USING CDIO FOR DEVELOPMENT OF STUDENTS' SUSTAINABILITY MINDSET

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ABSTRACT

This paper uses the CDIO Framework to reconcile 2 separate areas of development work related to sustainable development: what constitute a set of key competencies for sustainability, and a set of sustainability mindset principles. To achieve the desired outcomes from education for sustainable development, that is, transformative learning, sustainability mindset is needed to drive actions, which requires a set of key competencies for sustainability. Our work argued that both are underpinned by the same set of skills and attitudes espoused in the CDIO Syllabus. Using the CDIO Standards, we also reconciled the apparent contradiction between "key competencies" which are meant to be context-independent (as in the work from the CDIO Community), and other authors who suggested "key competencies" which are clearly context-dependent. We suggested the use of a revised terminology that better reflect the current discourse and also the issues of order of hierarchy for the key competencies for sustainability. Notably, we improved on the work from the CDIO community and proposed a "bounded" model with values thinking competency as a "lower limit" and integrated problem-solving competency as the "upper limit". Values thinking competencies should be developed first based on underpinning skills and attitudes from the CDIO Syllabus. Our model allows other context-specific competencies to be incorporated as needed; and provides the flexibility of a program to formulate its own progressive pathway on how the rest of the key competencies for sustainability can be developed consistent with the program's own unique requirements. We also provide an application on how the model can be used for a hypothetical program. Lastly, we outlined some limitations in our work and how we can move forward in continuing to address this ever-evolving challenge.

KEYWORDS

Sustainable Development, Sustainability Mindset, Key Competencies for Sustainability, CDIO Syllabus, CDIO Standards: 1-12

INTRODUCTION

This paper outlines the work done to develop a general approach for any program in general, and Singapore Polytechnic (SP) in particular, that are interested in integrating key competencies for sustainability into a curriculum, guided by the CDIO Framework. This effort is an extension of the work done by the Diploma in Chemical Engineering (DCHE) after it introduced its integrated curriculum for sustainable development using the SP Common Core Curriculum (CCC). For more information, see Cheah et al (2022) and Oh et al (2023).

The work involves a pilot run involving 4 programs from 4 different schools in SP: School of Architecture and Built Environment, Chemical and Life Sciences, Electrical and Electronic Engineering, and Mechanical and Aeronautical Engineering. All programs had completed the integration of sustainable development into the respective curriculum, using selected United Nations Sustainable Development Goals (UNSDGs). Each program will build on the coverage of CCC to include disciplinary context to further enhance the coverage of sustainable development in each program. The goal is to develop a sustainability mindset among SP graduates.

This work brings together 2 different and separate strands of efforts related to sustainability: that of key competencies for sustainability and sustainable mindset principles, in order to equip SP graduates with sustainability mindset. The aim is to operationalize Education for Sustainable Development (ESD) to achieve the aim of transformative learning: students as "agents of change" (de Kraker et al, 2007), equipped with the capacity to go beyond just acquiring knowledge, but to use what they learnt to shape the future by proactively taking actions to address society's sustainability challenges. We believe the work shared in this work be of interest to other CDIO collaborators seeking to introduce ESD into their respective programs; as it provides a unified approach based on the CDIO Framework.

KEY COMPETENCIES FOR SUSTAINABLE DEVELOPMENT

The United Nations Educational Scientific and Cultural Organization (UNESCO) Publication Education for Sustainable Development Goals: Learning Objectives noted that key competencies represent cross-cutting competencies that are necessary for all learners of all ages worldwide, as they developed at different age-appropriate levels. They can be understood as transversal, multifunctional and context-independent (UNESCO, 2017). In the context of ESD, key competencies in sustainability are competencies that are relevant to all SDGs and enable individuals to relate the different SDGs to each other; representing what sustainability citizens need to deal with in today's complex challenges.

Within the ESD literature, various authors had suggested what constituted sustainability competencies or key sustainability competencies, e.g. Barth et al (2007), Frisk & Larson (2011), Kioupi & Voulvoulis (2019), Lozano et al (2017), Redman & Wiek (2021), Rieckmann (2012) and Wiek et al (2011). Many of these approaches had significant overlaps but despite this apparent convergence, there is no explicit consensus of a specific framework of key competencies in sustainability (Brundiers et al, 2021). Sterling et al (2017) described the situation as characterised by a sea of labels, terminological confusion, and relative inattention to pedagogic implications. Weinert (2001) is especially critical when he noted that: "The attempt to compile a comprehensive scheme above all possible and necessary key competencies is bound to fail right from the start since such a list must end in arbitrariness". Guia (2020) attributed this to the lack of universal competence framework for sustainability,

with the resulting proliferation of many definitions of what knowledge, skills, attitudes and values for sustainability are.

The starting point of our work is the same 8 UNESCO key competencies for sustainability, used by Rosen et al (2019) to evaluate the relevance of the CDIO Syllabus (then version 2.0) for promoting ESD in engineering. In the study, Rosen et al (2019) concluded that that the integrated problem-solving key competency in the UNESCO framework and aligned very well with the overarching Conceive-Design-Implement-Operate competences in the CDIO Framework. The 8 UNESCO key competencies for sustainability – systems thinking competency, anticipatory competency, normative competency, strategic competency, critical thinking competency, collaboration competency, self-awareness competency, and Integrated problem-solving competency – are formulated after extensive studies from other literatures noted earlier (Rosen et al, 2019).

In terms on terminology, which itself can be a source of confusion, anticipatory, normative and collaborative competencies as used above are the same as futures thinking, values thinking and interpersonal competencies suggested by Wiek et al (2015). Another reason why we choose the UNESCO publication is because it provided examples of cognitive, socio-emotional and behavioural learning objectives for each UN SDG; along with suggested topics for discussion and learning approaches. Another publication that provides examples for learning outcomes for key competencies for sustainability is from QAA-AdvanceHE (2021). This helped to address a challenge highlighted by Kioupi & Voulvoulis (2019) on the challenges of relating the SDGs to educational learning outcomes,

What the UNESCO document did not provide is the proficiency levels. To this end, we turn to the work of Wiek et al (2015) who introduced 3 levels of “mastery” to help operationalize the key competencies for sustainability: novice, intermediate and advance; which in turn can be translated to high school, undergraduate and graduate levels of sustainability education. This approach is consistent with the CDIO Framework; to aid the design of ESD via of an integrated curriculum to help progressively develop these key competencies for sustainability to the desired proficiency levels (learning outcomes); using appropriate UNSDGs as the learning context. In the case of SP, this translates to different competency level of our students’ sustainability mindset, as part of SP graduate attributes.

