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Undergraduates' Perspectives Regarding Interdisciplinary Learning Through Systems Thinking and Computer-based System Dynamics Modelling

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ABSTRACT

Systems thinking (ST) and system dynamics (SD) curriculum and pedagogy facilitate higher order thinking and a holistic understanding of real-world problems through a systems level and interdisciplinary approach to course content. For this to occur, the teaching methods, learning activities and assessments should be aligned with the intended learning outcomes to achieve the desired holistic thinking skills and interdisciplinary perspectives. As a learner-centric approach, project/problem-based learning is highly suitable to instruct ST through computer modelling and simulations. This framework also allows instructors to design projects based on global challenges and real-world problems so as to engage students to learn within interdisciplinary settings. It also allows instructors to represent complex systems as visual model diagrams through computer modelling platforms such as Vensim. Training students using ST and computer-based modelling projects will augment their learning, whereby they get to conceptualise, simulate, analyse, optimise models and document the dynamics of complex problem behaviours. This paper aims to explore students' perspectives regarding their interdisciplinary learning through projects based on ST and SD methodology while modelling and simulating real-world energy issues. Implications for teaching and learning are also discussed.

Keywords: Systems thinking (ST) and systems dynamics (SD) modelling, interdisciplinary learning, project-based learning, computer-based modelling and simulations, energy systems

INTRODUCTION

Interdisciplinarity is broadly studied and theorised (for example: Klein, 2010; Klein & Newell, 1997; Newell, 2001; Repko, 2012; Repko & Szostak, 2020). Research suggests that the systems thinking (ST) and system dynamics (SD) curriculum, in fact, supports students' ability to see the interconnections among different disciplines (Flynn et al., 2019). Interdisciplinary learning is defined as: a process of answering a question, solving a problem, or addressing a topic that is too broad or complex to be dealt with adequately by a single discipline, and draws on disciplines with the goal of integrating their insights to construct a more comprehensive understanding (Repko, 2012, p. 16). Interdisciplinary studies draw on multiple "disciplinary perspectives and integrates their insights through the construction of a more comprehensive perspective" (Klein & Newell, 1997, pp. 393-94).

Complex systems containing simple or complicated subsystems behave differently as the cause and effect relationships among such interdependent and interconnected multiple systems are non-linear. These systems within a bigger system interact through multiple feedback processes—both reinforcing (virtuous or vicious) and balancing (stabilising/negative) feedback loops as well as dynamic behaviours that display compounding or synergistic effects (Meadows, 2008; Jacobson, 2001; Richmond, 1993). Essentially, an interdisciplinary study comprises scrutinising a complex problem, theme, question or system by deriving and synthesising insights from various relevant disciplines in order to understand and then integrate the content and ideas into a more holistic, complete, and new framework of analysis (Newell, 2001). Thus, to understand the emerging complex behaviour of a system holistically, traditional reductionist thinking needs to be replaced by ST and dynamic modelling that involves non-linear thinking for recognising feedback loops and emerging behaviour patterns. (Arnold, 2017; Meadows, 2008). Real-world problems are inherently complex and also interdisciplinary in nature. Accordingly, the role of systems science/theory for interdisciplinary studies is well recognised in the literature (Newell, 2001; Repko, 2012). Interdisciplinary study focuses on trying "to understand the portion of the world modelled by…[a] complex system" (Newell, 2001, p. 2). However, relatively few studies at university level documented that ST and the modelling approach show promise in implementing interdisciplinary teaching and learning (Repko & Szostak, 2020; Mathews & Jones, 2008). Some reports show that project/problem-based learning methods are frequently adopted in inter- and trans-disciplinary education (Krajcik & Blumenfeld, 2006; Larmer & Boss, 2013; Mathews & Jones, 2008; Tejedor et al., 2018).

The ST curriculum favours learner-centric teaching and active learning approaches such as design activities (Hmelo et al., 2000), computer simulations (Riess & Mischo, 2010), systems modelling (Hung, 2008), and project-based learning (Nagarajan, 2019). Research suggests that the ST and SD curriculum, in fact, support students' ability to see the interconnections among different disciplines (Flynn et al., 2019). This paper presents undergraduate students' perspectives about their learning in terms of interdisciplinarity while attending a course based on the ST and SD modelling curriculum, and through project-based collaborative learning. Implications for teaching and learning will also be highlighted.

