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# Systems Thinking, Systems Design and Learning Power in Engineering Education*

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Educating Engineers in systems thinking and systems design require an approach to teaching and learning in which the purpose is to achieve competence rather than to acquire specialised subject knowledge, abstracted from its socio-technical context. Such an approach is structured by context-driven enquiry, supported by learning power, positioned at the interface of knowledge generation and use, and grounded in a commitment to sustainable development. Rather than beginning with pre-defined abstract subject knowledge, the students begin with an engineering problem in a particular territory or a place, and develop a systems architecture, a holistic way of defining that territory, which facilitates synergy as well as analysing performance. In order to do this, students need to be able to uncover the different knowledge systems through which their territory can be perceived and known, and explore the different parameters and measurements which can be applied to them. Such 'systems architecting' cannot be achieved through rote learning or the cognitive application of pre-defined knowledge, since by definition the solution to the problem to be solved cannot be known in advance. Rather it depends on the ability to learn, and to progress through an open-ended, formative, dynamic learning process. It is framed by a selected purpose, fuelled by learning power (including creativity, meaning making, curiosity and resilience) and co-generated through knowledge structuring processes. It begins with experience and observation and concludes with a product which is a unique application of knowledge for a particular engineering purpose. One of the challenges of technology enhanced learning is how to integrate learning design in an architectural framework which leverages mobile, social and 'big' data to enhance the processes and social relationships of learning, rather than simply providing information or evaluating outcomes. The approach presented in this paper outlines what can be understood as 'learning design principles' which support the development of semantic web applications, through the application of learning power and knowledge structuring processes. A pilot study demonstrates that students who successfully undertook an assignment requiring the development of a systems architecture increased in the strategic awareness—a key dimension of learning power. This small pilot study makes a contribution to the debate about the education of Chartered Engineers characterised "by their ability to develop appropriate solutions to engineering problems, using new or existing technologies, through innovation, creativity and change" (UK Engineering Council)

**Keywords:** systems designing; creativity; engineering education; knowledge structuring processes; learning power; identity; learning architecture; systems thinking; systems engineering

## 1. Introduction

The purpose of this paper is to explore how educating Engineers in systems thinking and systems design requires an approach to teaching and learning in which the purpose is to achieve competence in systems thinking rather than to acquire specialised subject knowledge, abstracted from its socio-technical context. Such an approach is structured by context-driven enquiry, supported by learning power, positioned at the interface of knowledge generation and use, and grounded in a commitment to sustainable development. Rather than beginning with pre-defined abstract, subject knowledge the students begin with an engineering problem in a particular territory or a place, and develop a systems architecture, a holistic way of defining that territory, which facilitates synergy as well as analysing performance. In order to do this, students need to be able to uncover the different knowledge systems through which their territory can be perceived and known, and explore the different parameters and measurements which can be applied to them. Such 'systems architecting' cannot be achieved through rote learning, or the cognitive application of pre-defined knowledge, since by definition the solution to the problem to be solved is not known in advance. Rather it depends on the ability to learn, and to

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progress through a formative, dynamic learning process which draws on higher order creative and critical thinking that begins with experience and observation and concludes with a product which is a unique application of knowledge for a particular engineering purpose.

Such a process is profoundly inter-disciplinary—since it is embodied, placed and contextualised around a particular purpose or purposes, some of which may be implicit. The knowledge systems which are uncovered in relation to it are technical, human and social and may be mathematical, linguistic, cultural, mechanical, visual, ethical and many more. It is also a process which directly influences how human beings interact with the world, because its outcome is a particular solution to a problem, selected from multiple alternatives—sometimes described as situational improvement. As such it is implicitly ethical—it can either inhibit or sustain life. We argue that systems thinkers—and their educators—need to be aware of, and able to take responsibility for developing their own ability to learn in order to successfully and mindfully lead themselves and others through this process. We report on a pilot study of fourth year engineering students in a 'Sustainable Systems' teaching unit, who undertook an assessment of their own learning power prior to their assignment, and a sub sample who undertook a post-test to measure change. Indeed, the purpose of the study was to explore and develop a systems architecture or design for the sort of learning system which best facilitates systems thinking and systems designing in student Engineers. The core process for this is shown in Fig. 1.

## 2. Rationale

There have been numerous publications and reports in recent years which call for higher education reform, particularly in engineering education [1–5]. Several reports have drawn attention to the widening gap between the competencies of young people and those needed in the information society [6] and many voices have identified concerns about the fragmented and disjointed curricula of higher education and how the world of education—from schools to universities—is governed by the inert, fragmented world of the narrowly chosen printed word, of the memorising of second hand information, of performance for the sake of performance and examination for the sake of examination [7–12]. The calls for reform in Engineering include a reconstruction of the connectedness and cohesiveness of engineering knowledge, education in systems thinking and design, enquiry based learning, experiential learning and community service [13, 14]. The changing nature of the material condition of humanity in relation to technology and information and the severe demands on our ecological, social and economic systems, mean that radical changes are required if future engineers are to be equipped by their education to integrate an appropriate response to these challenges with engineering solutions.

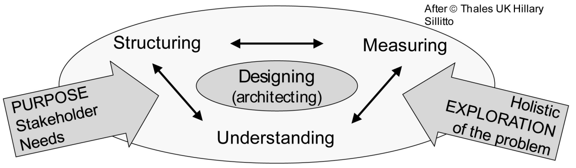
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**Fig. 1.** Complex Systems Design—Core Process.

These changes are reflected in the UK Chartered Engineer [15] Standard which focuses on the ways in which Engineers should 'act in the world'. These are set out as competencies which are sustained throughout an Engineer's working life and include the application of general and specialist knowledge to the application of existing and emerging technologies, problem solving, leadership, effective interpersonal skills and ethical commitment to professional standards. Clearly this is more than simply the accumulation of specialist knowledge—it includes intra and interpersonal orientations and commitments and the ability to apply these, as well as specialist knowledge, in the service of engineering solutions. The challenge is how to shape the contexts in which Engineers learn (both the University and the workplace) so that these qualities and capabilities constitute both the process and the product of that learning. Much has been done to address these issues at Engineering Faculties of UK Universities, including Bristol. But more is needed to change if this is to be embedded in Engineering Education generally [16].

## 3. Systems thinking and design

One important response to these conditions is to educate Engineers in systems thinking and its applications to problem structuring and solutions. Systems thinking is an approach which facilitates the integration of people, purpose, process and performance because it is a framework for seeing and working with the whole(s), rather than only the individual part, and for seeing the inter-relationships between parts [17, 18]. It enables the interrogation of a territory through relating systems to their environment and to each other and for understanding complex problems. Through taking the whole system (and its sub-systems) into view it helps to maximise outcomes and minimise unintended consequences. Significantly it transgresses the traditional boundaries between knowledge domains—particularly the empirical analytical, hermeneutical and emancipatory interests through which humans make sense of their world and experience [19–22]. Systems thinking is the 5th discipline for Senge's [23] model of a learning organisation.

Systems methodologies include a variety of strategies for knowledge construction and modelling complexity. A suite of tools, such as hierarchical process modelling; dynamic process modelling and so on, and models such as that developed by Blockley et al. [24]—thinking in loops, layers and processes—provide strategies and scaffolding for capturing and re-presenting a range of systems, sub-systems, their properties and the relationships between them. In learning contexts, a more simple model traces the journey from personal choice, through a series of nine recursive thinking and learning capabilities, through observation, generating questions, uncovering narratives, knowledge mapping, resourcing, negotiating assessment criteria, evaluation and application [25] whilst Benjamin's [26] Arcades project is perhaps the earliest version of this 'context driven' methodology.

