Complexity and the Art of Education: A Study of How to Approach Teaching More Challenging Engineering Systems Development Concepts

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The Barcelona Conference on Education 2021
Official Conference Proceedings

Abstract
As the demand for ever more capable products increases, so too does the inherent complexity of the product itself in order to facilitate increased functionality. This is broadly true of products of all sizes, from mobile phones to automobiles to large infrastructure projects. This increased complexity makes specification, design, development and implementation more difficult to understand and achieve, potentially making the process and nature of product development more difficult to teach. There are a number of pedagogical factors to this, including the complexity of the subject, the ability of available teaching methods and technology to communicate and provide coverage of the topic, and the educational preferences of the students involved. This paper considers this issue through the prism of the design of a new masters-level course on complex engineering systems. Literature is analysed to study the nature of complexity in engineering systems development and the challenges it causes, and what mix of taught and experiential-learning might be most appropriate. Experience in delivering courses to masters students is also taken into account to gauge from an andragogical perspective what teaching methods have previously been successful in communicating subject matter that is for some difficult to understand. Feedback from students past and present is analysed to understand how different preferences affect the ability to understand more complex topics, in an attempt to assess how different students respond to different teaching methods. This analysis is used to propose an approach to enhance the education of complex systems design and development for masters students.

Keywords: Complexity, Pedagogy, Engineering

Introduction

As the demand for ever-more capable products and services increases, and knowledge develops incrementally, so the systems that we understand become continually more complex in nature. This is true of most things from consumer goods (Sauer and Ruttinger, 2007; Pak et al, 2017) through medical understanding (Levine and Oren, 2009) to the procurement of defence (NAO 2017; 2020b) and infrastructure systems (NAO 2020a; 2021). Moreover, the emergent properties associated with the use of more complex concepts and ideas must also be considered (Sarkozi et al, 2003; Aghion et al 2020). This presents a number of challenges which might be seen to fall into two categories: that of creating – or specifying and designing more complex systems – and that of understanding the outcome – i.e. comprehending the effect of increased complexity to enable the use of a system, and understand its consequences. The former requires a broad understanding of all factors associated with the acquisition of the (new or revised) system (Warfield, 1994; Batty, 2007). As an example, designing and procuring an individual system might be seen as complicated in that it will involve many different interconnected parts or sub-systems, but it can be bounded in terms of system understanding, use and maintenance across a lifecycle. Procurement of a capability, however, is much more nuanced, and opaque, as the required capability may not be easy to understand, and the means of achieving it could be challenging to envisage or define. Thus, there are more factors needing to be considered, as described below:

- Understanding the capability – the nature of the requirement is likely to be orthogonal and multi-faceted in nature
- Multiple interacting independent systems – the solution could well involve multiple systems which may not be continually present, and interactions that are numerous, diverse, and potentially unpredictable in nature
- Different lifecycles – systems might exist within different lifecycles and timescales
- Greater potential for emergence and entropy – there is a increased likelihood of unpredictable systems behaviour and unforeseen events affecting development and use of the capability systems

Stakeholders must therefore ensure complete understanding and share consensus on an appropriate course of action in order for the complexity to be managed, and the capability to be successfully delivered.

The second category – understanding the outcomes and affects of increased complexity – in order to ensure public understanding. Abraham et al (2017) pointing to the importance of branding new and innovative technology properly so as to manage consumer expectations, whilst Aghion et al (2020) considered the effects of increased automation on employment. Such effects may be negative, and therefore communication is important, and ramifications need to be carefully considered and mitigated where possible. Moreover, as Stephens et al (2016) point out, there may be costs to the consumer of more complex products, and so benefits must clearly be understood and weighed against potential negatives.

The understanding of complexity and its effects can therefore be seen as important, and that raises the question: how do we educate people in the nature of complexity in a manner that promotes understanding and enables those people to deal with its challenges and effects? This paper will evaluate the nature of complexity, why it is difficult to understand and educate, and will analyse pedagogical factors and techniques which might impede or assist in that education. Past experience in teaching complex subjects at masters level is considered, as is the student view on how best to learn such material. Conclusions will be drawn as to the most suitable teaching approach.

