experiences of the participants. The second round of interviews is aimed at consensus or contrast of candidate threshold concepts and capabilities that are seemingly related based on the first-round analysis.

Method

Subject coordinators and lecturers from core electrical engineering subjects were invited to individual interviews; in the case where subjects are co-taught, both academics were interviewed together. This amounted to interviewing 27 (early career through senior) academics across 19 subjects covering topics in foundational electronics, signals and systems, embedded systems, as well as specialisations within the program focused on control systems, communication systems, power systems, and advanced electronics. Interviews lasted for between 1-1.5 hours.

To cover a sufficient breadth of topics in the relatively short interview time, interviews with academics were structured into the following three steps:

1. The researcher gives a brief summary of threshold concept and capability theory, and then discusses any questions or clarifications that the participant may have about the theory.
2. The participant is invited to list out in minimal detail any concept or capability from their respective subject that they think fits the description of a threshold concept.
3. The researcher leads the interviewee through each topic from step 2 one-at-a-time, asking questions that probe the seven characteristics for threshold concepts.

Based on Male et al. (2021), the following are some examples of questions used to interrogate a candidate threshold concept in step 3 above, with the characteristic that the question aims at indicated in [brackets]:

a. Please briefly describe the concept and how it is used within the subject.
b. Please describe how students find the concept troublesome. [Troublesomeness]
c. Please describe the transformation in thinking or practice that the concept provides. [Transformative]
d. In what way does grasping the concept alter the student's discourse or expand their use of language? [Discursive, irreversible]
e. What types of assessment methods are used for the concept? What are examples of "trick questions"? [Troublesomeness, reconstitutive]
f. Does the concept being discussed link-to or depend-on other threshold concepts? Which ones? How? [Integrative]
g. How do students think or act differently before and after they become comfortable with the concept? [Irreversible, reconstitutive]
h. What have you observed as a barrier to or useful approach for students becoming comfortable with the concept?

At the time of writing, we have completed the data collection for the first round of interviews with academics as described above. Each of the 19 interviews was transcribed, the candidate threshold concepts listed, and evidence against each threshold collated. Additionally, the data were analysed for related concepts across multiple subjects, both for subject pathways along program specialisations and across the whole curriculum.

Human ethics approval was obtained for the methodology and methods described above.

Results

We focus on presenting our preliminary results that relate to candidate threshold concepts reoccurring across two or more subjects as this aligns with the goal to identify those thresholds concepts and capabilities that reoccur throughout the program. Non-reoccurring threshold concepts are no less important and still can provide valuable prompts for adapting teaching and learning activities in their respective subjects.

We separate the presentation of our results under two categories titled: "Electrical Engineering Concepts" and "General Technical Engineering Capabilities". The latter category captures some of the broad capabilities that are considered part of becoming an engineer but is distinct from non-technical skills such as communication, teamwork, and leadership in an engineering context. The general technical engineering thresholds are distinguished as capabilities, as opposed to concepts, because, similar to the distinction in Baillie et al (2013), they are closely aligned with applying the relevant skills, knowledge, and understanding to new and previously unseen situations.

Electrical Engineering Concepts

The two threshold concept candidates that reoccurred across the largest number of interviews were:

- Time-frequency domain transformations (7 subjects),
- Stability notions and analysis (7 subjects).

Time-frequency domain transformations was identified as a threshold concept by Male et al. (2021). The following quote from one of our interviewees talks to the ongoing nature of this concept, both during a master's degree and beyond, and hence a plausible reason that it appears as a threshold in so many subjects:

> *"when do you actually master things, like it is really just a question of if you're just confused at a higher level… but it still throws up a few things at me that I have to really think about…. I don't think anyone dares to say they fully understand the Fourier transform."*

We leave aside a description of these candidate threshold concepts to instead focus the subsequent discussion on the opportunities created by uncovering the extent to which a threshold concept is present in the program. In the case above, 7 out of the 19 subjects interviewed independently used the language of threshold concepts to identify stability and time-frequency domain transformations as troublesome and transformative within those subjects.

Within the specialisation streams of the curriculum, the two most prominent reoccurring threshold concept candidates for each are summarised in the following table, with the number in brackets indicating the number of subjects in which that concept was discussed as a threshold:

Power Systems: • Reactive power (3) • Electromagnetic field theory (2)	Advanced Electronics: • Semiconductor basics (4) • Lumped Circuit Abstraction (2)
Communications and Networks: • Probability notions and analysis (4) • Bandwidth (2)	Control and Signal Processing: • Sampling (3) • Probability notions and analysis (3)

Reactive power was identified as a threshold concept by Scott and Harlow (2012) and electromagnetic field theory was identified in Flanagan et al. (2010). The authors were not able to locate published works which identified the other threshold concept candidates in the terms stated here.