These knowledge structuring processes facilitate individual and collective sense-making and problem solving. Such strategies are crucial in the conditions of complexity which face most Engineers (and arguably all professionals) because under these conditions individual and collective cognition are stretched to the limit as people engage in sense-making [27], namely the construction of plausible narratives around emergent patterns. Knowledge structuring strategies replace the acquisition and repetition of abstract, pre-defined knowledge which is often the traditional fare of the academic curriculum, because they enable the collection, interrogation and re-presentation of data generated in a real context and re-organised and re-defined towards a novel solution.

## 4. Learning power—for scaffolding systems design

However uncovering and structuring knowledge systems are only one of the dynamic processes which educators must integrate into their learning design. Another is the more personal and social process of learning— how an individual engages with the opportunities offered by a new learning opportunity—or how they mobilise their learning power. This requires particular personal qualities—the dispositions, attitudes and values that an individual needs in order to mindfully negotiate a learning pathway through the complex process represented by a new learning opportunity. 'Systems architecting' is by definition a highly sophisticated learning opportunity because, in Bauman's [28, p139] words, it is 'a formative process which is not guided from the start by the target form designed in advance'. The product is an authentic event—a new solution to a real problem—which the systems engineer arrives at through this dynamic process of learning.

These personal qualities are sometimes called learning power—a multi-dimensional construct that has come to be used widely in educational contexts in the last ten years. It is derived from literature analysis, and interviews with educational researchers and practitioners about the variables, which in their experience, make good learners. The seven dimensions represent dispositions for learning, and together harness what is hypothesised to be "the power to learn"—a form of consciousness, or critical subjectivity [29, 30] which leads to intentional learning, change and growth.

An extensive literature review informed the development of a self-report questionnaire called *ELLI (Effective Lifelong Learning Inventory)* whose internal structure was factor analysed, and validated through loading against seven dimensions [29]. These dimensions have been since validated with diverse learner groups, ranging in age from primary school to adults, demographically from violent young offenders and disaffected teenagers, to high achieving pupils and professionals, and culturally from middle-class Western society to Indigenous communities in Australia [31]. The inventory is a self-report web questionnaire comprising 72 items in the schools version and 75 in the adult version [32]. It measures what learners say about themselves in a particular dimension of learning power at a particular point in time. A brief description of the seven dimensions is set out below, with three examples from the questionnaire shown for each dimension:

*Changing & learning*: Effective learners know that learning itself is learnable. They believe that, through effort, their minds can get bigger and stronger, just as their bodies can and they have energy to learn (cf. [33]). The opposite pole of changing and learning is 'being stuck and static'.

*I expect to go on learning for a long time.*
*I like to be able to improve the way I do things.*
*I'm continually improving as a learner.*

*Critical curiosity*: Effective learners have energy and a desire to find things out. They like to get below the surface of things and try to find out what is going on. The opposite pole of critical curiosity is 'passivity'.

*I don't like to accept an answer till I have worked it out for myself.*

*I like to question the things I am learning.*
*Getting to the bottom of things is more important to me than getting a good mark.*

*Meaning Making*: Effective learners are on the lookout for links between what they are learning and what they already know. They like to learn about what matters to them. The contrast pole of meaning making is 'data accumulation'.

*I like to learn about things that really matter to me.*
*I like it when I can make connections between new things I am learning and things I already know.*
*I like learning new things when I can see how they make sense for me in my life.*

*Dependence and Fragility*: Dependent and fragile learners more easily go to pieces when they get stuck or make mistakes. They are risk averse. Their ability to persevere is less, and they are likely to seek and prefer less challenging situations. The opposite pole of dependence and fragility is 'resilience'.

*When I have trouble learning something, I tend to get upset.*
*When I have to struggle to learn something, I think it's probably because I'm not very bright.*
*When I'm stuck I don't usually know what to do about it.*

*Creativity*: Effective learners are able to look at things in different ways and to imagine new possibilities. They are more receptive to hunches and inklings that bubble up into their minds, and make more use of imagination, visual imagery and pictures and diagrams in their learning. The opposite pole of creativity is 'being rule bound'.

*I get my best ideas when I just let my mind float free.*
*If I wait quietly, good ideas sometimes just come to me.*
*I like to try out new learning in different ways.*

*Learning Relationships*: Effective learners are good at managing the balance between being sociable and being private in their learning. They are not completely independent, nor are they dependent; rather they work interdependently. The opposite pole of learning relationships is 'isolation and dependence'.

*I like working on problems with other people.*
*I prefer to solve problems on my own.*
*There is at least one person in my community/social network who is an important guide for me in my learning.*

*Strategic Awareness*: More effective learners know more about their own learning. They are interested in becoming more knowledgeable and more aware of themselves as learners. They like trying out different approaches to learning to see what happens. They are more reflective and better at self-evaluation. The opposite pole of strategic awareness is being 'robotic'.

*If I get stuck with a learning task I can usually think of something to do to get round the problem.*
*If I do get upset when I'm learning, I'm quite good at making myself feel better.*
*I often change the way I do things as a result of what I have learned.*

## 5. Learning power and identity

The ELLI Inventory is an assessment tool which was designed to stimulate awareness, ownership and responsibility for learning [34] The feedback from the questionnaire is powerful because it provides a framework for mediated self-reflection—who am I as a learner and where do I want to go? Sfard and Prusak, [35] define identities as 'collections of stories about persons that are 'reifying, endorsable and significant' and argue that a person's stories about themselves are profoundly influenced by the stories that important others tell about that person. The importance of this in understanding the challenges of educating in systems thinking for Engineers is that identity talk—i.e. reifying statements such as 'I am an Systems Engineer', or 'You are a creative systems thinker'—enables people to engage with new challenges or opportunities in terms of their past experiences and it locates learning within a community of practice, where learning is a collaborative endeavour. The aspiration of a professional community such as Engineers, to learn together and to become 'systems thinkers' is an important element in the process, because without this aspiration and affirmation, it is more challenging to face the uncertainty, challenge and open-ended nature of systems architecting—both for educators and students. This is particularly the case in traditional and conflicted pedagogical contexts. Figure 2 shows the relationships between identity, learning power, specialist knowledge and competence, four inter-related personal/social learning systems which need to be accounted for in the learning design of educators for systems thinking and its application in the Engineering solutions [36].

## 6. Educating as 'learning design'

In terms of the approach to learning and teaching required to develop systems thinkers, a traditional, transmission orientation to teaching, in which the expert simply presents their knowledge to students is necessary but not sufficient, because it does not attend to the more personal aspects of learning, nor to the student's authentic application of specialist knowledge in the world. To become a systems

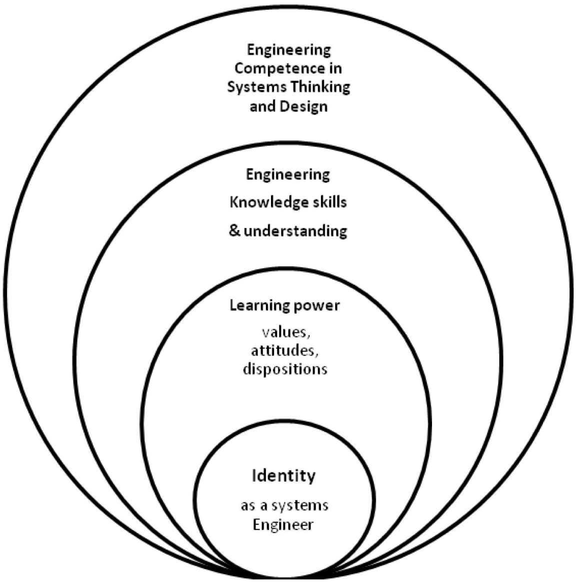


**Fig. 2.** Learning as a Complex, Dynamic Process.

thinker, capable of co-generating sustainable solutions in Engineering contexts, an individual needs to mindfully respond to their own learning process integrating personal development with their professional performance in real contexts. The purpose is to develop competence, integrating (rather than at the expense of) specialist knowledge in such a way that it equips the Engineer to continue as a learner, open to new approaches and to the unknown. A competent systems thinker will select appropriate specialist knowledge to serve a particular purpose. They will be self-aware, responsible lifelong learners, open to new ideas and what is not yet known.

