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Identifying threshold concepts in engineering mechanics: a Delphi study

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ABSTRACT

CONTEXT

The academic and career success of engineering students from a variety of disciplines hinges on students' understanding of fundamental engineering mechanics concepts. However, high failure rates of introductory mechanics courses are commonly observed. It is suggested that these are due to students struggling with the threshold concepts – concepts that underpin a discipline and transform a student's way of thinking. This study was based on the understanding that if threshold concepts in engineering mechanics could be identified, appropriate time and resource allocation in curriculum design could ultimately improve academic outcomes for engineering students.

PURPOSE OR GOAL

This study aimed to identify threshold concepts in engineering mechanics; and determine which may be considered the most critical concepts for students to learn. The identification of such concepts may allow for the focused allocation of time and resources in teaching students these most fundamental and pivotal concepts, and ultimately to best prepare them for their future studies.

APPROACH OR METHODOLOGY/METHODS

This study adopted the Delphi technique, which is an iterative method for collecting the opinions of experts to reach consensus on a given subject. Academics, researchers, and students from the University of Melbourne familiar with ENGR20004 Engineering Mechanics were engaged to provide input into the likelihood of a given concept being a threshold, and to anonymously review each other's opinions and adjust their own accordingly. In this way, participants were able to reach a consensus on the concepts that were and were not to be considered threshold concepts.

ACTUAL OR ANTICIPATED OUTCOMES

Participants initially identified 38 potential concepts, 9 of which were ultimately considered by the majority of the group (greater than 51%) to be threshold concepts. When the results were divided between students and academics, the concepts which were considered to be thresholds remained the same. However, an inadvertent finding of this research was that students and staff had vastly different ideas about the difficulty, or 'troublesomeness', of a number of these concepts.

CONCLUSIONS/RECOMMENDATIONS/SUMMARY

The aim of this study was to determine a set list of threshold concepts in engineering mechanics, and 9 such concepts were identified. However, in terms of curriculum design and resource allocation, professors of engineering mechanics would be best served by putting the time and effort into the threshold concepts which were considered the most troublesome by the students specifically, moment of inertia, stress and strain, coordinate systems, and work, energy and force.

KEYWORDS

Threshold concepts, Engineering mechanics, Delphi study

Introduction

Engineering is a notoriously difficult field of study that is increasing in popularity as the demand for engineers grows in Australia (Stewart, 2017). Engineering mechanics in particular often comprises up to 25% of engineering coursework at first year level and up to 40% at second year level, however, failure rates of introductory mechanics courses of up to 50% are commonly observed (McCarthy et al., 2010). It is suggested that these failure rates are due to students “struggling with the threshold concepts” (Prusty et al., 2011).

Threshold concepts

Threshold concept theory was first proposed by Meyer and Land (2003) to describe concepts within a discipline that are difficult to understand, but integral in progressing towards understanding higher level concepts. A threshold concept is one that satisfies several characteristics, the most important of which is that it is transformative, that is, it allows students to understand things in such a way that they can now do things that they could not do before (Meyer & Land, 2003). This crossing of the threshold may induce an emotional response or an ‘aha’ moment (Holloway et al., 2010).

To better distinguish threshold concepts from core concepts, the five common characteristics identified by Myer and Land (2003) were that they are:

1. Transformative in that, once understood, they will inspire a fundamental shift in understanding of subject matter;
2. Irreversible in that, once understood, they cannot be unlearned;
3. Integrative in that, once understood, they will expose connections to other concepts that were previously unseen;
4. Bounded in that they are contained within a discipline; and
5. Troublesome, that is, that they are inherently difficult to grasp.

Not only are threshold concepts challenging for students to grasp, but they are also difficult for educators to identify. Davies (2006) observes that the student and the teacher or lecturer are best placed to identify threshold concepts, while Barradell (2013) and Shinners-Kennedy and Fincher (2013) contend that subject matter experts or academics can also participate in this process.

