Understanding Engineering Competencies in Practice and the Educational Implications

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SESSION C1: Integration of theory and practice in the learning and teaching process, S1: Is Integrated Engineering Education Necessary?

CONTEXT Engineering professionals and educators have different interpretations or perspectives on certain engineering competency items, for example, mathematical modelling. The question here is how such differences impact the structuring and interpretation of engineering competencies at the general level.

PURPOSE This paper responds to the following questions: How can certain engineering competency items be clustered with others? Is there empirical evidence to support such structures?

APPROACH The research questions stems from a comparative literature review of existing national and international engineering competency standards. Empirical data used in this paper was collected from a small-scale survey. Social Network Analysis (SNA) was used as the method for data analysis – engineering competency mapping.

RESULTS A set of conceptual maps have been made to depict the clustering of 60 engineering competency items identified in a real-life engineering company in China.

CONCLUSIONS It is argued that the Social Network Analysis algorithm can be appropriated for the study of engineering competencies. This algorithm provides indicators of identifying relatively “important” competency items, which create implications for undergraduate engineering practice programs.

KEYWORDS Engineering Competencies, Conceptual Map, Social Network Analysis

Introduction

Despite scientific and technical challenges that engineers have confronted through history, a long lasting non-technical challenge may seem to be more evident in recent years. Such a challenge may be termed as “an identity challenge” (Christensen et al., 2009). This term can be interpreted from educational as well as industrial and/or professional perspectives.

Engineers Australia provides a typical professional interpretation of this term in its Stage 2 Engineering Competency Standards mentioning that “the community has certain expectations of experienced professional engineers, their competence, how they apply this competence and how they will conduct themselves” (Engineers Australia 2012, p.2). This indicates that engineering competency may be critical in shaping engineers’ professional identity.

Studies of engineering competencies can be approached from a comparative literature review of existing engineering competency standards and/or models. Not only do the narratives of certain competency items lead to interpretations from different perspectives, but also the structures of mapping engineering competency items may indicate different approaches of competency building.

From a brief comparative study of some existing engineering competency standards/models developed in different countries – Australia, United States, and China – mathematical modelling is found as a competency item which exemplifies a tension of interpretation from two different perspectives – the practical vs. the theoretical. On one hand, modelling is perceived as a practical skill of simulating real world problems, depicting the ability of problem solving (Dowling & Hadgraft, 2013 and International Engineering Alliance, 2013). On the other hand, it can also be perceived as a major part of theoretical knowledge focusing on understanding engineering sciences (United States Department of Labour, 2015). In between, modelling may not be considered as an independent competency item (Ministry of Education, 2013 and Engineers Australia, 2012).

This complexity poses two questions. First, how can competency items be clustered to create a structure for better understanding? Second, is there empirical evidence to support such a complexity in the real-life workplace?

This paper presents a method of mapping engineering competency items with empirical data collected from a Chinese nuclear power engineering company.

Research

The research question of this paper comes from a comparative literature review. Empirical data used in this paper was collected from a small-scale survey. Social Network Analysis (SNA) is used as the method for data analysis – engineering competency mapping.

Literature Review

The scope of literature covers 5 engineering competency standards or graduate and professional attributes standards published by national and international agencies from 2012 to 2015. These documents are listed as the following:

- Stage 1 Engineering Competency Standards, Engineers Australia 2012 (EA1)
- Stage 2 Engineering Competency Standards, Engineers Australia 2012 (EA2)
- Environmental Engineering Graduate Capabilities and the Stage 1 Competency Standard in the Define Your Discipline (DYD) project, Office for Learning and Teaching, Department of Industry, Innovation, Science, Research and Tertiary Education, Sydney 2013 (DYD)

- Graduate Attributes and Professional Competencies Version 3, Washington/Sydney/Dublin Accords, International Engineering Alliance 2013 (IEA)
- Nurturing Outstanding Engineers – General Standards, Ministry of Education China 2013 (MOE)
- Engineering Competency Model, United States Department of Labour 2015 (AAES)