The challenge of the process of acquiring specialist knowledge has to do with the sequencing of the students encounter with that knowledge—is it presented in pre-scribed format, in the neutral context of the lecture theatre or do they research, identify and generate the knowledge they need in the process of systems architecting. The starting point for the former is abstract knowledge and the movement is towards its application in an authentic context. The latter begins with an authentic context and purpose and moves towards abstract concepts and representations of knowledge. In Fig. 3 this is presented as a Knowledge/Agency Window where this movement forms the vertical axis. The horizontal axis is the development of personal competence in systems architecting in authentic contexts. The movement here is from the student being dependent on the tutor or texts for expert knowledge towards the student utilising their learning power and knowledge structuring processes in order to achieve solutions to authentic Engineering problems.

The learning design challenge for educators of systems engineers is how to enable students to move easily between each of the Knowledge/Agency windows with the ultimate purpose of becoming capable of leading problem solving teams in authentic Engineering contexts. However a great deal of traditional university education, and particularly

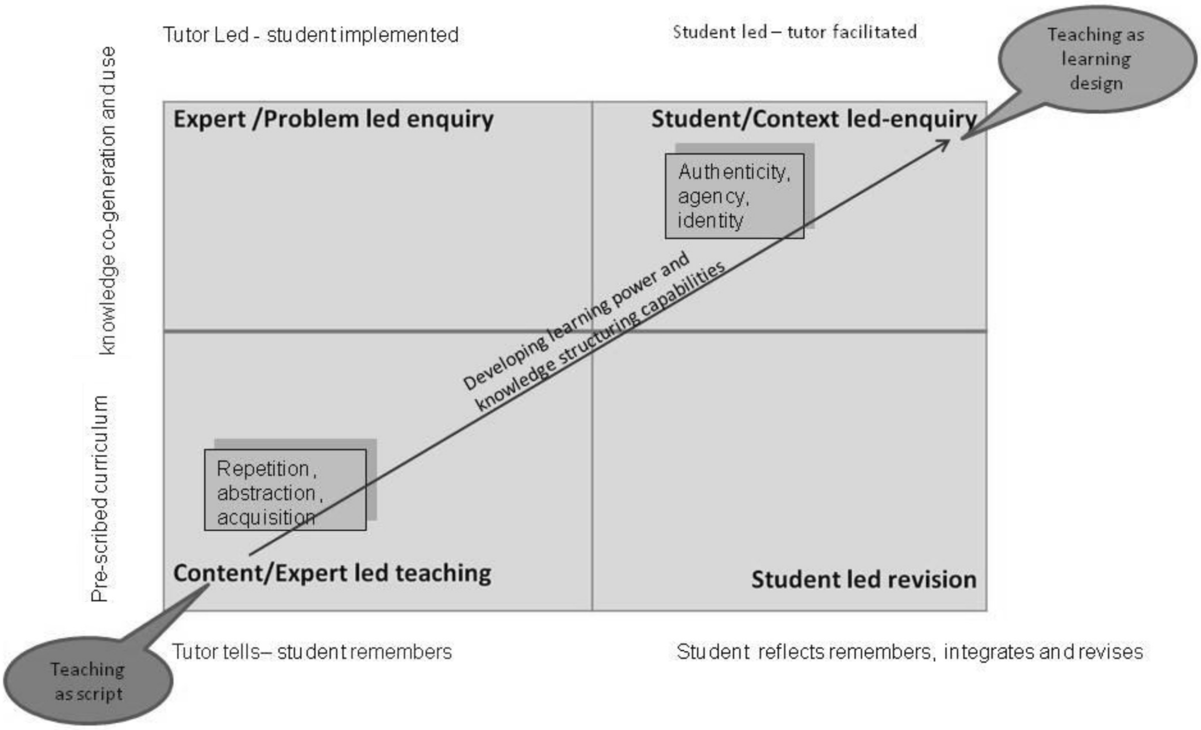


**Fig. 3.** Knowledge Agency Window.

its assessment regimes, remains in the bottom left quadrant, effectively suppressing the sorts of experiential and authentic enquiry required in industry contexts, where in practice Engineers have to learn from unordered, sometimes chaotic, complex information, in their every day work.

## 7. Sustainable systems unit

Design and critical thinking is implicit throughout the Engineering teaching courses at Bristol with students facing incomplete and fuzzy problems which require creative thinking right from the start in the first year. Building on this approach the Systems Centre at the University of Bristol offers a Masters level teaching unit, Sustainable Systems, aimed at fourth year Engineering Students. The purpose of the unit is to empower the Engineers to select, develop and apply an appropriate systems architectural framework to assess and improve the sustainability of a chosen target—a territory or place which presented an Engineering problem to be addressed. The learning outcomes from this unit are (i) to demonstrate a thorough understanding of the key challenges inherent in changing complex systems to become more sustainable (ii) to select and establish a measurement regime for a specified complex sustainability problem (iii) to select, develop and apply an appropriate systems architectural framework for the specified complex problem (iv) establish an implementation process that will recognise unintended consequences and provide opportunities for significant improvement in systems performance through synergy and (v) to demonstrate creative and innovative thinking in systems design. The unit was designed using the Bristol generic systems model, which relates an analysis of stakeholder needs to fundamental knowledge.

The unit, which takes place over a week, includes several traditional lectures from academic experts and professional engineers. Lectures are interspersed with debate, role-play, a sustainability game and coached formative exercises. Contact time available is 36 hours made up of 24 hour lectures, 8 hours of seminar and 4 hours of the sustainability game which is an experiential learning activity based on a systems dynamics model of the sustainability of fish stocks [37]. The formal teaching is followed up with an uncompromisingly challenging assignment to use systems thinking to improve the sustainability of a major project or industry. The assignment is intended to be completed in 65 hours. The syllabus is shown as Table 1. All lectures were recorded voice over visual aids and made available on the intranet to assist reflection and reinforce learning.

Each student chooses an assignment from the list shown on Table 2 and is required to:

1. Select and establish a sustainability measurement regime for their selected target project.
2. Select, develop and apply an appropriate systems architectural framework to assess and improve the sustainability of the target.
3. Establish an implementation process that will recognise unintended consequences and opportunities for synergy improvement

## 8. Managing blocks to learning

Throughout the assignments the students are encouraged to ask questions by email and all questions and answers are published back to all students, as they occurred. This facilitates *learning together*

Table 1. Syllabus of sustainable systems unit

| | |
|---|---|
| Bio-fuels debate | |
| What are systems? | |
| What is sustainable? | |
| Entering the ecological age | |
| How engineers deal with sustainability | |
| Evidence based decision-making—a practical case study | |
| Systems architecture, viewpoints and process mapping | |
| Understanding systems architecting frameworks | Group Exercise |
| Architecting systems | |
| Sustainable systems in defence | |
| Sustainability Game—Gone Fishing! | Facilitated group activity |
| Measures and metrics | |
| Creating sustainable buildings | |
| Qualitative research methods | |
| Using models and tools | Group Exercise |
| Management and delivery of sustainable systems | |
| Sustainable Transport—case study | |
| How to make a difference | Talks by 3 young engineers |
| Systems integration of your assignment | Reflections |
| NB: class exercises integrated into lectures are not shown. | |

The assignment report is limited to 10 pages, 2 of which can be A3.