The Nature of Complexity

Complexity can be defined as a state "consisting of many different and connected parts" which are "not easy to analyse or understand" (OED, 2010), and as "The degree to which a system's design or code is difficult to understand because of numerous components or relationships among components" (ISO/IEC, 2009). The common factor is that it is difficult to comprehend and understand. This is confirmed by Sheard and Mostashari (2009) who state that complexity is "a measure of how difficult it is to understand how a system will behave or to predict the consequences of changing it". Given this challenging precept, it is useful to try to breakdown, codify, and understand the concept of complexity as best as is possible. Sheard and Mostashari (2011) identified types of complexity, these being structural, dynamic, and socio-political, as defined below:

1. **Structural Complexity** looks at the system elements and relationships. In particular, structural complexity looks at how many different ways system elements can be combined. Thus, it is related to the potential for the system to adapt to external needs.
2. **Dynamic Complexity** considers the complexity which can be observed when systems are used to perform particular tasks in an environment. There is a time element to dynamic complexity. The ways in which systems interact in the short term is directly related to system behaviour; the longer-term effects of using systems in an environment is related to system evolution.
3. **Socio-Political Complexity** considers the effect of individuals or groups of people on complexity. People-related complexity has two aspects. One is related to the perception of a situation as complex or not complex, due to multiple stakeholder **viewpoints** within a system context and social or cultural biases which add to the wider influences on a system context. The other involves either the "irrational" behaviour of an individual or the swarm behaviour of many people behaving individually in ways that make sense; however, the **emergent** behaviour is unpredicted and perhaps counterproductive. This latter type is based on the interactions of the people according to their various interrelationships and is often graphed using systems dynamics formalism

From this, we can deduce that structural, or physical, complexity increases with the number of system elements and their interactions, whilst dynamic complexity concerns modes of use over time, bringing in notions of configurations and reconfigurations of elements and their interactions. Socio-political complexity then considers the actions, perspectives, and viewpoints of humans within the system. This can be used to develop a categorization of factors which might help identify or recognize complexity, as described at table 1 overpage (Barker, 2021). These characteristics in the left-hand column are primarily structural in nature, and one of the characteristics of a complex system or situation is that it will embody a greater level of detail in terms of the number of nodes or elements than a simple system. It can be seen that should the number of elements or nodes, and/or their interconnections change over time, especially should this happen at a high tempo, then the result will be dynamic complexity. How individuals perceive the complexity both structurally and behaviourally, and form conclusions and courses of action as a result, will add the dimension of socio-political complexity. Complex situations can involve all three types, which only increases the difficulty in understanding the system and its environment.

Characteristics	Exacerbating Factors
No. of nodes	What we understand
No. of connections	What we think we understand
Size	What we don't understand
Distribution	Human involvement
Location	Organisation
Level of Detail	Context and Environment

Table 1: Characteristics of Complexity (Barker, 2021)

The right-hand column of table 1 contains factors which might influence and increase complexity. With the exception of the organizational structure, these relate largely to human activity in terms of what is known or not known, how individuals act and react, and how the context and systems environment is perceived. A crucial aspect of this is the rationale: why do people behave in the way they do and perceive things as they do. Suh (2005) and Zenouzi and Dehghan (2012) both point to perception as being crucial to the understanding of complexity, and the wrong perception, perhaps based on incorrect assumption or incomplete information, can lead misunderstanding the nature and extent of complexity, leading in turn to poor decision-making and its consequences.

The structure – and behaviour – of an organization can also contribute to complexity. Anderson (1999) notes that organisations can display nonlinear behaviour which may well be unpredictable in its nature, which makes the situation harder to understand and comprehend. Rouse (2007) reinforces this by pointing to the fact that there ae several issues with Complex engineered, organizational systems which need to be understood further.