Hierarchy of Key Competencies for Sustainability

Several authors had spoken of “convergence” of key competencies for sustainability, for example, Brundiers et al (2021), Redman & Wiek (2021). These authors also spoken of the interdependencies of key competencies as each contributed to the overall integrated problem-solving competency. This is a positive development, moving away from what Wiek et al (2011) called “laundry lists” of competencies rather than conceptually embedded set of interlinked competencies.

However, even with the emerging “convergence”, there is still a lack of consensus among authors what constitute key competencies. These authors (Redman & Wiek, 2021, Brundiers et al 2021) readily acknowledged these unresolved debates and differing perspectives in their reported work. Brundiers et al (2021) for example suggested a need for a hierarchy of competencies; and improved on the initial framework of Wiek et al (2011) by introducing 2 new key competencies: intrapersonal competency and implementation competency. Like Wiek et al (2011), they do not consider critical thinking as a key competency, but rather as a general competency that underpin the other key competencies.

Likewise, Redman & Wiek (2021) introduced a unified framework that showed somewhat different relationship between the key competencies as articulated earlier by Wiek et al (2011). Their framework also considered critical thinking as a general competency along with creativity and learning that underpin other key competencies. They also introduced 3 new key competencies: Implementation competency (which brings together the 4 competencies of systems thinking, futures thinking, values thinking and strategic thinking), intra-personal competency (addressing need for self-awareness and self-regulation) which complements interpersonal competency, and also underpins other competencies. Integration competency is then the key competency that brings together all other key competencies for advancing sustainability transformations.

SUSTAINABILITY LITERACY, SUSTAINABILITY MINDSET AND SUSTAINABILITY MINDSET PRINCIPLES

Another seemingly parallel track under investigation with regards to ESD is the notion of sustainability literacy and sustainability mindset. Sustainable literacy appears in the literature as sustainable development literacy, literacy for sustainable development, and/or sustainability literacy. Sustainable literacy is generally conceived as an understanding of sustainability and the identification and translation of issues that have sustainability implications (Perkins et al, 2019). Ansari & Stibbe (2009) explored the concept of sustainability literacy in terms of what skills, values, attributes and dispositions would learners need to navigate their lives in the challenging conditions of the twenty first century, in relation to sustainability and well-being.

Sustainability mindset is defined as a way of thinking and being that result from a broad understanding of the ecosystem's manifestations, from social sensitivity, as well as an introspective focus on one's personal values and higher self, and finds its expression in actions for the greater good of the whole (Kassel, Rimanoczy & Mitchell, 2016). Sustainability mindset is to be developed as a new lens through which individuals can look into the world, analyzing data and making better decisions. Hermes & Rimanoczy (2018) noted that developing a sustainability mindset means engaging head, heart and hands; whereby the values, purpose, and emotions provide a holistic and deep learning experience with transformative power towards a sustainability mindset. Further effort by Rimanoczy & Llamazares (2021), who based on their work on qualitative exploratory study of what motivated leaders to champion sustainability initiatives, identified 12 elements that guides development of a sustainability mindset, grouped under 4 central areas. Table 1 showed the synthesis of these ideas.

Table 1. Sustainability Mindset – Central Areas, Dimensions and Principles

Central Areas	Sustainability Principles	Dimensions		
		Knowledge (Thinking)	Being (Values)	Doing (Action)
Ecological Worldview	• Ecoliteracy • My Contribution	Ecoliteracy	Biospheric Orientation	Protective / Restoration Practices
Systems Perspective	• Both-And Thinking • Cyclical Flow • Interconnectedness • Long-Term Thinking	Systems Theory	Inter-connectedness	Stakeholder Engagement
Emotional Intelligence	• Self-Awareness • Reflection • Creative Innovation	Self/Other Awareness	Compassion	Proactive Glocal Sensitivity
Spiritual Intelligence	• Oneness with Nature • Mindfulness • Purpose	Purpose/ Mission	Oneness with All That Is	Contemplative Practice

In terms of outcomes, Parkin et al (2004) noted that a sustainability literate person would be expected to attain the following, expressed at the highest level:

- Understand the need for change to a sustainable way of doing things, individually and collectively
- Have sufficient knowledge and skills to decide and act in a way that favours sustainable development
- Be able to recognize and reward other people's decisions and actions that favour sustainable development

DESCRIPTION OF WORK DONE FOR THIS PAPER

We had earlier shared how we used the 12 CDIO Core Standards to integrate key competencies for sustainability into the SP DCHE Curriculum as the adopted the CCC (Cheah et al (2022), and the evaluation of the effort (Oh et al 2024). The next step in the integration of ESD is to build on the effort of CCC, to continue to develop students' competencies in sustainable development, in progressively deeper coverage using with domain-specific knowledge, to further contextualize the learning using selected UNSDGs. The aim is to develop students' sustainability mindset as a key element of SP's graduate attributes. As graduate attributes are common for all students – regardless of the program – there is a need to explore a common approach whereby any program can adopt/adapt, even though each may likely integrated ESD in its own unique way.

While the pathways explored by different program may be different, they are guided by the same approach using the CDIO Framework, towards the desired outcome of transformative learning among students. Mezirow (2003) explained "transformative learning" as "learning that transforms problematic frames of reference – sets of fixed assumptions and expectations (habits of mind, meaning perspectives, mindsets) – to make them more inclusive, discriminating, open, reflective, and emotionally able to change". Scarff-Seatter & Ceulemans (2017) further elaborated that transformative learning is a process that:

(i) allows students to question taken for granted frames of reference to become more discriminating, open, and reflective
(ii) produces major changes in thinking, feeling, acting, relating, and being
(iii) allows for evaluating values and assumptions for their effectiveness towards shared goals

To achieve these desired outcomes, we noted that there is lot of complementarity between the 2 strands of work on ESD: Development of key competencies for sustainability on one hand, and development of sustainability mindset on the other. Both are like 2 sides of the same coin: The approach towards sustainability mindset is decidedly more person-centric, focusing of the belief, values, attitudes and disposition of an individual towards his/her surroundings, e.g. "My Contribution" under Ecological Worldview, and "Oneness with Nature" under Spiritual Intelligence. The emphasis is greater on the "developing awareness" and "exploring paradigm" part as shown on the right-side of Figure 1. On the other hand, the approach to key competencies of sustainability is more task-oriented, with some considerations of the individual involved in the change effort. The focus is more on the "getting into action" part of right-side of Figure 1. The elements of emotional intelligence and spiritual intelligence in particular, can reinforce the self-awareness competencies needed for integrative problem-solving. Overall, the 4 elements of the sustainability mindset principles helped to highlight the need to consider "time-scale" relationship in addressing sustainability issues.