A summary of the literature review can be seen in Table 1:

Table 1: Comparative review of competency standards

	MOE	IEA	EA1	EA2	AAES	DYD
Level	BA/MA/PhD	Graduate/Professional	Graduate	Professional	Professional	Graduate
Style	Summarized narratives	Tables	2 Column table	3 Column table	Pyramid in tiers	4 Dimensional diagram
Engineering Discipline	All	All	All	All	All	Environmental
Number of competency items	Not specified	Graduate:12 Professional: 13	16 Elements + a list of indicators of attainment	16 Elements + a list of indicators of attainment	Tier1:7 Tier2:7 Tier3:10 Tier4:10 Tier5:Not specified	Technical:7 Process:6 Generic:7 Context: Not specified

Table 1 demonstrates several methods of identifying, structuring and presenting engineering competency items at graduate and professional levels. Such diversity stems from what H.J Passow and C.H. Passow (2017) have identified as a language problem – consistency of wording and difficulty in defining the scope – in a meta-analytical research of this topic.

Although, these well-established standards revealed the complexity of presenting engineering competency items, they did not provide effective ways – in terms of visual expressiveness – of illustrating the “relative importance” (Passow & Passow, 2017) of some items. On top of that, the practical vs. theoretical tension embodied in such competency items remains ambiguous. This ambiguity can be exemplified by the cluster of some items with similar features.

Another example is “procedure compliance”. In the tier 4 competencies in the AAES competency model, engineering sciences are grouped with procedure compliance competencies such as quality control and assurance (United States Department of Labour, 2015). While Engineers Australia Stage 2 Standards (2012) address the routine aspects in the interpretation of individual responsibility. This indicates two possible focuses for the notion of procedure compliance, in the sense that academics may emphasize the systematic approach of engineering design or systems engineering based flows of work, which is, in fact, an academic training, while professionals focus on compliance of organizational routines manifested by individual responsibility.

The academic aspect of procedural competencies is identified as a series of process capabilities in the DYD project (Dowling & Hadgraft, 2013). Although the Chinese standards touched upon both aspects, they were all regarded as a form of knowledge because graduates are only required to be familiar them. Evidence for application seems quite obscure in the Chinese standards (Ministry of Education, 2013).

Empirical data collection

Empirical data used in this paper was collected from a Chinese nuclear power engineering company, which included almost all major engineering disciplines and typical engineering activities such as design, procurement, construction and commissioning. In this respect, such data represents understanding of engineering competencies from a professional perspective in China. Two methods of data collection were adopted. In the first phase, a free listing survey was carried out and in the second phase, another group of participants were invited to take part in a sorting survey.

The free listing survey involved 14 participants. They were asked to list at least 20 competency items related to their daily work. From a disciplinary perspective, these participants included nuclear physicists, mechanical engineers, structural design engineers, digital control engineers and electrical engineers.

At the beginning of the free listing survey, initial data collected represented a range of narrative styles, from summarized sentences to short phrases and words. All these were in Chinese. This brought in two major difficulties. The first difficulty is that expressions of engineering competency items in a synthetic way will lead to unavoidable misinterpretations by the researcher, attempting to break down such synthesized information. It also generated a difficulty for translating the research findings into English, in order to perform a study in an international context, hence to depict possible cultural characteristics. One example of this can be found in Appendix 1 C47 Philosophical Thinking. This translation came out from a compromise of both its English and Chinese meanings. In fact, in most cases, critical thinking in English may be the most appropriate equivalent. But, the notion of critical thinking in Chinese normally refers to dialectics which changes the original meaning to a limited scope. However, using the term philosophical thinking may bring in some redundancy with C2 Logical Reasoning. As a consequence, participants were asked to provide answers in short phrases in the second round. Eventually, 60 relatively independent items (refer to Appendix 1) were identified and translated into English by the researcher.

This list of 60 engineering competency items was used as an input for the following sorting survey which involved 31 participants who were asked to sort these 60 items into groups based on whatever criteria that the participants considered appropriate. Each individual sorting result can be illustrated by a 60X60 data sheet with “1” indicating that those two competencies have been grouped together while “0” indicates those were not grouped together (Appendix 1).