Other factors making the concept of complexity harder to understand can be the academic theory behind it; Complexity Theory (Jackson, 2019) and the idea of propagation and systemic feedback (Boulton et al, 2015) are not necessarily readily understandable by those unfamiliar with the concept, and so a means needs to be found to articulate and explain such concepts meaningfully in a clear and understandable manner. A further complicating factor is that different terms and language are used to describe complex situations in different settings and circumstances (Sussman, 2002). This would seem to be backed up by the work of several authors including Salura (2013), Bury et al (2019) and Levinson (2019), who have commented on how the use of language can be confusing and affect understanding. Beyond such factors is then the unpredictable, such as the advent of the coronavirus pandemic of 2019, which made even relatively simple tasks and perceptions imminently more complex (Lee, 2020) and could serve to bring about significant change in the way individuals carry out tasks (Coombs, 2020).

As result of this we can summarise that there are a number of causal factors associated with the difficulty in understanding complexity, as described below:

- Complexity is often defined as something that is difficult to understand, comprehend, or describe
- It involves an increased level of detail or sophistication, meaning that it is less easy to quantify
- Complexity can be difficult to conceptualise: It is "More than a (single) headful"
- Complexity can be confusing, and therefore hard to recognise or characterise?
- Dynamic in nature: complexity inherent within a system can present a moving target and exhibit a tendency to self-perpetuate

To aid and facilitate understanding of the topic, we might identify a number of questions that can guide us in terms of determining a suitable means of articulating the nature of complexity, and the characteristics associated with it, in order that we can move toward devising a suitable method of teaching and educating people about the concept. These are listed below:

- What is ‘Complexity’? - and what is not ‘complexity’?
- Why are things ‘complex’?
- How does ‘complexity’ manifest itself?
- When are things ‘complex’? – does the thing being considered alter state?
- Where are things ‘complex’? – does location or context affect complexity?

The next section of this paper will analyse the challenges that this presents to teaching complex systems concepts and suggest an approach which might facilitate it.

Challenges in Teaching Complexity Systems Concepts

The above concludes that there are a number of challenges inherent to the understanding of complexity and its attendant systems concepts. This is at least in part because complexity is in itself complex to understand, but also because different individuals exhibit different preferences (Briggs Myers, 2000) and have different learning styles (Barker, 2014). Moreover, evidence from literature suggest that different teaching mechanisms achieve differing outcomes where effectiveness of learning is considered (Ramsden, 2003), whilst students have an expectation that teaching methods will be varied to meet different learning styles and individual experience (Biggs and Tang, 2007). In this light, consideration needs to be given to:

- What teaching methods are best suited to informing understanding of multi-faceted, orthogonal subjects involving multiple systems and stakeholders?
- How can these be structured into a coherent pedagogical/andragogical approach?
- How can such an approach be moulded to student expectations and their different learning styles?

Building upon the understanding of the nature of complexity, it might be seen that the teaching methods must be able to facilitate study of the complexity-related aspects within the relevant engineering domain, as described in table 2 over page.

<table>
<tr><td>Detail: number of nodes or components, depth of organisational or system development ‘layers’</td><td rowspan="4">Stakeholders: number – and variety – of stakeholders, and their
• views,
• intentions,
• Needs, and
• Motivations</td></tr>
<tr><td>Interconnections: Number and variety of links between components</td></tr>
<tr><td>Multi-faceted nature: Multiplicity of competing/conflicting factors needing consideration</td></tr>
<tr><td>Variation and behaviour, especially across time</td></tr>
</table>

Table 2: Challenges to Teaching Complex Engineering Concepts

The task of educating individuals in the nature of complexity is exacerbated by the fact that to some, the concept is daunting, and the enormity of the subject is off-putting, and that complexity evolves not necessarily at the same rate of knowledge concerning it (Foster et al, 2001). It is therefore essential that the topic be broken down into digestible chunks and related to student knowledge and experience for ease of understanding as advised by Ramsden (2003). Use of multiple, complimentary teaching techniques can further facilitate this endeavour (Fry et al, 2009). In the light of this, and questions raised in the previous section, the following topic areas can be used to structure a taught offering:

- The "essence" of complexity
- How to recognise complexity
- How to understand the 'severity' of the situation
    - What is the extent of the issue?
- How to describe complexity
    - The degree to which it can be modelled and formalised
- How to communicate the situation
    - How to 'keep tracks' on the spread of complexity