MAPPING AGAINST SUSTAINABILITY COMPETENCIES		CONCEIVING, DESIGNING, IMPLEMENTING AND OPERATING SYSTEMS IN THE ENTERPRISE, SOCIETAL AND ENVIRONMENTAL CONTEXT – THE INNOVATION PROCESS	Systems Thinking	Anticipatory	Normative	Strategic	Collaboration	Critical Thinking	Self-Awareness
2.1 ANALYTIC REASONING AND PROBLEM SOLVING	2.1.1	*Problem Identification and Formulation*	✓✓✓	✓	✓			✓	
	2.1.2	*Formulate a Strategy to Solve Problems*	✓✓✓	✓		✓			
	2.1.3	*Analyze Results*	✓✓✓					✓	
	2.1.4	*Conclude Study and Make Recommendation*	✓✓✓						
2.2 EXPERIMENTATION, INVESTIGATION AND KNOWLEDGE DISCOVERY	2.2.1	*Formulate Hypothesis*	✓						
	2.2.2	*Conduct Literature Review*	?						
	2.2.3	*Conduct Experimental Inquiry*	✓						
	2.2.4	*Analyse Data and Write Report*							
2.3 SYSTEM THINKING	2.3.1	*Understand the basis and methods of system thinking*	✓✓✓		✓			✓	
	2.3.2	*Understand Interactions in Systems, and External to Systems*	✓✓✓	✓✓✓	✓			✓	
	2.3.3	*Apply System Thinking in Problem-Solving*	✓✓✓		✓			✓	
	2.3.4	*Understand Trade-offs, Synergies, Judgment and Balance in Resolution*	✓✓✓	?	✓✓✓	✓✓✓		✓	
2.4 ATTITUDES, THOUGHT AND LEARNING	2.4.1	*Demonstrate Positive Attitude and Willingness to Make Decisions in Face of Uncertainty*	✓	✓					✓
	2.4.2	*Demonstrate Perseverance, Sense of Urgency and Will to Deliver*	✓	?		✓	✓	✓	✓
	2.4.3	*Demonstrate Resourcefulness and Flexibility in Adapting to Change*	✓	?					✓
	2.4.4	*Demonstrate Creative Thinking*	✓						
	2.4.5	*Demonstrate Critical Thinking*	✓✓✓	✓	✓	✓	✓	✓✓✓	
	2.4.6	*Demonstrate Self-Awareness, Self-Reflection, Metacognition and Knowledge Integration*		✓✓✓	✓			✓✓✓	✓✓✓
	2.4.7	*Demonstrate Learning Agility, Engage in Lifelong Learning and Educating*	✓						✓✓✓
	2.4.8	*Manage Time, Technology and Resources*	✓	✓✓✓		✓✓✓			
2.5 ETHICS, EQUITY AND OTHER RESPONSIBILITIES	2.5.1	*Apply Knowledge of Sound Values and Ethics, and Demonstrate Social Responsibilities*			✓✓✓		✓	?	
	2.5.2	*Demonstrate Professional Behaviour at Work and in Society*		?	?		✓		✓
	2.5.3	*Develop Self-Awareness in Life Planning*		?	?		✓		✓✓✓
	2.5.4	*Stay Current on One's Own Professional Field (e.g. Engineering, Business, etc)*	✓	✓		?			✓
	2.5.5	*Demonstrate Respect for Equity, Justice, Diversity and Inclusiveness*					✓✓✓	✓	
	2.5.6	*Exhibit Trust and Loyalty*					✓✓✓		
3.1 TEAMWORK AND COLLABORATION	3.1.1	*Form Effective Teams*					✓✓✓		
	3.1.2	*Manage and Participate in Teams*					✓✓✓		
	3.1.3	*Participate in Multi-perspective Collaboration*					✓✓✓	✓	
	3.1.4	*Engage Stakeholder, Establish Diverse Connections and Networking*		✓		✓	✓✓✓		
3.2 COMMUNICATION	3.2.1	*Design Appropriate Communications Strategy*				✓			
	3.2.2	*Design Appropriate Communication Structure*							
	3.2.3	*Demonstrate Effective Written Communication*							
	3.2.4	*Demonstrate Effective Digital Communication*							
	3.2.5	*Demonstrate Effective Graphical Communication*							
	3.2.6	*Demonstrate Effective Oral Presentation*							
	3.2.7	*Demonstrate Effective Interpersonal Communication, Inquiry, Listening, Dialog and Argumentation*			✓		✓✓✓	✓	
	3.2.8	*Demonstrate Effective Negotiation, Compromise and Conflict Resolution*			✓✓✓	?	✓✓✓	✓	
	3.2.9	*Demonstrate Advocacy*	✓	✓		?		?	?