**Table 2.** List of assignment topics to improve sustainability

| Countries | Haiti | Institutions/ companies | NHS |
|---|---|---|---|
| | Afghanistan | | Supermarket Chain |
| **Mega projects** | 3 Gorges dam | | BP |
| | Crossrail, London | | University |
| | Olympics | **Leisure** | F1 Motor sport |
| | Aircraft carrier | | Rugby World Cup |
| | Airbus A380 | | Eden Project |
| **Managing resources** | Polar Mineral Extraction | | Ski resort in Dubai |
| | Rainforest | **Infrastructure** | Nuclear Power |
| | Carbon capture, coal fired Power stations | | Air Transport |
| | Hydrogen Infrastructure | | Sustainable Tourism |
| | Eating Meat | | An eco-district |
| | Rare earth metals | | Internet infrastructure |
| | Euro currency | | |

and has enabled us to address some blocks to systems thinking. Three blocks are commonplace and reflect the students' scientific reductionist education:

1. Students focused on the purpose of the 'project' and understanding how, through stakeholder needs and requirements, this helps to form an architecting framework and measurement system. However they had difficulty applying the same design approach to the creation of the assignment report. The concept of a generic process seemed to be alien to some.
2. Some were concerned that the boundaries were too broad. They seemed to want to immerse themselves in the detail of a narrow aspect of the target subject or restrict the report to a single strand of sustainability e.g. Carbon emissions or food; missing the point that sustainability is derived from the interdependence of the issues.
3. In spite of encouragement to be creative and innovative, and a specific learning outcome requiring these attributes, some students were concerned that they would be marked down for not using a prescribed structure!

## 9. The pilot study: systems thinking and learning power

At the beginning of the unit all of the students were introduced to the concept of learning power and were invited to complete the ELLI Inventory which provided immediate, personalised feedback on the seven dimensions of learning power. Feedback was in the form of a simple visual analytic which is helpful when it comes to communicating a 7-dimensional construct such as learning power. On completion of an ELLI web survey, the Learning Warehouse generates a spider diagram (Fig. 4) providing a visualization for the learner to reflect on their perception of their own learning power. The scores produced are a percentage of the total possible score for that dimension. The spider diagram graphically depicts the pattern and relative strength of individual scores. Note that unlike most spider diagrams, the axes are not numbered, but labelled *A little like me, Quite like me*, and *Very much like me.* A visual analytic such as this has a number of important properties, which can be both empowering, but also potentially demoralising, and it is a principle behind the approach that learners are not left to ponder its meaning alone. The extent to which the learner validates and thus 'owns' the profile is a matter for the coaching conversation that follows with a trained mentor.

Students were facilitated in coaching each other and providing feedback aimed at supporting their learning process on the Unit. Sixty eight students completed their ELLI profiles before the Unit and a sub-group of seventeen completed a post unit profile. The attrition rate was due to the fact that the post-test was voluntary and took place after term

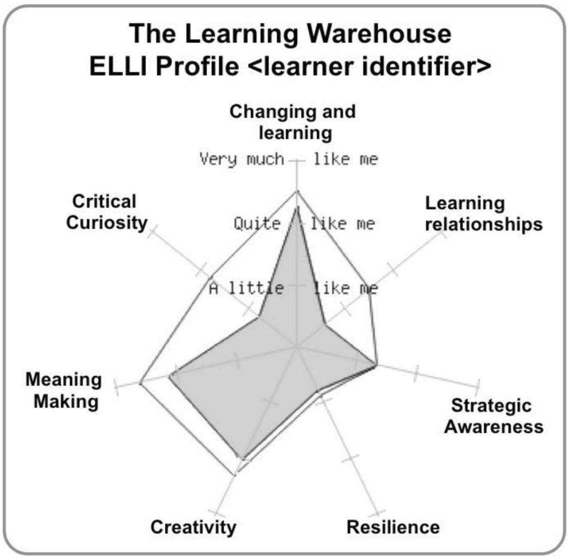


**Fig. 4.** An ELLI learning power spider diagram generated from the Learning Warehouse. The shaded region shows the initial profile, while the outer line profile indicates 'stretch' on certain dimensions later in the learning project.

had finished. The study explored the reliability and validity of the seven learning power scales in this population, describes the learning power characteristics of this cohort of students, and explores the relationship between learning power and learning performance in this unit. For the subset of students, an investigation into the degree of change in participants' learning power before and after taking this unit is also presented.

## 10. Data preparation and determination of valid cases

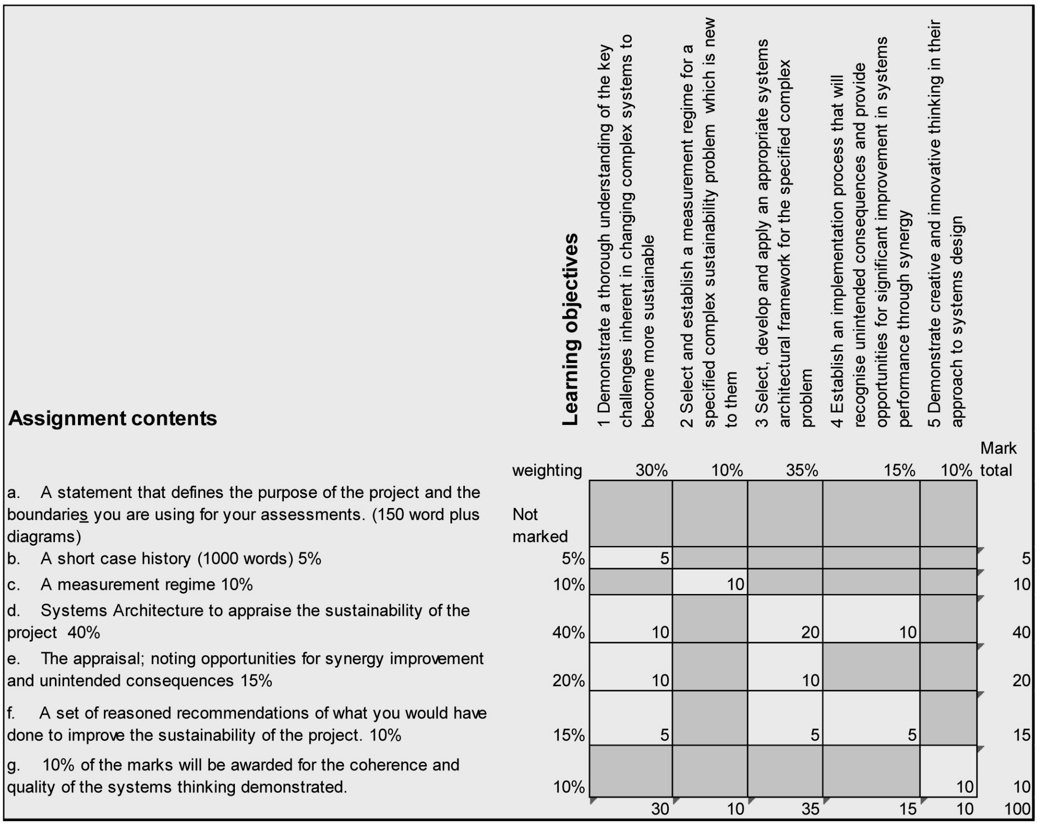
This analysis is based on a dataset drawn from three different sources: 1) marks the student participants achieved in their Sustainable System Unit, 2) basic demographic data collected at registration and 3) ELLI survey data. Eighty students had valid marks on their assignment which was structured in six