	A	B	C	D	E	F	G
1		C1	C2	C3	C4	C5	C6
2	C1	1	1	0	0	0	1
3	C2	1	1	0	0	0	1
4	C3	0	0	1	0	0	0
5	C4	0	0	0	1	1	0
6	C5	0	0	0	1	1	0
7	C6	1	1	0	0	0	1
8	C7	0	0	0	1	1	0
9	C8	0	0	1	0	0	0
10	C9	1	1	0	0	0	1
11	C10	1	1	0	0	0	1
12	C11	0	0	1	0	0	0
13	C12	0	0	1	0	0	0

Figure 1: Individual sorting sheet

Thirty one individual sorting sheets were then aggregated with each participant given a weight of 1/31 (the arithmetic mean).

	A	B	C	D	E	F
1		C1	C2	C3	C4	C5
2	C1	1	0.354839	0.193548	0.419355	0.451613
3	C2	0.354839	1	0.548387	0.193548	0.225806
4	C3	0.193548	0.548387	1	0.193548	0.16129
5	C4	0.419355	0.193548	0.193548	1	0.83871
6	C5	0.451613	0.225806	0.16129	0.83871	1
7	C6	0.322581	0.612903	0.290323	0.322581	0.322581
8	C7	0.580645	0.258065	0.16129	0.580645	0.483871
9	C8	0.129032	0.290323	0.354839	0.129032	0.129032
10	C9	0.548387	0.483871	0.290323	0.483871	0.483871
11	C10	0.096774	0.354839	0.290323	0.096774	0.129032
12	C11	0	0.064516	0.290323	0.032258	0
13	C12	0	0.064516	0.290323	0.032258	0

Figure 2: Aggregation (n=31)

This aggregated data sheet is used as the input data for a Social Network Analysis (SNA) to generate a graphic structure of engineering competency items identified in this company. SNA has been used to study individual knowledge sharing relationships in a company and the validity of depicting relationships of concepts (Brandes & Erlebach, 2005). Hence it was assumed to be an effective way of giving a visual structure for engineering competency items. A high number indicates an average high level of relatedness.

Mapping Engineering Competencies by SNA

In order to render an SNA diagram using UCINET 6.0, a threshold value indicating valid relationship is critical. Theoretically, the strength of relationship between each pair of competency items can be quantified by the aggregated value in Figure 2. In practice, such threshold value is found on a trial-error test. Three threshold values were tested. The first possible value is 8/31=0.258 which indicates that approximately1/4 of the participants consider that such a pair of items relate to each other. In this respect, 0.258 can be considered as a possible threshold value. The second possible value tested is 16/31=0.516 (1/2) and the third value is 24/31=0.774 (3/4).

At each threshold value the SNA diagrams can be illustrated as the following:

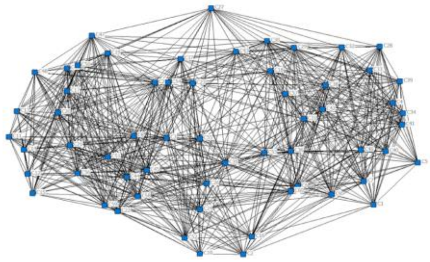

Figure 3: SNA mapping at the value of 0.258

In Figure 3 (threshold = 0.258), nodes are almost evenly distributed. Inter-relationships among nodes are too complicated. 1686 ties were identified above the threshold.

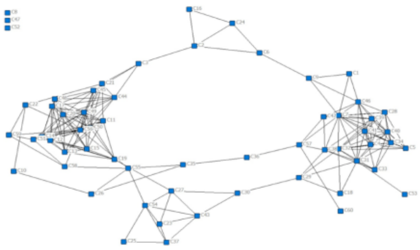

Figure 4: SNA mapping at the value of 0.516

In Figure 4 (threshold = 0.516), nodes can be regarded as clustered into 4 groups with some bridging nodes connecting the major clusters. Three isolated nodes are listed on the top corner. They are C8 Objectivity, C47 Philosophical thinking and C52 Social concerns. An explanation for their isolation perhaps derives from the ambiguity of their definitions. 404 ties were found.