General Technical Engineering Capabilities

In addition to the technical concepts discussed in the previous section, interviewees highlighted many capabilities that are technical in nature but not specific to any subdiscipline within Electrical Engineering. In fact, these general technical capabilities are broader than a single discipline, being in some sense key aspects associated with what it means to practice engineering. We highlight those general technical capabilities that arose most frequently in interviews across the widest breadth of the program:

- *Associating meaning to mathematics* (7 subjects) – It was suggested that many students find it troublesome to connect the mathematical tools they are learning with underlying real-world phenomena that these tools model. Students who find this capability troublesome are often able to solve pre-formulated problems but struggle to map a real-world description of a problem to an appropriate mathematical formulation that can then be solved based on existing techniques. In many ways this capability may be describing what is seen in any threshold concept – a mimicry of understanding while transitioning through the liminal state – so may simply be an indication that the underlying mathematical tool or the physical phenomenon is itself a threshold concept for students.
- *Systems approach and systems-level thinking* (5 subjects) – A hallmark of engineers is the ability to break down a complex problem into more manageable subsystems and then design solutions for each subsystem while accounting for the interactions of the whole. This systems approach to problem solving is another capability interviewees suggested students have difficulty mastering. One of the primary barriers encountered in developing a systems approach is that students often do not encounter problems large enough such that a systems approach is necessary to manage complexity. When encountered, students may try to solve a complex problem monolithically rather than decomposing it into reasonable subsystems. If they do decompose the problem, they may fail to iterate on their subsystem designs to account for system-wide interactions. A good indicator that a student has begun to grasp this capability is when they can provide a minimum (or at least a lower) complexity solution rather than an unwieldy one hacked together.
- *Abstraction* (5 subjects) – Closely related to systems-level thinking, abstraction was expressed as the ability to describe only the "essence" of something and knowing when and when not to do this. Part of the challenge students may have with developing this capability is that there can be many different choices about how to abstract an entity, some of which may prove useful for analysis and system design and others which may not. Adding to this complexity is the fact it may be necessary to make multiple abstractions of the same entity to perform different types of analysis. For instance, circuit analysis may require an engineer to make both a large and small circuit abstraction.
- *Approximation* (3 subjects) – Multiple academics raised the concern that students are uncomfortable with the notion that a property can hold approximately, or they are uncertain when it is appropriate to approximate a quantity. As an example, in communication systems the bandwidth of a signal may be strictly infinite but for all practical purposes can be considered finite, as its magnitude is miniscule outside a finite range of frequencies. It was suggested the troublesomeness of this capability comes from an inability of the instructor to make its application precise, as it cannot be made precise. Engineers need real-life experience to know when approximations can and cannot be made, which can often be a crucial step in going from a system that works in theory to one that can operate in the real-world.

A number of these general technical capabilities are proposed in Male (2012) as potential threshold capabilities, albeit with differences in phrasing.

Discussion

Value in discussing a threshold concept already published:

The time and effort of re-identifying threshold concepts across multiple subjects in the curriculum may seem unnecessary or unjustified. For example, if Male et al. (2021) already identified time-frequency domain transformations as a threshold concept, then why not just look at the syllabus to identify the 7 subjects within our curriculum where this concept is relevant? Our answer is that it is precisely because a previously identified threshold concept is present across multiple subjects within the curriculum that we should be conducting threshold concept investigations to understand the extent to which our cohort overcomes the threshold, or struggles to overcome the threshold as the case may be. It could have been the case that time-frequency domain transformations, although present in 7 subjects, was only considered as a threshold in a handful. As curriculum review and renewal is often a constrained resource-allocation problem, knowing which threshold concepts and capabilities continue to be troublesome across multiple subjects can inform decisions for how to allocate resources towards the greatest improvement in the learning outcomes of electrical engineering graduates.

We found curriculum-wide threshold concept interviews to be equally valuable whether or not the existing literature identifies threshold concepts for the topic at hand. In fact, results are sparse for the later years of an existing master's level curriculum because many works investigating threshold concepts do so for undergraduate topics (Loertscher et al., 2014; Male & Bennet, 2015; Reeping et al., 2017), or for general engineering skills (Male, 2012). Many master's level subjects dive into complex technical details bespoke to that subfield of study, and curriculum discussions often revolve around the questions of: what is niche; what is mainstream; what is out-dated; which classic and emerging technologies are widely used in industry today? Although valuable, such discussions tend to focus on obtaining a "list" of topics without consideration for the student's pathway to becoming a master of such a list of topics. We found that using the language and framework of threshold concept theory largely avoided these questions. The interview guide, given in the methods section, focused the interviewees on the experience of the cohort of students, hence evoking examples of where their students have: struggled, been transformed, adopted new language and behaviours, been tricked; and what thresholds they need to overcome for continued development in the discipline. In this way, the results showing candidate threshold concepts present across multiple subjects is highly relevant to the curriculum renewal process, regardless of whether it is published elsewhere or not.