MAPPING AGAINST SUSTAINABILITY COMPETENCIES		CONCEIVING, DESIGNING, IMPLEMENTING AND OPERATING SYSTEMS IN THE ENTERPRISE, SOCIETAL AND ENVIRONMENTAL CONTEXT – THE INNOVATION PROCESS	Systems Thinking	Anticipatory	Normative	Strategic	Collaboration	Critical Thinking	Self-Awareness
4.1 EXTERNAL, SOCIETAL AND ENVIRONMENTAL CONTEXT	4.1.1	*Identify Roles and Responsibility of Engineers or Other Professionals*			✓	✓			✓
	4.1.2	*Address the Impact of Engineering on Society and the Environment*	✓✓✓	✓✓✓	✓	✓		✓✓✓	✓
	4.1.3	*Recognise How One's Profession is Regulated in Society*	✓✓✓		?				✓
	4.1.4	*Understand Historical and Cultural Context in Engineering or Other Professions*	?		?				
	4.1.5	*Understand Contemporary Issues and Values*	✓		✓✓✓			✓	
	4.1.6	*Describe a Vision for the Future*	✓	✓	?	?			✓
	4.1.7	*Develop an International and Global Perspective*			✓✓✓	✓✓✓		?	
4.2 ENTERPRISE AND BUSINESS CONTEXT	4.2.1	*Appreciating Different Enterprise Cultures*	?		?				
	4.2.2	*Understand Different Enterprise Stakeholders, Strategy and Goals*	?		✓		✓		
	4.2.3	*Understand Technical Entrepreneurship*		?				?	
	4.2.4	*Understand Working in Local Organizations*					✓✓✓		
	4.2.5	*Understand Working in International Organizations*			?		✓✓✓		
	4.2.6	*Understand New Technology Development and Assessment*		✓		✓			
	4.2.7	*Understand Project Finance and Economics*		?	?	✓			
4.3 CONCEIVING, SYSTEM ENGINEERING AND MANAGEMENT	4.3.1	*Understand Societal and Planetary Goals and Constraints*	✓✓✓	✓	✓	✓		✓	
	4.3.2	*Understand Needs and Goal-setting*	✓	✓	✓	?			
	4.3.3	*Evaluate Function, Concept and Architecture*	✓						
	4.3.4	*Develop System Engineering, Modelling and Interfaces*	✓						
	4.3.5	*Develop a Project Management Plan*			?	?			
	4.3.6	*Develop a Product Information and Knowledge Management Plan*							
4.4 DESIGNING	4.4.1	*Formulate the Design Process*	✓✓✓		✓	✓			
	4.4.2	*Plan the Design Process Phasing and Approaches*					?	?	
	4.4.3	*Utilize Knowledge in Design*							
	4.4.4	*Understand Disciplinary Design*					?		
	4.4.5	*Understand Multidisciplinary Design*		?			?		
	4.4.6	*Design for Sustainability, Safety, Aesthetics, Operability and Other Objectives*	✓✓✓	✓✓✓		✓		✓	
4.5 IMPLEMENTING	4.5.1	*Design a Sustainable Implementation Process*	✓✓✓	✓		✓		✓	
	4.5.2	*Plan Hardware Manufacturing Process*		?			?		
	4.5.3	*Plan Software Implementing Process*		?			?		
	4.5.4	*Plan Hardware-Software Integration*		?			?		
	4.5.5	*Conduct Test, Verification, Validation and Certification*				?			
	4.5.6	*Manage Implementation Process*	?			?			
4.6 OPERATING	4.6.1	*Design and Optimizing Sustainable and Safe Operations*	✓✓✓	✓	✓	✓		✓	
	4.6.2	*Plan Training and Operations*				?			
	4.6.3	*Plan Support for Product, Process, Service, System Life Cycle*	✓			?			
	4.6.4	*Manage System Improvement and Evolution*		?		?			
	4.6.5	*Manage Disposal, Circularity and Life-End Issues*	✓✓✓			✓			
	4.6.6	*Plan for Operations Management*	✓✓✓	✓		✓			

Any cell with 3 or more (✓✓✓) will be recorded as such. Same for 3 or more (✓). Entry with mix of (✓✓✓) and (✓) will be recorded as (✓). Entry with (✓✓✓) or (✓) AND (?) will be recorded as (?). Entry with 1 (✓) and 1 or more (?) will be left BLANK.

✓✓✓ Explict / Strong ✓ Implicit / Partial

? Potential / Need for Improvement

Figure 1. Mapping between UNESCO Key Competencies for Sustainability and CDIO Syllabus version 3.0 (this work)

What we strive to do, is to harmonize these 2 threads into a unified approach towards a holistic development of ESD, guided by the CDIO Framework. We continue with the findings of the usefulness of key competencies for sustainability, which had been reported to be widely used in university masters programs by Salovaara et al, (2020).

Convergence of Key Competencies for Sustainability and Sustainability Mindset

With the release of CDIO Syllabus version 3.0 (Malmqvist et al, 2022), we have also revised our own SP-CDIO Syllabus to match that of version 3.0. In the CDIO Syllabus version 3.0, the needs and opportunities identified in Rosén et al (2019) have been further refined, and additional references were consulted and changes implemented. For our work, we adopted the same approach of Rosen et al (2019), with the 5 authors of this paper each studied the competencies and mapped them against the revised SP-CDIO Syllabus version 3.0. The outcome shown is in Figure 1. It showed that we are in good agreement with regards to the skills and attitudes that underpins the key competencies for sustainability (dark shaded box with 3 tick marks). There are some small degrees of uncertainty over other supporting skills and attitudes (light shaded box with 1 tick mark), reflecting the different perspective each author has over how direct/remote a given skill or attitude is supporting a given key competency of sustainability, probably due to varying needs of the domain-specific knowledge. Lastly, the team also surfaced some areas where improvements may be useful (non-shaded box with question mark), which again can be influenced by domain-specific knowledge.

The relationship between key competencies for sustainability and sustainability mindset principles appeared to be under-researched. Our research of the literature yielded a paper from Cripps & Smith (2023) that briefly compared the 12 sustainability mindset principles to the UNESCO key competencies, and a paper from Ansari & Stibbe (2009) that provide a list of skills and attitudes needed for sustainability mindset.

We then map skills and attitudes needed for sustainable mindset from the Ansari & Stibbe (2009) paper to sustainability mindset principles. Each of the 5 authors again did his/her own mapping using the SP-CDIO Syllabus version 3.0, and the first author then reconcile all submissions and the results is shown in the left part of Figure 2. Here we also found good match with the topics covered in the SP-CDIO Syllabus, and not surprisingly, each principle can also be mapped to many skills and attitudes. On the right part of Figure 2, we showed the skills and attitudes that mapped strongly with the key sustainability competencies – results of mapping that was showed in Figure 2 earlier. Figure 2 clearly showed that sustainability mindset principles and key competencies for sustainability are 2 sides of the same coin.

With these mapping done, we proceed to put together a framework needed. We aim to develop a framework that is not only useful for programs in SP to use, but also valuable for other CDIO collaborators. This will also help to address challenges at operationalizing competencies for sustainability as highlighted by various authors (e.g. Brundiers et al, 2021, Wiek et al, 2016, Wilhelm et al, 2019).