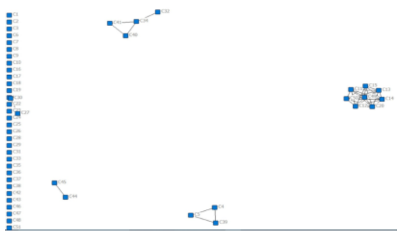

Figure 5: SNA mapping at the value of 0.774

Figure 5 is the SNA diagram rendered at the threshold value of 0.774. A long list of isolated nodes appears at the left margin. Five groups of competencies are identified. 74 ties are visible mainly within the largest group (all of them are generic items). The relationships between the largest group and other nodes are not presented. Therefore, it is an over-simplified demonstration of engineering competencies in the workplace.

Node attributes such as *degree centrality* (the number of links incident upon a node) and *betweenness* (the degree of which nodes stand between each other indicating control of the network) are useful to depict relative “importance” of certain nodes in an SNA diagram (Brandes & Erlebach, 2005). Modifying Figure 4 with these measurements leads to further interpretations of some “important” nodes (See Figures 6-7). Further analysis on the data is based on Figure 4, using a threshold value of 0.516.

Figure 6 shows the SNA diagram at 0.516 modified by setting node size based on *degree centrality*, which is a count of connected nodes.

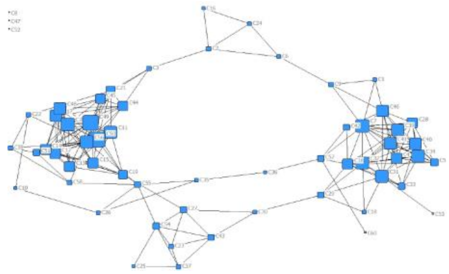

Figure 6: SNA mapping at 0.516 Degree Centrality

Figure 7 shows the SNA diagram at 0.516 by setting node size based on *betweenness*.

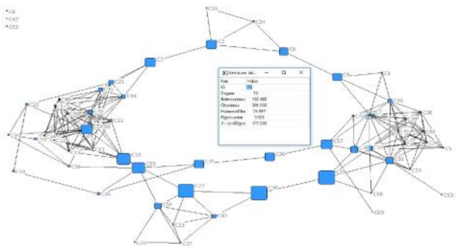

Figure 7: SNA mapping at 0.516 Between-ness

Figure 8 derives from Figures 6 and 7 by picking up significant nodes indicated by *degree centrality* and *betweenness* measurements. Node geometric locations are kept unchanged.

						Context					
				C16 Common Sense	2, 0	C24 Problem Simplification	3, 12				
Generic				C2 Logical Reasoning	4, 206	C6 Problem Clarification	3, 176				
		C3 Curiosity	4, 200					**C9 Mathematical Modelling**	**4, 179**	*Technical*	
C56 Resolve Confrontation	**13, 226**									**C7 Drawing**	**13, 192**
C50 Emotional Control	15, 73									C31 Project Experience	12, 145
C49 Work under Pressure	15, 73									C41 Operation and Maintenance	11, 6
C48 Sceptical	11, 6									C40 Erection and Commissioning	11, 6
C12 Prudence	10, 8									C32 Technical Standards	12, 95
C14 Hardworking	10, 8									C38 Reference Projects	10, 141
C20 Work in a Group	13, 24									C34 Manufacturing Techniques	12, 7
C17 Open Minded	11, 6					*Process*				C57 Literature Study	5, 215
		C19 Aesthetics	8, 278	**C55 Variations**	**5, 263**			C30 Industrial Health and Safety	3, 343		
								C29 Procedure Compliance	**5, 340**		
				C27 Environmental Consciousness	5, 321	C43 QA and QC	5, 68				
				C54 Risk Control	6, 122	C23 Cost Control	4, 3				
				Node	Name	Degree Centrality	Betweenness				
				C7	Drawings	13	192				

Figure 8: SNA mapping interpretation

Engineering competencies in Figure 8 are divided into 4 groups, a *generic* group, a *process* group, a *context* group and a *technical* group. A detailed illustration of constituents in each group can be found in Appendix 2. This finding largely corresponds to the DYD research.