Threshold concepts that cross multiple sub-disciplines:

A common challenge of threshold concepts and capability identification is reaching agreement amongst the participants of what are the thresholds (Barradell, 2013). The preliminary nature of our results, i.e. only one round of interviews with academics, means that this challenge is certainly present in our results. As we work through the steps of interviews with tutors/demonstrators, student focus groups, and a second round of interviews or consultation with the academics, we may find that the threshold concept of, for example, "stability notions and analysis" may in fact be multiple thresholds bespoke to each sub-discipline. This will require careful consideration of the bounded characteristic of threshold concepts and whether, for example, a student that has overcome the stability threshold for power systems would readily overcome the stability thresholds for electronics and control systems.

Bounds on the general technical capabilities:

The general technical capabilities identified in our results as potential thresholds are clearly not bounded nor limited to a single discipline or sub-discipline of engineering. In many ways they are synonymous with what it means to think like an engineer. For some of the proposed capabilities, e.g., associating meaning with mathematics, there is the question of whether it is a distinct capability or whether it is merely the manifestation that a specific concept being taught is itself troublesome. For other capabilities, e.g., approximation, there is the question of whether the capability is a general threshold covering a wide range of application areas, or whether each individual scenario of approximation is a unique threshold itself. In the former case a student mastering the capability to make approximations in one scenario would find it easy to transfer this skill to future unseen scenarios. In the latter case, each new scenario of approximation may require the student to struggle through some liminal space. There may also be a mid-point where a student needs to engage with approximations in multiple contexts to progress-through and exit-from the liminal space of approximation as a general technical threshold capability. Each case has different implications for how the capability can be developed within the curriculum.

Big ideas first, thresholds second:

The work of Reeping et al. (2017) describes a similar setting to that considered in this study, whereby they present the process of beginning a restructure of their electrical and computer engineering undergraduate degree at Virginia Tech by engaging the majority of academics in their department over a short period of time. Their participants engaged in individual reflection, focus groups, and workshops, using the so-called "content representation" instrument to generate the "big ideas" of their degree. Threshold concepts were used in the final stages of their analysis to connect the big ideas with threshold concepts in the literature. There is a very close correspondence between the reoccurring threshold concepts from our results, and the "big ideas" visualisations from the focus groups of Reeping et al. (Figure 1, 2017), including both the electrical engineering concepts and general technical capabilities. With "big ideas" as the starting point, the results of Reeping et al. (2017) tend towards being a list of topics with threshold concepts as post analysis. We advocate for using the threshold concepts framework as the starting point for identifying where a curriculum revision must focus, which raises topics, concepts, and capabilities not readily found in the threshold concepts literature. "Big ideas", or a similar instrument, can then be used for prioritising which additional topics to include/retain.

Epistemological Discussions

One of the constructive by-products of interviewing academics for threshold concept identification was prompting discussion covering their outlooks on the nature of discipline knowledge and how students best come to master such knowledge. This was largely driven by the brief explanation of threshold concept theory given at the beginning of each interview. Differences in outlook of the academics were evident in their feedback on the explanation of threshold theory, the concepts and capabilities they suggested as possible thresholds, and the reasoning given for the proposed concepts and capabilities. Outlooks ranged from: a hearty embrace of threshold theory and the idea of there being a few key concepts in each subject that transform student thinking; to the belief that every atomic concept transforms a student's way of thinking; to scepticism at the utility of threshold theory for analysing curriculum within the department. Numerous interviewees made a note-to-self during the interview that they should subsequently discuss one of the topics raised with another subject coordinator, hence interviews prompted deeper coordination among related subjects.

Conclusion

In this study, we used semi-structured interviews to investigate threshold concepts within the breadth of a master's level engineering program. Based on our experience, this approach is recommended as a valuable tool for discipline-wide teaching and learning renewal for a number of reasons. Firstly, they put the student cohort and their learning experiences at the centre of the discussion. Secondly, the extent and manifestation of specific thresholds will be different at each institution. Finally, the language of threshold concepts creates a space for epistemological self-reflection. A key direction for further investigation is the transferrable nature and precise description of threshold concepts and capabilities that span multiple sub-disciplines or even multiple disciplines.