The Delphi technique

Introduced in the 1950s, the Delphi technique describes an iterative method for collecting the opinions of experts to reach consensus on a given subject (Goodman, 1987; Lilja et al., 2011; Linstone & Turoff, 1975; Yousuf, 2007). The process involves a multi-stage survey in which participants review each other’s responses at each iteration and are asked to change or justify their response accordingly to achieve a general consensus amongst the participants (Yousuf, 2007). Goodman (1987) outlines the four key characteristics of the Delphi technique which distinguish it from other consensus methodologies:

1. Anonymity of the participants, which is adopted to encourage honesty without external influence or peer pressure;
2. Iteration with controlled feedback, which is achieved through a multi-stage questionnaire in which participants are given a summary of the current opinion of the group;
3. Statistical group response, which requires a quantitative output in each round in order to allow participants to see where their view lies in relation to that of the group. This is usually achieved through the use of a Likert scale ranging from strongly disagree to strongly agree; and
4. The use of experts.

There are three main factors that come into the design of a Delphi study: selection of the panel of experts, the number of participants (sample size), and criteria for termination of the study (Lilja et al., 2011; Powell, 2003; Trevelyan & Robinson, 2015). Numerous studies have adopted the Delphi technique in the identification of threshold concepts in various fields including information literacy

(Townsend et al., 2016), occupational therapy (Nicola-Richmond et al., 2016) and outdoor education (Thomas et al., 2019).

Threshold concepts in engineering mechanics

The identification of threshold concepts in Engineering Mechanics in the literature is limited, with only one known study explicitly listing topics using this terminology. In this study the knowledge of engineering educators and students were combined through several meetings, discussions, and consultations to identify threshold concepts in engineering mechanics (Prusty et al., 2013).

Several of the concepts identified by Prusty et al. (2013) coincided with those identified by another study (Streveler et al., 2006), which adopted the Delphi technique to identify difficult concepts in engineering mechanics, although this study made no mention of threshold concepts or troublesome knowledge. These studies both identified truss elements and analysis, friction, torsion, shear force and bending moments, impulse and momentum, and work and energy. More broadly, modelling, analysis and testing were identified as troublesome and pivotal for engineering science students (French et al., 2012; Holland et al., 2012).

A number of attempts to improve educational outcomes in engineering mechanics have been documented such as increasing active learning and engagement in the classroom, computer simulation and learning modules, and hands-on activities for students (Goldfinch et al., 2008). The identification of threshold concepts would allow such attempts to be more focused and ultimately may hold the key to improving academic outcomes for engineering students.

Contribution of study

This study adopts the Delphi technique to:

1. Identify threshold concepts in engineering mechanics; and
2. Determine which are the most critical threshold concepts in engineering mechanics

This identification of threshold concepts will inform development of a more focused curriculum and may assist not only in the teaching of more difficult concepts within engineering, but also in improving academic outcomes for students.

Methodology and Method

This study adopted the Delphi method for its suitability over other research methods as outlined by Linstone and Turoff (1975), including:

- The infeasibility of face-to-face meetings due to the ongoing COVID-19 pandemic.
- Time constraints of the research project necessitating a quick turnaround of results.
- The desire for the input of more individuals than can effectively interact face-to-face.
- The use of anonymity to prevent the opinions of academics influencing or dominating those of the students.

The process of this Delphi study included the following steps: (i) Formation of the panel of experts, (ii) Termination criterion, (iii) Provision of information, (iv) Round 1, (v) Round 2, (vi) Round 3.

Setting

A panel of academics, researchers, and students from the University of Melbourne familiar with the subject ENGR20004 Engineering Mechanics were engaged to participate in a multi-stage survey in order to achieve this outcome. ENGR20004 Engineering Mechanics is a mandatory subject within the civil, mechatronics, environmental and mechanical engineering disciplines.

The study was conducted over a six-week period from 24th August 2021 when the first recruitment email was sent, to 5th October 2021 when the last survey closed. Full human research ethics approval was granted by the University of Melbourne.