In this figure, “important” engineering competencies can be defined as those with both high values of *degree centrality* and *betweenness*. High values of these measurements represent both high frequency of appearance of one competency item in multiple types of engineering tasks and the impact of it to overall performances in work.

Regarding an engineering project as a social process, resolving and assimilating different opinions serves as the theme of the *generic* group (Bucciarelli 1996). This may be the reason why C56 ‘Resolve confrontations’ is identified as the most important *generic* item, with both high value of *degree centrality* and *betweenness*. The node connects to 13 engineering competencies and is situated in a “favoured” position to facilitate overall practical performances.

In the *technical* group, C7 Drawing, is considered as the most important item because the focus of the nuclear power engineering company is design. In reality, making drawings is a fundamental technical skill that a design engineer needs to master in order to pass complex technical information to others, including to construction teams.

Compared to the *generic* and the *technical* groups, there are fewer nodes in the *context* and *process* groups. But, on average, they hold higher *betweenness* values. This suggests that they serve as the major brokering items between personal attributes and individual technical knowledge and skills.

C9 Mathematical Modelling is placed in the *context* group adjacent to the technical group because in real life engineering practice, modelling requires a deep understanding of the context of application. In this respect, it explains why a high *betweenness* value appears.

C55 (Contract) Variations is placed in the *process* group but serves as linkage between *generic* and *process* competencies because, in practice, variation orders often re-shape technical and commercial agreements. The negotiation process of agreeing to a variation involves personal attributes.

C29 Procedure Compliance is a brokering competency that connects the *process* group and the *technical* group. The earlier discussion in the literature review is supported by the particular geometric location of this node.

Discussions and Implications

The research presented in this paper demonstrates the usefulness of conceptual maps (Wheeldon & Ahlberg, 2012) in the study of engineering competencies. The Social Network Analysis (SNA) algorithm has been used as a mapping tool to model perceived relatedness between competencies. It sheds light on a previous attempt to use the Multidimensional Scaling (MDS) algorithm (Hadgraft, Tilstra & Thebuwana, 2014) to generate statistically more rigorous concept maps – in terms of competency item clustering. Compared to MDS maps, SNA maps may have stronger expressiveness in relationship interpretations and pointing out relative “importance”.

Undergraduate engineering education in China is experiencing a practical shift and has long gone into internationalization. This perception can be strengthened by the nation’s participation in the Washington Accord in the year 2016 (International Engineering Alliance, 2017). However, what can be observed in Table 1 is that many differences between China’s domestic engineering graduate competency standard and the international standard exist. These differences may lead to some difficulties for academics in other countries to understand the Chinese paradigm of engineering education. This paper provides some empirical evidence and translations to fill this gap.

Rather than a historical perspective towards the characteristic of Chinese engineering culture, this paper proposes an analytical approach. As is indicated in this paper, the structural and narrative features of engineering competency items gathered from Chinese engineering professionals may lead to new understandings of the contemporary reality.

From an educational perspective, *process* and *context* competencies should be emphasised in the practice programs such as projects and internships in undergraduate engineering education. *Process* competencies should not be limited to the knowing of particular manufacturing or construction processes based on theoretical demonstrations. In fact, process competencies largely refer to compliance to certain organizational regulations and managerial agendas. The attainment of these competencies requires an understanding of both an organization and the scope of the tasks defined in a particular context.

Context competencies support *technical* performances because problem solving starts with problem identification and definition in which an understanding of the context is a pre-requisite. In this respect, they are likely the competencies that can better be developed in the workplace.

Conclusions

This paper has presented a way of creating a conceptual map by Social Network Analysis for engineering competencies with survey data collected from a real-life company. The authors acknowledge that language translation has likely had some impact on the study.