References

Baillie, C., Bowden, J.A., & Meyer, J.H. (2013). Threshold capabilities: threshold concepts and knowledge capability linked through variation theory. Higher education, 65(2), pp. 227-246

Barradell, S. (2013). The identification of threshold concepts: a review of theoretical complexities and methodological challenges. Higher education, 65(2), pp. 265-276.

Carstensen, A., & Bernhard, J. (2008). Threshold concepts and keys to the portal of understanding: some examples from Electrical Engineering. In Threshold Concepts within the Disciplines, pp. 143-154.

Crosthwaite, C. (2021). Engineering Futures 2035: Engineering Education Programs, Priorities & Pedagogies. Australian Council of Engineering Deans (ACED). https://www.aced.edu.au/downloads/Engineering%20Futures%202035%20R2%20report%20to%20ACED.pdf

Flanagan, M.T., Taylor, P., & Meyer, J.H. (2010). Compounded thresholds in electrical engineering. In Threshold concepts and transformational learning, pp. 227-239.

Flanagan, M. Threshold Concepts Bibliography. Retrieved July 14, 2022 from: https://www.ee.ucl.ac.uk/~mflanaga/thresholds.html

Kilgour, P., Reynaud, D., Northcote, M., McLoughlin, C., & Gosselin, K.P. (2019) Threshold concepts about online pedagogy for novice online teachers in higher education, Higher Education Research & Development, 38:7, pp. 1417-1431.

Loertscher, J., Green, D., Lewis, J. E., Lin, S., & Minderhout, V. (2014). Identification of threshold concepts for biochemistry. CBE—Life Sciences Education, 13(3), pp. 516-528.

Male, S. (2012). Engineering Thresholds: an approach to curriculum renewal: integrated engineering foundation threshold concept inventory 2012. Australian Government Office for Learning and Teaching.

Male, S., & Baillie, C. (2014). Guided Teaching Practices: Engineering Threshold Concepts as an Approach to Curriculum Renewal. In Cambridge handbook of engineering education research, pp. 393-408, Cambridge University Press.

Male, A., & Bennett, D. (2015) Threshold concepts in undergraduate engineering: Exploring engineering roles and value of learning, Australasian Journal of Engineering Education, 20:1, pp. 59-69,

Male, S.A., Togneri, R.B., & Jin, L.C. (2021). Novice to Postgraduate Researcher Perceptions of Threshold Concepts and Capabilities in Signal Processing: Understanding Students' and Researchers' Perspectives. In IEEE Signal Processing Magazine, 38(3), pp. 30-36.

Meyer, J. H. F., & Land, R. (2003). Threshold concepts and troublesome knowledge: Linkages to ways of thinking and practising within the disciplines. In *ISL10 Improving Student Learning: Theory and Practice Ten Years On* (pp. 412-424). Oxford Brookes University.

Nicola-Richmond, K. M., Pépin, G., & Larkin, H. (2016). Transformation from student to occupational therapist: Using the Delphi technique to identify the threshold concepts of occupational therapy. Australian occupational therapy journal, 63(2), pp. 95-104.

Nicola-Richmond, K., Pépin, G., Larkin, H., & Taylor, C. (2018). Threshold concepts in higher education: a synthesis of the literature relating to measurement of threshold crossing. *Higher Education Research & Development*, 37:1, pp. 101-114.

Parker, A., & Mcgill, D. (2016). Modular Approach and Innovations in an Engineering Program Design. In: Land, R., Meyer, J.H.F., Flanagan, M.T. (eds) Threshold Concepts in Practice. Educational Futures. Sense Publishers, Rotterdam.

Reeping, D., McNair, L.D., Wisnioski, M., Patrick, A.Y., Martin, T.L., Lester, L., Knapp, B., & Harrison, S. (2017). Using threshold concepts to restructure an electrical and computer engineering curriculum: Troublesome knowledge in expected outcomes. In IEEE Frontiers in Education Conference (FIE), pp. 1-9.

Scott, J. & Harlow, A. (2012) Identification of threshold concepts involved in early electronics: Some new methods and results. *Australasian Journal of Engineering Education*, 18 (1), pp. 1-8.

Townsend, L., Hofer, A. R., Lin Hanick, S., & Brunetti, K. (2016). Identifying Threshold Concepts for Information Literacy: A Delphi Study. Communications in Information Literacy, 10 (1), pp. 23-49.

Acknowledgements

The authors would like to thank Prof. Sally Male for her support and guidance in conducting the study.

Copyright statement