The CDIO Way: From Key Competencies for Sustainability to Sustainability Mindset

In this part of the development, we took notes of the apparent paradox of ESD: On one hand, much work had been done to “harmonize” what constituted key competencies for sustainability, intending these to be context-independent so that any resulting model can be adoptable by any disciplines and fields of study. On the other hand, there are challenges in operationalizing them: developing a key competency – which by definition is made up of several other (i.e. hitherto “non-key”) competencies – requires learning these set of

competencies; and such learning requires context. In fact, competencies had been described as “learnable but not teachable” (Barth et at, 2007). Competence is linked to domain and dependent on context (Vitello et al, 2021). Mochizuki & Fadeeva (2010) charged that “Competences have no meaning unless they are enacted in practice and connected to assessment in a particular context”. Likewise, sustainability education is inextricably linked to context (Sterling et al, 2017). This is a point also highlighted by Wilhelm et al (2019) who wrote on challenges operationalizing competencies for sustainable development, noted that “theoretical debates on competences insist on the fact that competences can neither be transferred nor taught, but only acquired in a specific context”.

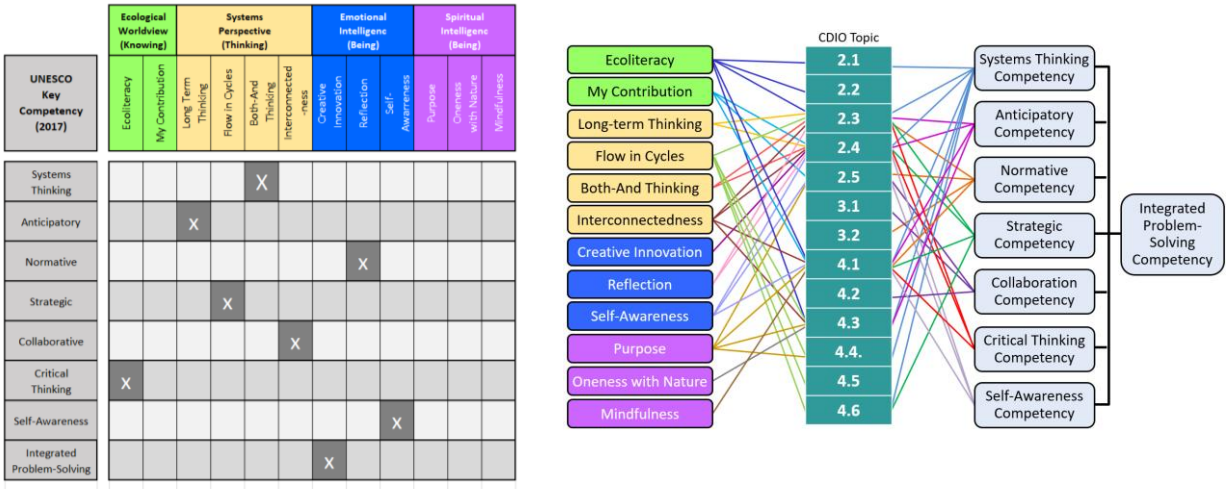

Figure 2. Aligning Sustainability Competencies to Sustainability Mindset Principles (Right: with Cripps & Smith, 2023; Left: This work via SP-CDIO Syllabus)

We build on our earlier efforts in using CDIO to integrate CCC and ESD; and added the considerations for sustainability mindset principles along with the selected CDIO Core Standards to develop the required key competencies for sustainability. We argued that the CDIO Framework will provide the “missing link” between the context-independent key competencies for sustainability, and the context-dependent development of their underpinning competencies. Most notably is Standard 1 The Context which will provide the necessary context under which a given program can used as the basis for designing ESD specific for the discipline or field of study. We further argued that the 12 sustainability mindset principles can be used to provide further guidance to the design of an integrated curriculum (Standard 3) which in turn can be imparted to students via a series of touchpoints, such as projects of increasing level of complexity (Standard 5 Design-Implement Experiences), laboratory experiments, workshops, assignment, etc (Standard 7 Integrated Learning Experiences), etc that provide actual hands-on experience to progressively develop the desired competencies over the program’s duration. The result is shown in Figure 3.

The next step is to explore concerns raised by some authors by investigating the relationship between the key competencies for sustainability with a view of “organizing” them into a form of hierarchical relationship (Brundiers et al, 2021).

Relationship between Key Competencies for Sustainability and Hierarchy of Development

Guided by the CDIO Framework, we proceed to explore the development of our own framework, we studied the previous efforts as detailed in the literature section earlier – for example the works of Brundiers et al (2021) and Redman & Wiek (2021). In particular we

focused on the challenge of formulating the hierarchy of competencies. The resulting framework is shown in Figure 4, comprising the following competencies:

- Integrated Problem-Solving Competency
- Systems Thinking Competency
- Futures Thinking Competency
- Values Thinking Competency
- Strategic Thinking Competency
- Interpersonal Competency
- Intrapersonal Competency
- Implementation Competency

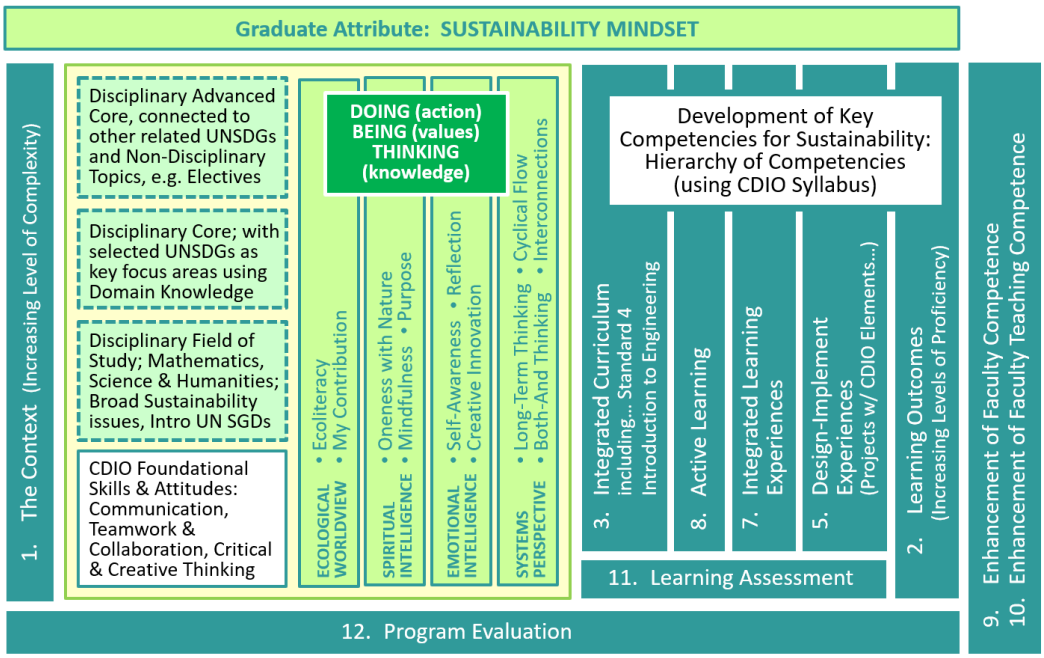

Figure 3. How Selected CDIO Standards along with Sustainability Mindset Principles can Support Development of Key Competencies for Sustainability