**Table 3.** Codes for marked assignment content

| Code | Assignment content marked |
|---|---|
| ACa | A short case history (1000 words) 5%. |
| ACb | A measurement regime 10%. |
| ACc | Systems Architecture to appraise the sustainability of the project 40%. |
| ACd | The appraisal; noting opportunities for synergy improvement and unintended consequences 20%. |
| ACe | A set of reasoned recommendations of what you would have done to improve the sustainability of the project. 15%. |
| ACf | The coherence and quality of the systems thinking demonstrated 10%. |

**Table 4.** Codes for learning objectives to be demonstrated in the assignment

| Code | Learning objectives |
|---|---|
| LO1 | Demonstrate a thorough understanding of the key challenges inherent in changing complex systems to become more sustainable 30%. |
| LO2 | Select and establish a measurement regime for a specified complex sustainability problem which is new to them 10%. |
| LO3 | Select, develop and apply an appropriate systems architectural framework for the specified complex problem 35%. |
| LO4 | Establish an implementation process that will recognise unintended consequences and provide opportunities for significant improvement in systems performance through synergy 15%. |
| LO5 | Demonstrate creative and innovative thinking in their approach to systems design 10%. |



| Assignment contents | Learning objectives | 1 Demonstrate a thorough understanding of the key challenges inherent in changing complex systems to become more sustainable | 2 Select and establish a measurement regime for a specified complex sustainability problem which is new to them | 3 Select, develop and apply an appropriate systems architectural framework for the specified complex problem | 4 Establish an implementation process that will recognise unintended consequences and provide opportunities for significant improvement in systems perfomance through synergy | 5 Demonstrate creative and innovative thinking in their approach to systems design | Mark total |
|---|---|---|---|---|---|---|---|
| | weighting | 30% | 10% | 35% | 15% | 10% | |
| a. A statement that defines the purpose of the project and the boundaries you are using for your assessments. (150 word plus diagrams) | Not marked | | | | | | |
| b. A short case history (1000 words) 5% | 5% | 5 | | | | | 5 |
| c. A measurement regime 10% | 10% | | 10 | | | | 10 |
| d. Systems Architecture to appraise the sustainability of the project 40% | 40% | 10 | | 20 | 10 | | 40 |
| e. The appraisal; noting opportunities for synergy improvement and unintended consequences 15% | 20% | 10 | | 10 | | | 20 |
| f. A set of reasoned recommendations of what you would have done to improve the sustainability of the project. 10% | 15% | 5 | | 5 | 5 | | 15 |
| g. 10% of the marks will be awarded for the coherence and quality of the systems thinking demonstrated. | 10% | | | | | 10 | 10 |
| | | 30 | 10 | 35 | 15 | 10 | 100 |

**Fig. 5.** Marking Criteria showing relationship between content and objectives.

parts. Five of the six parts were marked with an additional mark about the overall coherence and quality. These contents were coded as ACa to ACf in this analysis as shown in Table 3. The marking criteria also specify five learning objectives that are expected to be demonstrated in the assignment. These were coded LO1 to LO5 as detailed in Table 4. The relationship between the two marking criteria is shown in Fig. 5.

After merging marking data with survey and demographic data there were 68 valid cases. Of these, 17 students went on to complete a second learning profile four months after the first one, and after completing their assignments.

**Table 5.** Gender composition of the whole group.

| Gender | Frequency | Percent | Valid Percent | Cumulative Percent |
|---|---|---|---|---|
| **F** | 12 | 17.6 | 17.6 | 17.6 |
| **M** | 56 | 82.4 | 82.4 | 100.0 |
| **Total** | 68 | 100.0 | 100.0 | |

**Table 6.** Age composition of the group

| Age at 1 Feb 2011 | Frequency | Percent | Cumulative Percent |
|---|---|---|---|
| 21 | 16 | 20.6 | 25.0 |
| 22 | 37 | 54.4 | 79.4 |
| 23 | 9 | 13.2 | 92.6 |
| 24 | 3 | 4.4 | 97.1 |
| | 2 | 2.9 | 100.0 |
| **Total** | **68** | **100.0** | |

## 11. Demographic and assignment marks

There were 12 females and 56 males in the data set, aged between 21 and 26 years old. Tables 5 and 6 summarise the gender and age compositions of these 68 participants. These 68 participants received overall marks ranging from 44 to 89 with an average mark of 63.47 out of 100. Detailed breakdowns of marks received within sections of the assignment or marks relating to individual learning objectives are shown in Table 7.

## 12. Dispersion of learning power dimensions at time one

The mean scores for each learning power dimension were computed and are presented in Table 8.

## 13. Reliability and validity of learning power scales

In order to explore the internal reliability of each of the learning power dimension scales Cronbach's alpha coefficients were calculated. The result was compared with a previous study about the internal consistency of ELLI scales for a larger adult population reported in [31]. Cronbach's alpha values of 0.7 and higher are commonly taken as indicating good internal validity overall of a scale construct. The findings from this previous study yielded alpha reliability coefficients ranging between 0.71 and 0.81. That is, items forming each of the seven dimensions of ELLI were consistent in measuring

**Table 7.** Descriptive statistics for assignment marks

| Assignment contents or objectives | N | Minimum | Maximum | Mean | Std. Deviation |
|---|---|---|---|---|---|
| **Total** | 68 | 44 | 89 | 63.47 | 10.75 |
| **Assignment Content a** | 68 | 2 | 5 | 3.71 | 0.670 |
| **Assignment Content b** | 68 | 4 | 9 | 5.94 | 1.23 |
| **Assignment Content c** | 68 | 16 | 36 | 25.94 | 4.87 |
| **Assignment Content d** | 68 | 7 | 18 | 11.88 | 2.41 |
| **Assignment Content e** | 68 | 6 | 15 | 10.04 | 2.20 |
| **Assignment Content f** | 68 | 4 | 9 | 5.96 | 1.32 |
| **Learning Objectives 1** | 68 | 13 | 28 | 19.65 | 3.51 |
| **Learning Objectives 2** | 68 | 4 | 9 | 5.94 | 1.23 |
| **Learning Objectives 3** | 68 | 15 | 31 | 22.43 | 3.97 |
| **Learning Objectives 4** | 68 | 7 | 13 | 9.50 | 1.67 |
| **Learning Objectives 5** | 68 | 4 | 9 | 5.96 | 1.32 |

**Table 8.** Descriptives of t1 learning power dimension of the whole group

| | N | Minimum | Maximum | Mean | Std. Deviation |
|---|---|---|---|---|---|
| **changing and learning** | 68 | 33 | 100 | 68.82 | 16.10 |
| **critical curiosity** | 68 | 17 | 96 | 60.36 | 15.33 |
| **meaning making** | 68 | 30 | 100 | 70.69 | 15.87 |
| **creativity** | 68 | 19 | 89 | 50.65 | 16.42 |
| **learning relationships** | 68 | 7 | 93 | 61.62 | 18.48 |
| **strategic awareness** | 68 | 28 | 83 | 57.19 | 12.76 |
| **fragility and dependence** | 68 | 12 | 73 | 38.28 | 13.84 |