Research done by Lohse et al (1994) demonstrates that visual means such as images and graphs improve the likelihood of comprehension, and so pictorial models are likely to convey more powerfully the 'essence' of complexity in terms of engineering system or problem structure, detail and interaction, and elements that might facilitate the emergence and spread of complexity. And by extension, multiple interconnected models might then illustrate the multi-faceted nature of complex problem situation better than a textual representation, described the holistic nature of the situation in a clearer and more digestible manner. In this way, 'simple ideas' can be utilised to convey difficult messages, using pictorial images supported by short descriptions, worked examples, and exploratory case studies to increase understand and relate ideas of complexity directly to students' knowledge and understanding. These methods can be linked together to provide a step-by-step approach to learning and bring structure to the unstructured. Different models can highlight understanding of different aspects of the situation, some, for example, focusing on structure, and behaviour, of the engineering design whilst others describe human activity and perception of the problem. Other techniques can then be used to show how complexity might propagate and spread throughout an engineered system over time and illustrate what the effects of his might be. The way in which this is packaged will be key to student understanding, and could differ depending on subject, circumstance, and cohort size and type.

Constructing a Teaching Andragogy

In order to combine these ideas into a coherent teaching strategy, we need to revisit student expectations and learning styles. Barker (2014) suggested, based upon experience of teaching multiple cohorts across different levels of attainment, and feedback from students, that student expectations of education are centred around an interactive mixture of teaching techniques to provoke debate, challenge assumptions, and encourage reflection – an essential ingredient to the learning experience (Ramsden, 2003). Students also differ in their preferences (Briggs Myers, 2000) and learning styles (Honey and Mumford, 1982). Some students may exhibit a natural preference for formal lectures with worked examples, whereas others may be more comfortable with a more exploratory open-ended modelling approach and independent student-driven learning. Authors such as Bligh (1998) have debated the merits and otherwise of various teaching techniques to facilitate learning for different styles and circumstances.

If this is taken in the context of a potentially limited attention span (Bradbury, 2016) available to impart high-quality learning, then short instructional segments to convey the "essence" of complexity, such as essential principles, definitions and characteristics of complexity and related concepts would seem appropriate. Given the difficulty in comprehending the subject, establishing a firm foundation of basic knowledge is essential to further understanding. This can then be underpinned through the use of pictures and images, or metaphors, to create an 'image' of complexity to provide visual understanding of the nature of complexity, whilst worked examples and mini-case studies taking in complex systems across different engineering domains and industries can be used to make the concept 'relatable' by locating it within the experience and understanding of the student's 'own world'. If such devices are poorly used, however, the risk of misunderstanding can increase.

Once initial understanding of key concepts and ideas of complexity is achieved, then more advanced factors can be addressed by a variety of means as follows:

- Cross-cutting examples
  - Provides continuity of understanding across different ideas and concepts
  - Links teaching segments together
  - Maximises the opportunity for student understanding
- Modelling and exploration of multiple, orthogonal viewpoints
  - Provides a holistic view of the problem situation
  - Demonstrate how contrasting views or use of terminology can increase misunderstanding
  - Illustrate need to clarity and consensus
- Range of interactive case studies
  - Illustrate complexity in different context
  - Increases chance of relevance to individual experience, therefore increasing likelihood of understanding
  - Allows students to bring their own knowledge and understanding to bear on realistic complex issues and problem situations and scenarios

In allowing students to interact with modelling exercises and case studies, attention span may be enhanced (Geri et al, 2017) whilst a natural variety is added to the teaching andragogy which can only help the learning experience. In this way, basic principles can be inculcated, whilst more detailed and intricate real-world examples can be used to reinforce understanding and put the subject matter in context. This pedagogical/andragogical approach can then be enhanced still further by assessment – both formative and summative – which invites students to challenge their assumptions and reasoning and test their understanding in representative situations.

Whilst these provides a means to support education of ideas of complexity, it must be highlighted that the educational offering should be varied according to the students education level (so, for example, a degree-level student is likely to require more formal instruction, whilst a masters-level student can be expected to grasp more advanced concepts more quickly), and so factors such as prior knowledge and experience, and previous qualifications gained, will affect the students ability to understand, as will learning preferences, and the educational offering should be carefully and appropriately tailored. The next section will consider how this approach can be put into practice.