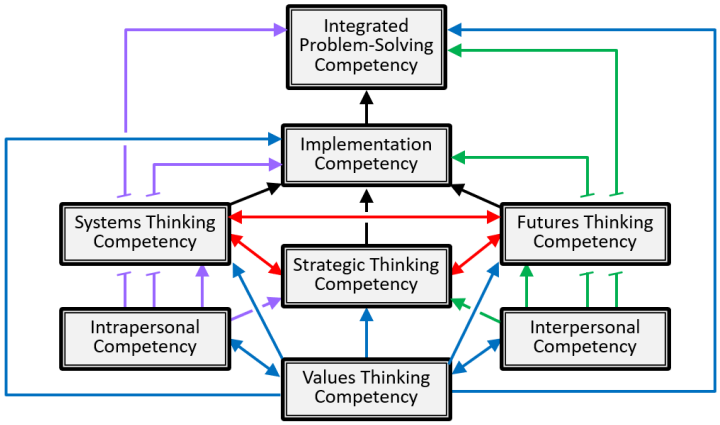

Figure 4. Key Competencies for Sustainability – Hierarchy and Possible Relationships

As a framework, the key competencies are not compiled as a list to select from; instead, all key competencies need to be integrated for advancing sustainability transformations (Redman & Wiek, 2021). The following are our key considerations:

- Values thinking competency (Wiek et al, 2015) is preferred over normative competency (UNESCO, 2017) for its emphasis on values; simply because sustainable development challenges had remained a contested and value-laden concept (Sterling, 2011, Harding, 2005). In fact, Brundiers et al, (2021) opined that it should be providing the normative orientation for the other competencies.
- Futures thinking competency likewise replaced anticipatory competency.
- Interpersonal competency will be used in place of collaboration competency from UNESCO (2017), as it broadens the engagement process to include use of communication (Genc, 2017) and applicable to a range of different stakeholders including transdisciplinary teams (Frisk & Larson, 2011).
- Intrapersonal competency will subsume self-awareness competency from UNESCO (2017), and will also include other skills and attitudes such as self-regulation, and to continually improve oneself (Brundiers et al, 2021)
- Interpersonal competency and intrapersonal competency are to underpin all other competencies (Brundiers et al, 2021; Ayers et al, 2023)
- Added implementation competency as suggested by Redman & Wiek (2021), as well as Brundiers et al (2021), although later work by Brundiers et al (2023) excluded it. We acknowledged that this is still a contested area. For example, it can be argued that implementation skills is part of the overall problem-solving process. We are agreeable to include it for the reason that it distinguish itself from other key competencies in its focus on “doing” that leads to integrated problem-solving.
- We agree with the views aired by Brundiers et al (2021) and Redman & Wiek et al (2021) that critical thinking is not considered a key competency. Rather, these authors opined that critical thinking is a basic academic competency developed in any educational program.
- All key competencies in sustainability are referenced as a framework as they are interdependent; each contributes its part to sustainability problem-solving processes (Brundiers et al, 2021).
- Lastly, and most importantly, we suggest that – in terms of the “quest” for a hierarchy of key competencies – there is more than one way to structure the various key competencies bounded by values thinking competency and integrated problem-solving competency,

Values thinking competency is considered the underpinning competency that holds together all other key competencies. It particularly had a strong influence over interpersonal and intrapersonal competencies; and collectively they guide the development of the next 3 key competencies, namely: strategic thinking, future thinking, and systems thinking; which in turn, drives the implementation competency leading to the integrated problem-solving competency.

In our model, we argued that these 3 key competencies (strategic thinking, future thinking, and systems thinking) mutually influence one another when addressing sustainable development issues; and often requires several iterations (shown as double-headed arrows in Figure 4) to arrive at an optimal solution before proceeding to the implementation stage. Hence, we suggested that the competencies suggested by Kassel et al (2016) pertaining to the “Doing” dimension of Sustainability Mindset – notably Proactive Glocal Sensitivity (under the area of Emotional Intelligence) and Protective/Restorative Action (under Ecological Word – should be considered specific areas to be addressed by the integrated problem-solving competency. Similarly, the Stakeholder Competency under Systems Perspective and Contemplative Practices under Spiritual Intelligence (Kassel et al, 2016) and be examples of specific areas under interpersonal competency and intrapersonal competency respectively. We argued that the formulation of these strategies should synergistically and simultaneously involve several key competencies for sustainability – strategic, systems thinking and futures thinking – depending on the nature of sustainability issue to be addressed.

DISCUSSION

We acknowledged that the search for key competencies will continue unabated. We believe our model is a first of its kind that attempted 2 things. The first is to reconcile the theoretical underpinning of sustainability mindset principles to the development of key competencies for sustainability. This is achieved via the use of CDIO Syllabus. The second is to operationalize the key competencies for sustainability using the CDIO Standards.

Taken together the CDIO Framework enable us to arrive at a plausible approach to integrate ESD into any educational program; by leveraging on the context-independence nature of key competencies for sustainability that "translate" (via the CDIO Standards) the more generic competencies (from the CDIO Syllabus) into context-specific scenarios where disciplinary knowledge is used alongside skills and attitudes to address sustainability issues. We believe this approach will help to reconcile the decontextualized nature of key competencies which are meant to drive curriculum design on one hand, and the necessity for context to be integrated when operationalizing these competencies. As noted by Ploum et al (2017): "Sustainability challenges and tasks often become meaningful in one's specific work environment".