**Table 9.** Reliability test results, compared with previous study

| | Adult (19+) study in 2007† N = 942 | Whole group in the present analysis N = 68 | Sub-group in the present analysis N = 17 |
|---|---|---|---|
| **Changing and learning** | 0.76 | 0.63 | 0.75 |
| **Critical curiosity** | 0.77 | 0.69 | 0.72 |
| **Meaning making** | 0.71 | 0.76 | 0.74 |
| **Creativity** | 0.84 | 0.72 | 0.72 |
| **Learning relationships** | 0.81 | 0.79 | 0.88 |
| **Strategic awareness** | 0.84 | 0.68 | 0.70 |
| **Fragility and dependence** | 0.81 | 0.83 | 0.89 |

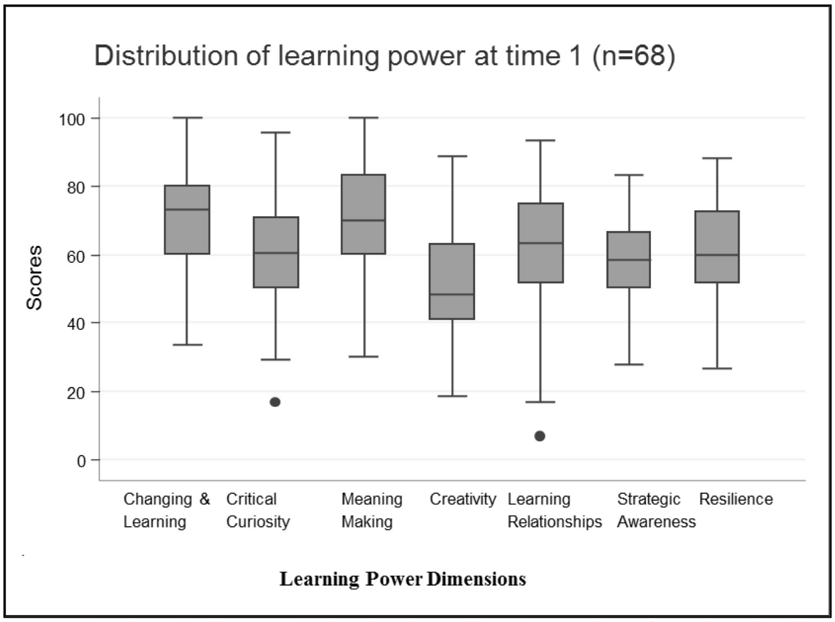
† Reported in [31].

the *same* underlying trait. The Cronbach's alpha coefficients from the present analysis using all 68 subjects range between 0.63 and 0.83. Analysis of the sub-group of 17 participants who completed the second ELLI profiles did demonstrate a good level of reliability in all seven learning power dimensions with alpha coefficients ranging between 0.70 and 0.89. Alpha coefficients for each of the seven learning power dimensions based on the whole group, the sub-group and the larger sample used in the 2007 study are listed in Table 9.

## 14. Differences between learning power dimensions

The mean scores for these 68 participants on each of the seven learning power dimensions vary. Figure 6 gives a visual account of the difference between dimensions. The fragility and dependence dimension is presented as resilience (reverse coded) to facilitate the reading of this diagram.

To explore whether these mean scores are significantly different from one another, a one-way ANOVA was conducted. The results indicate that there were significant differences between mean dimension scores, Wilks' Lambda = 3.17, F (6, 62) = 22.306, $p < 0.001$. Post hoc paired sample t-tests were conducted to determine which mean scores were different. The findings suggest that these 68 participants self-assessed as having significant strengths in the dimensions of meaning making, changing and learning, they self-assessed as good in the dimensions of critical curiosity, strategic awareness, learning relationships and resilience, but they identified a perceived significantly weakness in the dimension of creativity. Detailed results of these post hoc comparisons are given in Appendix One. It should be noted that this does not necessarily mean that these students are not creative—rather that they did not report themselves as creative, or identify with the language which the ELLI instrument measures this dimension.



Bars show Median score, 25th and 75th quartile, extreme values of sample, and outliers

**Fig. 6.** Differences between time 1 self-reported learning power dimensions.

**Table 10.** Changes on learning power dimensions between time 1 and time 2

| Learning power dimension | Time 1 | | | Time 2 | | |
|---|---|---|---|---|---|---|
| | 25th | 50th (Median) | 75th | 25th | 50th (Median) | 75th |
| changing and learning | 60.00 | 73.33 | 76.67 | 60.00 | 73.33 | 86.67 |
| critical curiosity | 50.00 | 62.50 | 70.83 | 56.25 | 66.67 | 77.08 |
| meaning making | 65.00 | 73.33 | 86.67 | 65.00 | 80.00 | 93.33 |
| creativity | 40.74 | 48.15 | 68.52 | 50.00 | 55.56 | 74.07 |
| learning relationships | 45.00 | 60.00 | 76.67 | 41.67 | 66.67 | 80.00 |
| strategic awareness | 50.00 | 61.11 | 68.06 | 56.94 | 69.44* | 80.56 |
| fragility and dependence | 29.17 | 40.00 | 48.33 | 24.17 | 36.67 | 49.17 |

* $p < 0.005$.

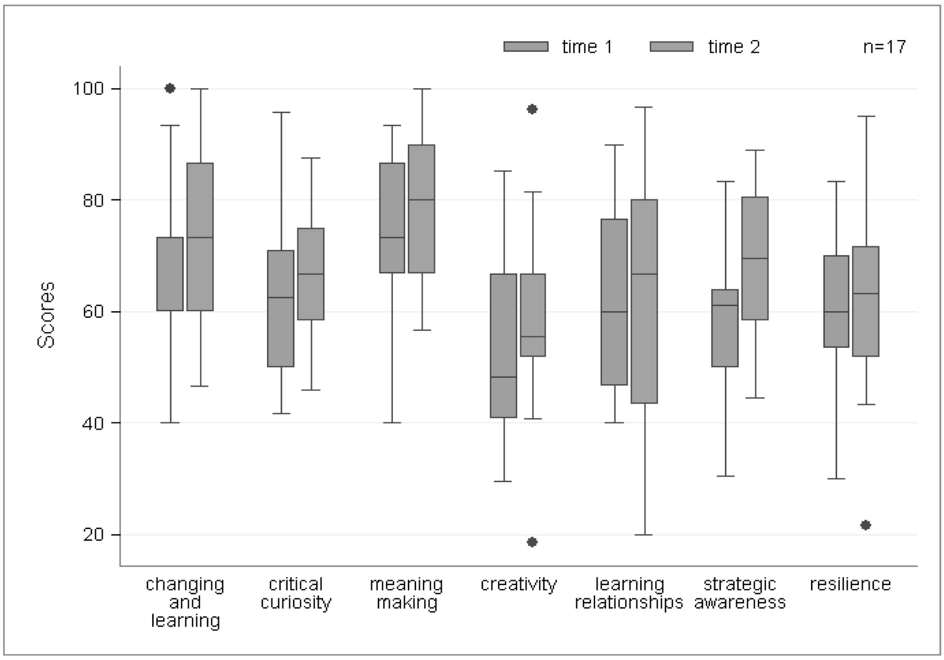
### *14.1 Changes in learning power between time 1 and time 2*

In the subgroup of 17 students, their second profiles show a general increase in learning power. A Wilcoxon Signed Rank Test revealed a statistically significant increase of the median score of strategic awareness from time 1 to time 2, z = –3.215, p < 0.005, with a large effect size (r = 0.78). This indicates that change on these 17 participants strategic awareness dimension was not by chance. Wilcoxon tests were also applied on other five dimensions including critical curiosity, meaning making, creativity, learning relationships and fragility and dependence to detect whether there was a statistically significant change in median scores between time 1 and time 2. The median scores of time 1 and time 2 profiles on each of the seven learning power dimensions are listed in the 10. The box plot in Fig. 7 compares the distribution of time 1 and time 2 profiles on each dimension. This also indicates a trend of growth on all dimensions.