Formation of the panel of experts

Although a Delphi study requires the input of experts (Goodman, 1987), there is precedent to suggest that students may also be included in the panel of a Delphi study when used for the identification of threshold concepts, although they must be highly familiar with the course (Nicola-Richmond et al., 2016). As a deep understanding of engineering mechanics was required to be able to distinguish threshold concepts from any other concept, the inclusion criteria for the expert panel were defined as follows:

- Any academic within the University of Melbourne from within the Infrastructure Engineering, Mechanical Engineering or Mechatronics Engineering faculties.
- Students who achieved a high distinction in ENGR20004 Engineering Mechanics in the past three years. This timeframe was chosen to ensure students' knowledge was current and relevant.

Participation was voluntary, and participants were able to withdraw from the study at any stage. To increase validity of the results, there was no limit set on the number of participants. A recruitment email was sent to 733 academics, researchers, and students from the University of Melbourne, and 113 people initially showed interest.

Termination criterion

It was decided that termination of the study would occur after 3 rounds. This was not only to avoid participant fatigue and/or attrition, but also due to the time constraints, which would not allow for another round to operate within the allotted time frame.

Provision of information

Drawing from previous studies which adopted the Delphi technique to identify threshold concepts, participants were provided with an overview of threshold concepts and their definition, as well as definitions of their characteristics (Nicola-Richmond et al., 2016; Thomas et al., 2019; Townsend et al., 2016). Given the inclusion criteria, it was assumed that participants were familiar with engineering mechanics but not necessarily threshold concepts. Participants also received the list of already identified threshold concepts within mechanics for their reference.

Round 1

In round 1, the panellists responded to a survey which was hosted through Qualtrics. Each participant was asked general questions relating to their role at the University of Melbourne. This survey then invited participants to generate a list of concepts they believe may be considered threshold concepts in mechanics based on the information provided. They were then asked to rate, on a 7-point scale (1 = *strongly disagree*, 7 = *strongly agree*), how strongly they agree with each of the following questions for each of the threshold concepts they have identified:

I. How strongly do you agree that this concept is transformative?
II. How strongly do you agree that this concept is integrative?
III. How strongly do you agree that this concept is irreversible?
IV. How strongly do you agree that this concept is bounded?
V. How strongly do you agree that this concept is troublesome?

Guided by their own responses to these questions, they were then asked to comment on a sixth and final question:

VI. Given your responses to the previous 5 questions, how strongly do you agree that this concept is a threshold concept?

Round 2

Participants who contributed to round 1 were invited to participate in round 2 and received a collated list of the threshold concepts that were identified by more than one participant in round 1.

There is fair precedent for the omission of concepts contributed by a single participant for the purpose of maintaining the list at a manageable length (Nicola-Richmond et al., 2016; Streveler et al., 2006).

Participants then received the average rating for questions I-VI from round 1 and were asked to choose at least 10 concepts they most believed to be threshold concepts, and again responded to questions I-VI for each. However, if a participant voted more than one point away from the group average on the Likert scale, they were asked to provide a written justification for their rating. Although providing a justification was strongly encouraged, it was made optional in order to promote honesty of responses, as respondents may have been inclined to change their rating to avoid the extra work.

Round 3

In round 3, only participants who contributed to round 2 were asked to participate. They again received a summary of the average ratings of questions a – f from the previous round, along with the written justifications from participants who voted away from the average. For a third and final time, they were asked to choose at least 10 concepts they most believed to be threshold concepts, and again responded to questions I – VI for each.

The iterative nature of the Delphi technique encourages participant responses to converge to a consensus response by the final round. As a consequence, the recommendations from this study have been made using the responses from round 3 alone.

Results

Demographic data

Sixty-six, 61 and 58 participants from the University of Melbourne took part in rounds 1, 2 and 3, respectively (Table 1). Participant attrition was minimised through reminder emails and extensions where possible. Eight-nine per cent of participants were retained from the initial round, which well exceeds the minimum requirement of 70% as outlined by Walker and Selfe (1996).

Table 1: Participation

Role	Round 1	Round 2	Round 3
Student	41	37	35
PhD student	7	6	6
Research fellow	2	2	1
Associate lecturer	1	1	1
Lecturer	3	3	3
Senior lecturer	4	4	4
Associate professor	3	3	3
Professor	5	5	5
Total	**66**	**61**	**58**

Identified threshold concepts in engineering mechanics

In round 1, a list of 413 concepts was generated by the 66 participants who took part. These were both combined and split to condense the list into 56 unique concepts. Concepts that were not considered within the scope of ENGR20004 Engineering Mechanics were removed, as well as concepts that were only suggested by one participant, leaving 38 remaining concepts.