The paper reveals different perspectives of certain engineering competency elements and how such differences are represented in the workplace. Four clusters of skills: *generic*, *process*, *context*, and *technical*, have been revealed by the modelling, in a similar way to the DYD research mentioned earlier.

The research described in this paper supports the notion that conceptual maps "assist people to produce patterns of how they organized and structured their thoughts; concept maps were later developed into meta-cognitive tools for learning and teaching" (Wheeldon and Ahlberg, 2012, p23). Specifically, the Social Network Analysis algorithm can be appropriated for the study of engineering competencies.

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Appendix 1 Engineering competency items sorting example from the company

No.	Competency	Sorting	No.	Competency	Sorting
C1	Experiments and tests	1	C31	Project experience	1
C2	Logical reasoning	1	C32	Technical standards	3
C3	Curiosity	2	C33	Industrial trends	3
C4	Knowledge of one discipline	3	C34	Manufacturing techniques	3
C5	Cross-disciplinary knowledge	3	C35	Project goals	1
C6	Problem clarification	1	C36	Feasibility study	1
C7	Drawing	3	C37	Marketing	2
C8	Objectivity	2	C38	Reference projects	3
C9	Mathematical Modelling	1	C39	Materials	3
C10	Interfaces	1	C40	Erection and commissioning	3
C11	Honesty	2	C41	Operation and maintenance	3
C12	Prudence	2	C42	Foreign language	3
C13	Patience	2	C43	QA and QC	2
C14	Hard-working	2	C44	Judgment	2
C15	Persistence	2	C45	Independent thinking	2
C16	Common sense	1	C46	Coding and Software	1
C17	Open-minded	2	C47	Philosophical thinking	2
C18	Compliance with regulations	1	C48	Sceptic	2
C19	Aesthetics	2	C49	Work under pressure	2
C20	Work in a group	2	C50	Self-control	2
C21	Creativity	2	C51	Leadership	1
C22	Communication	1	C52	Social concerns	1
C23	Cost control	2	C53	Peer review	1
C24	Problem simplification	1	C54	Risk control	2
C25	Scope of work	2	C55	Variations	1
C26	Planning	3	C56	Resolve confrontations	2
C27	Environmental consciousness	2	C57	Literature study	3
C28	Ergonomics	3	C58	Negotiation	1
C29	Procedures	1	C59	Initiative	1
C30	Industrial health and safety	2	C60	Data collection	1

Appendix 2 Engineering competency sorting in 4 dimensions

Generic	Context	Process	Technical	Isolated
C3 Curiosity	C2 Logical reasoning	C23 Cost control	C1 Experiments and tests	C8 Objectivity
C10 Interfaces	C6 Problem clarification	C25 Scope of work	C4 Knowledge of one discipline	C47 Philosophical thinking
C11 Honesty	C9 Mathematical Modelling	C27 Environmental consciousness	C5 Cross-disciplinary knowledge	C52 Social concerns
C12 Prudence	C16 Common sense	C29 Procedures	C7 Drawing	
C13 Patience	C24 Problem simplification	C30 Industrial health and safety	C18 Compliance with regulations	
C14 Hard-working		C35 Project goals	C28 Ergonomics	
C15 Persistence		C36 Feasibility study	C31 Project experience	
C17 Open-minded		C37 Marketing	C32 Technical standards	
C19 Aesthetics		C43 QA and QC	C33 Industrial trends	
C20 Work in a group		C54 Risk control	C34 Manufacturing techniques	
C21 Creativity		C55 Variations	C38 Reference projects	
C22 Communication			C39 Materials	
C26 Planning			C40 Erection and commissioning	
C44 Judgment			C41 Operation and maintenance	
C45 Independent thinking			C42 Foreign language	
C48 Sceptic			C46 Coding and Software	
C49 Work under pressure			C53 Peer review	
C50 Self-control			C57 Literature study	
C51 Leadership			C60 Data collection	
C56 Resolve confrontations				
C58 Negotiation				
C59 Initiative				