Further analysis was carried out to examine the difference of characteristics of the subgroup of 17 students who took both pre and post-test and the other 51 students who only took the pre-test, the result shows that these two groups did not differ in time 1 or time 2 learning power, nor overall marks received for their assignment, but there was significantly higher proportion of female students in the subgroup than in the rest of 51. However, there was no significant gender difference in terms of their learning power at both times or of the change of learning power from time 1 to time 2.

## 15. Summary of findings

The analysis demonstrates that the ELLI learning power scales returned an acceptable level of relia-



Bars show Median score, 25th and 75th quartile, extreme values of sample, and outliers.

**Fig. 7.** Changes of mean scores in each of the seven learning power dimensions.

bility within this population on four of its seven dimensions. Reliabilities of the dimensions of *changing and learning*, *critical curiosity* and *strategic awareness* remained lower than 0.7 at time one, but at time two they reached an acceptable level.

The 68 participants as a cohort reported significant self-perceived strengths on the scales measuring *meaning making* and *changing and learning*, but significantly less strength in the scales measuring *creativity*. Pre and post comparison based on the sub-group of 17 participants suggests that over those four months they made a significant increases in their perceptions of themselves as learners on the scale measuring strategic awareness, which is an important learning power dimension.

## 16. Discussion

The growth in strategic awareness in the small sample of 17 students, with a large effect size, is significant and surprising given the sample size. The post-test was voluntary and after term had ended. However these students by definition were willing and able to engage in the practice of learning power and took advantage of the coaching conversations they were offered. The assignment which they were tasked with was open ended, and authentic—i.e. it was a genuine, real world engineering problem. It required them to negotiate their way through complex data, to identify a problem, and to explore ways of structuring that complex problem so that it could be re-presented in a way that could inform improvement. In an authentic context they would then have to persuade colleagues of the value of the improvement they proposed and thus be offering leadership, although in this context the process ended at the assessment event.

The task of problem structuring and systems architecting or designing requires the individual (and their team) to engage in learning, through a process of systematic data gathering, in a particular context or territory and for a selected purpose. Relevant data may come in many forms. If we take, for example, an assignment on the long term environmental, social, and economic aspects of Formula One Racing, at the first stage of the enquiry the student chose the domain, then identified the problem of sustainability in terms of $CO_2$ emissions. Next she identified relevant knowledge systems—which were technical, environmental, interpersonal, psychological, historical and more.
She analysed the 'holon's or subsystems relating to the domain. Following this she recursively developed a high level functional integrative architecture. What followed was an exploration of the reinforcing loops and boundary interactions between the subsystems, after which she moved on to develop a measurement system and make recommendations for improving sustainability.

The systems thinking processes into which students were initiated on the unit provided a variety of sophisticated knowledge structuring (or mapping) mechanisms which were tailored to this domain. What was also happening, and becoming visible for those students who chose to attend to it, was that they were necessarily developing their personal ability to learn—their learning power—at the same time. This began when they took responsibility for choosing a site for their enquiry and embarked on a self-selected learning pathway, fuelled by the purpose identified in the assessment specification—the sustainability of their chosen site. Their purpose, plus knowledge structuring (or mapping) mechanisms plus learning power enabled them to negotiate a pathway through the mass of data and pursue the process to a final product. Key milestones in the project pathway included:

- Taking responsibility for selecting a domain of interest.
- Identifying a significant problem.
- Negotiating a personally chosen pathway through a knowledge structuring process.
- Identifying and selecting relevant measurements
- Producing a meaningful result, on time.

Strategic awareness, as a key dimension of learning power, is about becoming self-aware as a learner and taking responsibility for one's own learning pathway. It is also about managing the processes of learning—knowing what to do next, or what to do if you don't know what to do—as well as managing the feelings entailed, which may range from excitement to confusion and despair. Negotiating a pathway towards a systems design or architecture requires learning power—in a real sense it is fuelled by the learning power of the individual or team who is driving the process. Creativity enables the identification of novel concepts or ideas, and the use of imagination and intuition. Meaning making facilitates an understanding of the connections between concepts and systems as well as alignment with purpose. Critical curiosity stimulates the interrogation of the different systems and the generation of a range of questions. Learning relationships facilitate synergy and support, whilst resilience is an outcome of a personal learning 'system' which utilises all of its learning power. In other words to be resilient, a person or team need to utilise their positive, active learning power dimensions in order to be able to adapt and respond to the challenges of the task. These are crucial qualities of interdependent and pro-active learners who are able to engage effectively with new learning opportunities and innovation possibilities, rather than simply being passive imbibers of expert knowledge from other people for the purpose of passing examinations.

The main limitation of this study is that it was a small pilot, optional at post-test and without a control cohort. Some of this is due to the authentic pedagogical setting in which traditional experimental studies are difficult and even inappropriate when working with variables relevant to learning. The ELLI instrument itself is a self-report questionnaire which measures what people say about themselves rather than an 'objective' measure with which traditional science is more familiar and the findings have to be understood in this light. However in learning and teaching what we say and think about ourselves is highly relevant and the language used in learning design frames what is possible and what is valued.

In this study the cohort reported a significantly lower mean score in their self assessment of creativity. Accordingly this does not *necessarily* mean that they are not creative. Inspection of the outputs from the students design projects and the assignments for this unit show considerable creativity and innovation. So we deduce that they were not familiar with the language of intuition, imagination, risk-taking and open-endedness in their learning. Arguably in their thinking (and their tutors' teaching) about systems designing these concepts and approaches were not common currency. Having a language with which to understand, own and articulate one's approach to learning is a key element of learning power. The core purpose of the assessment framework and its feedback processes in coaching conversations is to facilitate this through introducing a language for learning which names and describes these processes. In fact the dimension of strategic awareness, which increased at time two, is precisely about being aware of one's own learning power and using language to identify and articulate ways of approaching tasks which are going to be fruitful in achieving a personally chosen purpose.

Creativity, arguably critical for any open-ended process of knowledge co-generation such as systems architecting, is not something which is encouraged or assessed by our traditional educational assessment frameworks. By definition, standardised outcomes, which are what is often measured for political reasons, are about uniformity rather than diversity and innovation. In two studies of school age populations in learning power, five out of seven dimensions drop significantly at three key stages—and creativity is the one which demonstrates most significance [29, 31]. This finding is also consistent with a study into the competencies required for the development of systems thinking in their workforce, undertaken at DTSL the UK's defence science and technology laboratory, which has 2500 scientists and engineers [38–40].