In rounds 2 and 3, this list of 38 concepts was provided to participants who were then asked to comment on at least 10 of the proposed concepts which they most strongly believed to be threshold concepts. A minimum of 10 was set to encourage participants to truly consider which may or may not be threshold concepts. Although this was the minimum, they were asked to contribute to as many concepts as they believed could be threshold concepts, and so a participant’s absence of input on a particular concept was considered disagreement. Participants who felt they did not agree that even ten concepts could be considered as such could express this by voting from ‘1 = *strongly disagree*’ to ‘4 = *neither agree nor disagree*’ for the concepts they were less strongly in favour of. If, however, they voted for ‘5 = *somewhat agree*’, ‘6 = *agree*’ or ‘7 = *strongly agree*’, it was considered that they agreed this was a threshold concept.

Consensus was defined as majority agreement (strictly greater than 50%) amongst all participants. As there were 58 participants in the final round, this meant that 30 participants had to rate a concept from ‘5 = *somewhat agree*’ to ‘7 = *strongly agree*’ on a given concept in order for it to be considered a threshold concept. This immediately excluded 28 concepts from possibly reaching agreement, as less than 30 contributions were made for these.

Ultimately, the nine concepts that can be considered threshold concepts in engineering mechanics as a result of this study can be seen in Table 2 along with the corresponding level of consensus in round 3.

Table 2: Threshold concepts in engineering mechanics and level of consensus

Concept	Number of contributions	Number in agreement	Consensus (of 58 participants)
Newton’s laws	55	54	93%
Free body diagrams	50	50	86%
Stress and strain (including linear elasticity)	47	47	81%
Work, energy, and force	44	44	76%
Equilibrium	43	40	69%
Momentum and impulse	37	37	64%
Moment of inertia	37	37	64%
Normal force, shear force and bending moment	38	36	62%
Coordinate systems	33	32	55%

Characteristics of the identified threshold concepts

Participants were also asked to comment on how strongly they agreed that each concept was transformative, integrative, irreversible, bounded, and troublesome. Displaying the ‘transformative’ characteristic is the only non-negotiable characteristic of a threshold concept (Meyer & Land, 2003), and consensus was reached among the participants that each of these threshold concepts were transformative in nature. This contributes to the validity of these results.

Possibly the most actionable characteristic, however, is how ‘troublesome’ a concept is. Although participants agreed that the identified concepts were transformative threshold concepts, they did not necessarily consider them troublesome. As an example, clear consensus was reached on equilibrium being a threshold concept. However, only 3% of participants agreed this concept was troublesome. On the other hand, moment of inertia was considered to be the most troublesome concept of all 38 that had been identified, with some 59% of participants agreeing that moment of inertia was a troublesome concept.

Student and academic opinion

In terms of the threshold concepts, opinions across the two groups of participants aligned, although to varying extents. Newton’s laws and free body diagrams easily topped both lists, with an almost equal amount of agreement across the groups. Academics agreed much more strongly than students that equilibrium should be considered a threshold concept, while students agreed more strongly on almost all other concepts than academics. Academics alone did not consider moment of inertia to be a threshold concept, where students ranked it as the fourth most likely threshold concept. It is evident, however, that on some topics, academics and students have vastly different ideas on their difficulty.

More than half of the students considered stress and strain and coordinate systems to be troublesome, while fewer than 30% of academics agreed. However, academics considered Newton’s laws, free body diagrams and equilibrium to be more troublesome than students. For the nine identified threshold concepts, the level of agreement on troublesomeness by both academics and students is shown in Table 3.