Grounded solidly in the CDIO Standards, Figure 3 serves as a useful starting point for any program owner to consider how best to utilize the courses within the given program to develop students' sustainability mindset. Figure 4 provides broad guidance to structure the skills and attitudes development needed for key competencies for sustainability, emphasizing the development of skills, in a progressive manner over the program duration. For example, underpinning knowledge to be covered in year 1 (not exhaustive) would include: (2.4.5) *Demonstrate Critical Thinking*, especially in teamwork and collaboration, e.g. (3.1.2) *Manage and Participate in Teams*, (3.2.1) *Design Appropriate Communication Strategy* and (3.2.2) *Design Appropriate Communication Structure* (3.2.2), and values and attitudes such as (2.5.5) *Demonstrate Respect for Equity, Justice, Diversity and Inclusiveness*, (4.1.1) *Identify Roles and Responsibility of Engineers or Other Professionals*, (4.1.5) *Understand Contemporary Issues and Values*. The build-up will continue in subsequent years of study, for example (4.1.7) *Describe a Vision for the Future*, on to (2.4.2) *Demonstrate Perseverance, Sense of Urgency and Will to Deliver* and (2.5.6) *Exhibit Trust and Loyalty* etc.

We had earlier suggested that, based on Figure 4, after building up students' values thinking, interpersonal and intrapersonal competencies, a program can pursue different pathways to continue to build up students' strategic thinking, systems thinking and futures thinking competencies; instead of following a specific sequence. This can be based on specific nuances of the program seeking to integrate these competencies; for example, facility constraints, sequencing of courses, etc. Furthermore, different program may need different proficiency levels for different key competencies. For example, Wiek et al (2011) noted that key competencies would hold varying degrees of relevance to different cultural and academic contexts. Likewise, Mochizuki and Fadeeva (2010) commented that it is important that individual programs formulate their own competencies together with strategies for achieving these (Missimer & Connell, 2012; Brundiers & Wiek, 2017; Downs et al, 2017).

Figure 5 showed a hypothetical example of how the framework of Figure 4 can be operationalized, guided by the mapping between the SP-CDIO Syllabus version 3.0 and the underpinning skills and attitudes needed for key competencies for sustainability.

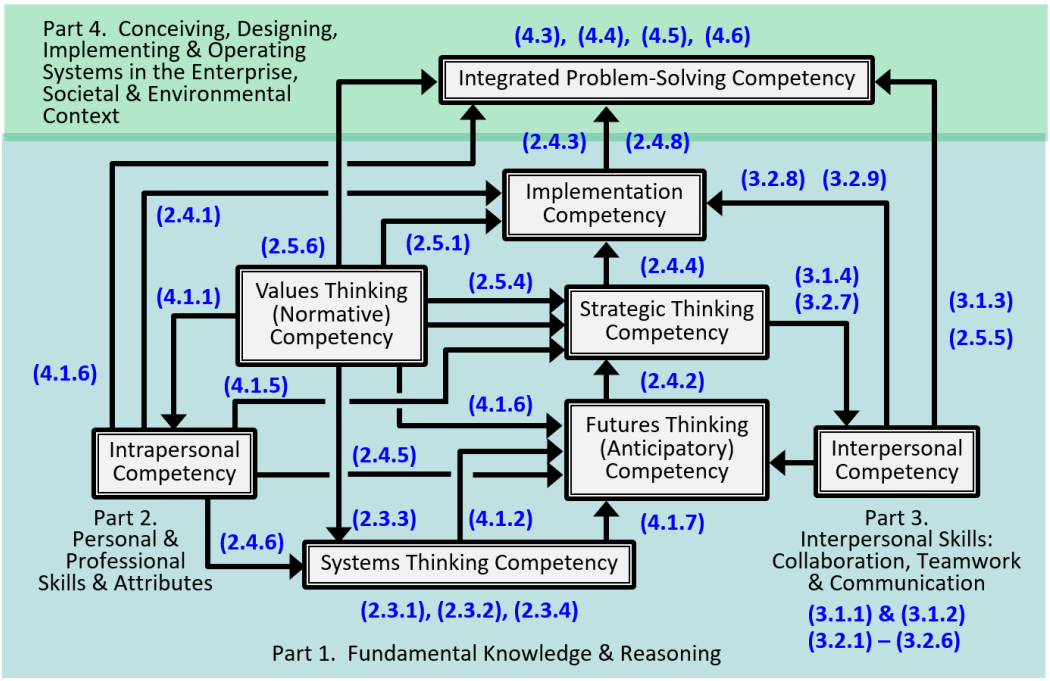

Figure 5. Possible Development Pathway to Integrated Problem-Solving Competency

In this manner, the model afforded program owner with the flexibility to sequence the development of strategic thinking, systems thinking and futures thinking competencies that best meet the program's overall learning outcomes. This approach also helped to avoid the dilemma of sequencing them in a rigid manner.

An example application of the model is provided by Yang & Cheah (2025), who shared how the suggested approach can be operationalized for the chemical engineering program, that had adopted the CDIO Framework as the basis for its curriculum redesign. The authors firstly established the relevant UNSDGs that the program seek to address, by conducting a gap analysis of coverage of selected UNSDGs following the adoption of the SP CCC. Ascertain the program's key competencies for sustainability needed to address the sustainability issues for the selected UNSDGs, and the required proficiency levels of each. The program then leverage of the foundational skills and attitudes already developed via the SP CCC, and identify core modules to further deepen the required proficiencies using the CDIO approach. A development pathway can then be designed that progressively develop the required proficiencies, using the underpinning skills and attitudes such as critical and creative thinking, teamwork, collaboration and communication, ethical reasoning, etc.

Usefulness of the Model

We believe our proposed model is useful in addressing the risk of key competencies for sustainability being compiled into a "laundry list" as other authors/researchers proposed new items based on their work. This can be illustrated with an example. A new entry termed "transboundary competence" is suggested by de Kraker et al (2007) for transdisciplinary collaboration to address sustainability issues. By inspecting the underlying skills and attitudes for the competency, we argued that this competency can be considered part of interpersonal competency – an "existing" key competency for sustainability, rather than a new, separate key competency. In this manner, the model (Figure 3) offers us the flexibility to continually refine it as "new" competencies were proposed; and the interrelationship between the competencies clarified (Figure 4).

As another example, Brundiers & Wiek (2017) called for the inclusion of a set of professional competencies with 6 domains, namely collaborative teamwork, effective and compassionate communication, responsive project management, advanced continuous learning, preventative self-care. The process outlined in this paper can provide guidance on where and how the set of professional competencies can be situated.