A Delivery Mechanism for the Teaching of Complex Systems Concepts

The analysis of the pedagogy/andragogy shows that short, impactful instructional sessions interspersed with worked examples to demonstrate key principles, and interactive case studies to allow the exploration of the effects of complexity is likely to be the most successful method of educating students in the nature and concepts of complexity. It is essential that students engage with this way of teaching and delivery, so discussion with students as to how the subject will be delivered is key to success, and this should take place before, throughout, and after the course is run. Experience of previous delivery allowed student expectations to be understood, and subsequent discussions via student feedback forums indicated that those initial indications were indeed valid. Feedback suggested the need for an incremental, step-by-step approach to building up knowledge gradually, with short, concise instructional lectures backed up by examples, and mini-exercises with sample solutions, so that students can ground their understanding before citing it within the domain of the real-world. It was also thought appropriate that the instructional lectures should be held as ‘conversations’ to allow the students a more immersive participation which might further their understanding, and that regular question and answer tutorial sessions should be scheduled to ensure student understanding and to repeat material if necessary. Realistic case studies, as described in the previous section, were thought to lend an opportunity to explore complexity, especially is these were used to link up ideas and build knowledge and expertise across the course. As a result of this consultation, the following mechanism was implemented:

- Live sessions held as ‘conversations’ rather than formal lectures
- Short follow-on individual exercises to embed understanding
- Provision of worked solutions/model answers
- Q&A/Tutorial sessions to answer queries and repeat material if needed
- Self-paced research exercises to explore particular aspects of relevance
- Longer, group interactive workshops to simulate reality and foster peer-to-peer understanding and learning
- Seek regular feedback from students: session-by-session to ensure understanding and test different ideas
- Consistent ‘storyline’ through course

Initial feedback during the course indicated that the variety of pedagogical techniques used helped understanding and succeeded in engaging the students with the subject matter. It was found that some combination of the above would work for students at different levels of educational learning; for masters students, the expectation would be that the students would move from basic principles more quickly, and focus more extensively on the more detailed interactive case studies, bringing their knowledge and experience to bear, and reflecting on lessons which could be applied to their individual working environments.

Conclusions and Further Work

In conclusion, it has been demonstrated that the topic of complexity, its effect upon systems of whatever type, and its tendency to propagate in a self-perpetuating manner, is one that is difficult to comprehend and understand. This can be for a variety of reasons ranging from the inherent complexity of the subject itself through the learning preferences of the student to the degree of advancement of members of the learning cohort, and the level at which it is being taught. Consideration of a suitable pedagogy (or andragogy) led to the identification of the need for interactive exploratory sessions, because it is of the essence that students are able to explore the effect of such detailed and extensive concepts, and this notion received positive feedback. It should also be noted that choice of teaching mechanism, be it imagery, phraseology, or use of metaphor, can induce confusion and reduce understanding. The delivery mechanism should make use of a suitable variety of teaching techniques to deliver the intended outcome at the intended level of qualification. For degree-level students, this mechanism will tend to focus more on the theoretical, but for masters-qualification students, a greater emphasis can be placed upon independent study, exploration, and reflection. Key conclusions of this work are therefore as follows:

- Need to choose imagery and metaphors with great care, as can easily reduce understanding of such a complex topic
- Simple techniques and methods engendered greater understanding – but need to ensure that ILOs of qualification are still met
- 'Conversations' and workshops proved effective at relating topic and concepts to student experience – more so than lectures?
- Pace – and pitch – of learning has to be right
- Constant themes through course improve understanding

In terms of further work, it should be said that the work reported is an initial study, and ideas need to be developed in the light of continued student feedback, with the delivery mechanism being further attuned and making use of more developed case studies. It is therefore desirable that the teaching concept should be repeated on other cohorts to increase feedback and refine teaching andragogy. A further enhancement to the teaching concept would be te consideration of work-based projects to allow students to apply the lessons for managing complexity directly into their working practice, and there is also the possibility of including 'reinforcement' sessions at a period of time after the course to gauge how students have applied lessons and confirmed their understanding.

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