Table 3: Level of agreement on the troublesomeness of each threshold concept

Threshold concepts	Academics	Students
Newton's laws	30%	17%
Free body diagrams	30%	14%
Stress and strain (including linear elasticity)	26%	60%
Work, energy, and force	43%	51%
Equilibrium	9%	0%
Normal force, shear force and bending moment	30%	46%
Momentum and impulse	39%	49%
Moment of inertia	35%	74%
Coordinate systems	17%	57%

Discussion

The results of this study display similarities and differences to the concepts previously identified in the literature. In the only comprehensive study on identifying threshold concepts in engineering mechanics, Prusty et al. (2013) concurred with these results in finding that free body diagrams; normal force, shear force and bending moment; momentum and impulse; and work, energy and force ought to be considered threshold concepts. On the other hand, they identified friction, trusses, projectile motion, centroids, and torsion as key threshold concepts, where this study saw only 10%, 14%, 14%, 29%, and 29% of participants agree that these are threshold concepts, respectively. Similarly, modelling, testing, analysis, and evaluation was identified as a threshold concept by both French et al. (2012) and Holland et al. (2012), where only 17% of participants agreed that this should be considered a threshold concept. Unique to this study was the emergence of 'coordinate systems' as a threshold concept in engineering mechanics.

Causes for the differences in the threshold concepts identified by Prusty et al. (2013) and this study are not clear, but likely relate to the adopted methodology. A limitation of this study was that no formal definition of each concept was provided to or by participants, meaning an individual's perception on whether or not a concept is a threshold concept could be affected by their own interpretation of the concept, or by a total unfamiliarity with it. Moreover, concepts were limited to those included in a single subject at a single institution. Although this study did encourage participants to seek clarification at any time, Prusty et al. (2013) used ongoing meetings, discussions and in person consultations with mechanics educators and students. This would have allowed the participants and the researchers to clarify misunderstandings about the mechanics concepts, as well as the overarching idea of threshold concepts.

Characteristics

This study is the first of its kind to analyse all the five characteristics of threshold concepts as defined by Meyer and Land (2003) in engineering mechanics. A notable outcome was that consensus was reached on all identified threshold concepts in terms of being transformative, integrative, and irreversible, but participants failed to agree that almost any of these concepts were bounded or troublesome.

It is possible that concepts which are inherently unbounded have been identified due to the participants' heterogeneity. The academics and students who took part come from a wide range of engineering disciplines, and as such, concepts which are relevant across these disciplines are likely to appeal to a larger number of participants. For example, the concept of equilibrium is integral to mechanical and electrical engineering alike and is therefore not bounded within engineering mechanics.

The level of agreement on troublesomeness did not align with the level of agreement on whether or not the concept was a threshold concept. This suggests that the results of the troublesomeness metric may provide better guidance in terms of time and resource allocation in teaching students these most fundamental concepts.

Although it was observed that students and academics agreed on the identified threshold concepts, they had vastly different views about their troublesomeness. This information is highly pertinent in course and curriculum design. It is likely that academics would focus time and attention on the topics and concepts they believe to be difficult for students, but this research shows that students have a very different idea about which concepts are difficult for them.

The implications of these findings on the characteristics of the threshold concepts are broader. Meyer and Land (2003) speculate that threshold concepts are only possibly bounded and troublesome. This study finds that these may not be characteristics of threshold concepts at all.

Conclusion

The aim of this study was to determine a set list of threshold concepts in engineering mechanics in order to better allocate time and resources in teaching students these most fundamental and pivotal topics. 58 academics and students familiar with the subject ENGR20004 Engineering Mechanics at the University of Melbourne participated in a Delphi study to identify such concepts. 38 concepts were initially identified, 9 of which were considered by the majority of the group (greater than 51%) to be threshold concepts.

However, it was found that students and staff had vastly different ideas about the difficulty, or ‘troublesomeness’, of these concepts. In terms of curriculum design and resource allocation, professors of engineering mechanics may be better served by putting the time and effort into the concepts which were not only considered the most troublesome by the group, but by the students specifically.

The logical continuation of this research lies in developing teaching approaches which will best assist in helping students cross the threshold and understand these most fundamental concepts. This may not only include designing novel teaching practices, but also gaining a better understanding of what students find difficult about these concepts. It is recommended that these identified concepts act as a launching platform for informed, in-person discussions and consultation with academics and students, including those that struggled with engineering mechanics, to solidify the findings.

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