During the course of our effort to investigate the relationship between the key competencies for sustainability, we also came across various publications where specific work context is highlighted to derive competencies needed for a particular job role. Examples include entrepreneurship (Ploum et al, 2017; Lans et al, 2014), and research (Venn et al, 2022; Lambrechts & Van Petegem, 2016), where the respective author(s) suggested that these are competencies needed for work-related sustainability, and henceforth should be included in the list of competencies for sustainability. Venn et al (2022) also proposed a new, overarching sustainability intervention competency for sustainability professionals – defined as professional practitioner who secures his/her livelihood by contributing to sustainable development and taking stewardship for the profession – which consists of interpersonal collaboration competency, capacity building competency, intrapreneurial competency, strategic competency, political competency and implementation competency. These authors argued that the experience of practitioners who successfully operated in the field of sustainability is valuable, since it transcends the perspective of students and educational experts. This can help to mitigate the risk of gaps between what is taught in higher education and what is needed in practice.

Hence, despite the apparent convergence, there remained challenges as new articles appeared that calls for more “new” competencies to be added. This will once again run the risk of creating another “laundry list”, but now it is for key competencies for sustainability! This is perhaps unavoidable, given the complex and cross-cutting nature of competencies needed to address sustainability challenges. Coupled with the diverse conceptualizations of competencies, it is impossible to capture and define the required competencies for sustainability (Mochizuki & Fadeeva, 2010). Wilhelm et al (2019) charged that because of the fundamental context-boundedness of competences, trying to compare competence models developed in different contexts and based on different understandings of the role of education does not make it possible to answer the following question: “What competences are key competences for sustainable development?”

While we agreed that these work-related competencies are definitely necessary for the specified job role, whether they can be considered key competencies is debatable. Mochizuki & Fadeeva (2010) noted that “we need a democratic, deliberative and situated process of first specifying desirable competences (by asking whose needs and desires are being addressed for what purposes in what kinds of world) and then carefully articulating them in educational programs. Along this line of reasoning, we posit that the “work-related” competencies (e.g. entrepreneurship, research) are still generic in nature – much along the line why critical thinking is considered a generic competency – and applied in the CONTEXT of the job requirements.

Limitation of Our Work

We did not systematically search for publications related to key competencies for sustainability. We rely on seminal contributions from Barth et al (2007), Frisk & Larson (2011), and Wiek et al (2011, 2015) as starting point. We looked up the cited references from these articles to gain better understanding of work done.

For more recent publications, we relied on Google Search, using returns from various databases for the articles, rather than systematically searching for articles using Web of Science, SCOPUS, ScienceDirect and the like. We also did not apply any search criteria to refine the entries returned by Google Search. Instead we just read the abstracts and continue to read the full paper if its abstract looked promising; and we made a call on whether an article is to be included in our study or otherwise. We acknowledged that we could have missed out important articles that was not found by Google Search.

Another limitation is that our literature search omitted publications related to *sustainability science*, to explore its relationship with sustainability mindset and sustainability competencies. The name sustainability science implies that it is a science of sustainability – a scientific effort specifically oriented to produce sustainability, as compared to basic sciences which can be utilized to advance sustainability, i.e. science for sustainability (Spangenberg, 2011). Today sustainability science is usually understood as research providing the necessary insights to make the normative concept of sustainability operational, and the means to plan and implement adequate steps towards this end (Spangenberg, 2011).

Moving Ahead and Future Works

Our analysis of underpinning skills and attitudes for competencies for sustainability did not cover the "extended" section of the CDIO Syllabus, namely Leadership, Entrepreneurship and Research. As noted above, our current position is to consider these as generic competencies that can be adapted to the work-related context; rather than key competencies for sustainability per se.

At the time of this writing, each of the 4 diplomas had respectively embarked on developing sustainability mindset of their students in selected module(s). Each diploma is at a different stage of introducing key competencies for sustainability using the approach outline in this paper. Other works that can further enhance the current integration efforts include:

- Deep dive into the literature on sustainability science, to better understand how this emerging discipline can further strengthen the integration of key competencies for sustainability into a program
- Evaluation of students learning experiences
- Assessment of development of sustainability mindset

There is also a need to strengthen the linking of sustainability mindset principles to key competencies for sustainability. Our harmonization effort between the 12 sustainability mindset principled and CDIO Syllabus (Figure 2) revealed, perhaps not surprisingly, that the "weakest link" appears to be more on the "inner transition" aspects of the persons whose sustainability mindset we wished to develop. Many of the underpinning skills and attitudes need to be inferred from the CDIO syllabus; as they are largely written from the perspective on requirements of job roles or task requirements. Intrapersonal competency is a relatively new concept being added to the ESD literature, which increasingly turn to an individual's inner dimension and how it affects one's view on sustainability issues (Frank, 2021). It can be argued that without the transition of the self, one cannot be the change agent (Ayer at al, 2023) that advocates for the needed transformation towards a more sustainable world. As argued by Libertson (2023), lack of satisfactory progress in sustainable development can be due to a disconnect between the self, others and the environment. There is a need to revisit the mapping as more research on this topic emerges; and how to develop them in students.

Lastly, there is also a need to address the continuing professional development for the rest of our colleagues; when the development of sustainability mindset is cascade to more programs in SP. Following the United Nations Economic Commission for Europe, Wals (2014) suggested the use of ESD Competence as the educators' capacity to help others, referring to competence to facilitate the attainment of the key competencies for sustainability in students, through a range of innovative teaching and learning practices.

CONCLUSIONS

This paper synthesized the research from sustainability mindset principles and key competencies for sustainability to formulate an approach to integrate sustainable development into any educational program, based on the reasoning that sustainability mindset drives the empowerment of students to take positive actions to address sustainability issues; using a set of key sustainability competencies. The CDIO Framework is used to operationalize the key competencies for sustainability to progressively develop students' sustainability mindset via a model, that addresses current discourse on what constituted key competencies for sustainability and the need to arrange them in a hierarchical manner. Our model suggest that one first develop the values thinking competency with the end goal of developing integrated problem-solving competency. The model afforded the flexibility of each program to development of other key competencies consistent with the needs of the program. The usefulness of the model is discussed, notably how it can allow for new key competencies to be evaluated on the basis of the intent based on the CDIO Syllabus, if one to be added or subsumed into existing key competencies; to avoid generating a "laundry list" of key competencies.

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