The approach to systems designing described in this study offers some fresh ways of understanding how to develop e-learning architectures which go beyond simply social networking and sharing data. Through explicit attention to research-validated approaches to building learning power and knowledge structuring processes which serve a chosen purpose, technology may be used to more effectively catalyse the processes of learning and knowledge generation for individuals and collectives. The challenge in learning analytics is to render visible the learning dispositions and the transferable knowledge structuring processes which are associated with skilful and creative learning in diverse contexts. Information infrastructures, like all human products, embody and shape worldviews. The classification schemes embedded in an information infrastructure not only capture and preserve—but also forget and ignore, by virtue of what remains invisible [41, 42]. Thus any infrastructure scaffolds particular forms of human-computer and human-human interaction which may either enhance or inhibit sensemaking [43–47]. What this approach makes possible is the inclusion in learning architectures of design and functional decisions which use recommendation engines and learning analytics to enhance and scaffold authentic enquiry, which in this domain has been described as systems designing. Whilst the functional development of such an architecture is not the focus of this paper, and has been explored elsewhere, this paper does suggest certain learning design principles which can inform a requirement specification for such platforms [48, 49].

Despite its limitations this study suggests promising areas for further empirical and theoretical development in learning design for Engineering education and in learning analytics,, extending findings from research into learning power in other studies [25, 31, 32, 50]. What it suggests, albeit in a small pilot study, is the possibility of a rectifiable design fault in traditional learning systems, including those whose purpose is the education of Engineers. It is rectifiable because the solution can be designed and measured. Learning to design complex systems is itself a systems design challenge, which is both the focus and the modus operandi of this pilot study.

## 17. Conclusions

Through the application of systems design principles to the education of engineers, who will be required to deliver outcomes in the face of substantial uncertainty as is intrinsic in the concepts of sustainability, this pilot study has shown that:

1. Having been introduced to a variety of domain specific knowledge structuring processes, the students were able to creatively develop systems design frameworks for a range of complex engineering contexts and use them to recommend strategies to support sustainability.
2. Introduction to the concepts and practice of self-assessed learning power enabled them to consciously reflect on the learning processes themselves.
3. At the outset, the sample as a whole self-assessed themselves as having lower levels of creativity—imagination, intuition, risk-taking and open-endedness— than the average for the general population. This observation, which is consistent with other studies, may reflect the dominant assessment framework and the learning and teaching culture and language that accompanies it for Engineers. An interpretation could be that Engineers have to be, and often are, creative in their professional lives but perceive creativity to be linked to art and emotional responses so do not properly value this as a key aspect of learning power which can be understood and developed.
4. An opportunity exists to address these cultural issues and thereby help Engineers to appreciate the practical creative value they deliver.
5. Although the study had limitations in both size and scope, a sub-sample of students who chose to participate in the post tests demonstrated a significant increase in their strategic awareness—namely their ability to articulate and own their own learning processes. After three months and the successful submission of their unit assignment and substantial design project, they reported themselves to be more aware of their own learning processes, more able to act as agents in their own learning and more able to manage associated feelings.
6. The learning model described here offers design principles which offer a framework for the design of e-learning architectures which use technology to enhance the processes of learning in Education, as well as to assess the outcomes.

In the UK, the Engineering Council characterises Chartered Engineers "*by their ability to develop appropriate solutions to engineering problems, using new or existing technologies, through innovation, creativity and change*". The findings from this study, when taken together, suggest that there are opportunities for improvement in learning processes for Engineers, which if addressed might lead to improvements in our ability to develop professionally competent Engineers who are better equipped to deal with complex problems and deliver innovation in authentic contexts.

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## Appendix One

*Results of post hoc comparisons*

| (I) learning power | (J) learning power | Mean Difference (I-J) | Std. Error | Sig.$^a$ | 95% Confidence Interval for Difference$^a$ | |
|---|---|---|---|---|---|---|
| | | | | | Lower Bound | Upper Bound |
| 1<br>Changing and learning | 2 | 8.468* | 2.018 | 0.002 | 2.096 | 14.840 |
| | 3 | –1.863 | 1.882 | 1.000 | –7.807 | 4.082 |
| | 4 | 18.170* | 2.023 | 0.000 | 11.782 | 24.558 |
| | 5 | 7.206* | 2.185 | 0.033 | 0.306 | 14.106 |
| | 6 | 11.634* | 2.212 | 0.000 | 4.649 | 18.619 |
| | 7 | 7.108 | 2.266 | 0.053 | –0.050 | 14.266 |
| 2<br>Critical curiosity | 1 | –8.468* | 2.018 | 0.002 | –14.840 | –2.096 |
| | 3 | –10.331* | 2.103 | 0.000 | –16.972 | –3.689 |
| | 4 | 9.702* | 2.233 | 0.001 | 2.651 | 16.753 |
| | 5 | –1.262 | 2.721 | 1.000 | –9.856 | 7.332 |
| | 6 | 3.166 | 1.926 | 1.000 | –2.917 | 9.249 |
| | 7 | –1.360 | 2.065 | 1.000 | –7.883 | 5.162 |
| 3<br>Meaning making | 1 | 1.863 | 1.882 | 1.000 | –4.082 | 7.807 |
| | 2 | 10.331* | 2.103 | 0.000 | 3.689 | 16.972 |
| | 4 | 20.033* | 2.021 | 0.000 | 13.650 | 26.416 |
| | 5 | 9.069* | 2.056 | 0.001 | 2.575 | 15.563 |
| | 6 | 13.497* | 2.260 | 0.000 | 6.358 | 20.636 |
| | 7 | 8.971* | 2.674 | 0.028 | 0.525 | 17.416 |
| 4<br>Creativity | 1 | –18.170* | 2.023 | 0.000 | –24.558 | –11.782 |
| | 2 | –9.702* | 2.233 | 0.001 | –16.753 | –2.651 |
| | 3 | –20.033* | 2.021 | 0.000 | –26.416 | –13.650 |
| | 5 | –10.964* | 2.573 | 0.001 | –19.090 | –2.838 |
| | 6 | –6.536* | 1.893 | 0.020 | –12.514 | –0.558 |
| | 7 | –11.062* | 2.391 | 0.000 | –18.615 | –3.509 |
| 5<br>Strategic awareness | 1 | –7.206* | 2.185 | 0.033 | –14.106 | –0.306 |
| | 2 | 1.262 | 2.721 | 1.000 | –7.332 | 9.856 |
| | 3 | –9.069* | 2.056 | 0.001 | –15.563 | –2.575 |
| | 4 | 10.964* | 2.573 | 0.001 | 2.838 | 19.090 |
| | 6 | 4.428 | 2.474 | 1.000 | –3.386 | 12.242 |
| | 7 | –0.098 | 2.976 | 1.000 | –9.497 | 9.301 |
| 6<br>Learning relationships | 1 | –11.634* | 2.212 | 0.000 | –18.619 | –4.649 |
| | 2 | –3.166 | 1.926 | 1.000 | –9.249 | 2.917 |
| | 3 | –13.497* | 2.260 | 0.000 | –20.636 | –6.358 |
| | 4 | 6.536* | 1.893 | 0.020 | 0.558 | 12.514 |
| | 5 | –4.428 | 2.474 | 1.000 | –12.242 | 3.386 |
| | 7 | –4.526 | 1.917 | 0.444 | –10.581 | 1.529 |
| 7<br>Resilience | 1 | –7.108 | 2.266 | 0.053 | –14.266 | 0.050 |
| | 2 | 1.360 | 2.065 | 1.000 | –5.162 | 7.883 |
| | 3 | –8.971* | 2.674 | 0.028 | –17.416 | –0.525 |
| | 4 | 11.062* | 2.391 | 0.000 | 3.509 | 18.615 |
| | 5 | 0.098 | 2.976 | 1.000 | –9.301 | 9.497 |
| | 6 | 4.526 | 1.917 | 0.444 | –1.529 | 10.581 |

Based on estimated marginal means.

* The mean difference is significant at the 0.05 level.

a. Adjustment for multiple comparisons: Bonferroni.