RESEARCH QUESTION AND RATIONALE

As discussed in the above sections, despite 'interdisciplinarity' has been commonly practised and highly theorised, relatively few studies have reflected on university-wide attempts to foster the concept. This study's main research question and objective is to explore whether the application of ST concepts and SD modelling can effectively facilitate students' interdisciplinary learning through a semester-long formal course focused on modelling energy systems, and through the implementation of project-based learning in small groups. It is also intended to communicate the implications of formal ST and SD curriculum in higher education in view of developing interdisciplinary educational programmes.

The rationale for this study is guided mainly by the ST and SD framework because this framework itself—as a pedagogical approach—is very much suitable to facilitate multidisciplinary problem solving. It is suitable for learner-centric approaches like project-based learning in small groups (with multidisciplinary composition/settings); it involves a holistic systems approach to look at complex problems from multiple perspectives. The ST and SD framework offers a common language or platform for students from different disciplines to model complex real-world problems to gain interdisciplinary perspectives/knowledge.

Systems thinking (ST) tools and system dynamics (SD) modelling methodology

The term 'systems thinking' can be referred to a pack of related but distinguishable concepts. For example, it is a scientific discipline or a domain/field (Senge, 2006); a methodology with specific concepts, techniques, and tools (e.g., causal loop diagrams and behaviour-over-time graphs, simulation models) (Richmond, 2000); a complex higher order cognitive skill, or a combination of synergistic skills, such as mapping and visualising interconnected and interdependent interactions and relationships among various component parts of a system (Arnold & Wade, 2017).

System as an interconnected whole is much more than the sum/collection of its parts and hence exhibits emergent behaviours, whether or not desirable, as more is accomplished together than being apart. ST is a heuristic and higher order cognitive skill that involves identifying parts/elements/components, understanding the emergent dynamic behaviours of a system arising from interdependent interactions among various components (Arnold & Wade, 2017; Meadows, 2008). ST thinking enables one to see circular cause and effect interrelationships and feedback processes instead of linear cause-and-effect relationships. Various concepts and tools of system dynamics modelling include learning about behaviour-over-time graphs (BOTGs), causal loops diagrams (CLDs) with feedback and delays, stock and flow diagrams (SFDs) for formulation and computer simulations, system archetypes, and systemic root cause analysis (Anderson, 1997; Meadows, 2008; Sterman, 2000). Some of the key conceptual tools are shown in Figure 1. It can be hypothesised that these visual tools of ST would assist learners in developing higher order understanding of the real-world system/problem.

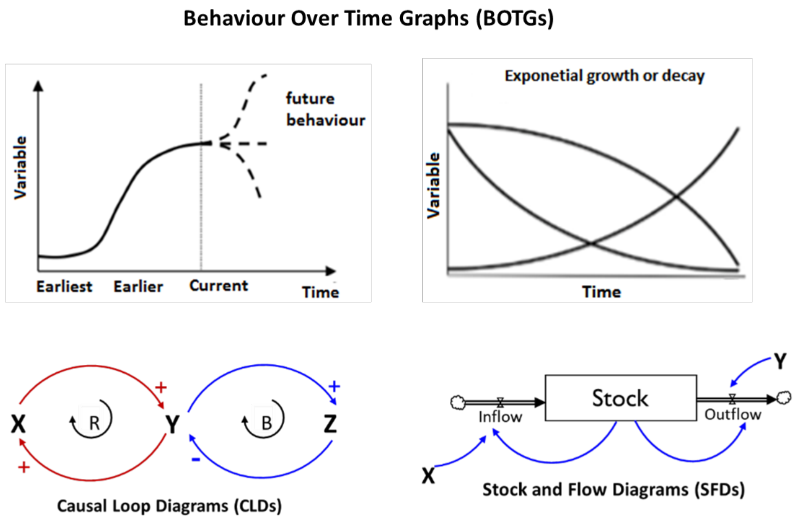

Figure 1. Key conceptual tools in ST and SD modelling

While ST is a qualitative approach to model a system/problem through feedback loops, SD is a quantitative modelling approach that combines feedback loops, stock and flow diagrams, time delays, and non-linear quantitative relationships as key concepts which require computer simulations for studying the complex dynamic behaviour of systems or real-world problems (Forrester, 1961, 2009; Sterman, 2002). The fundamental notion central to SD is that *models are approximations for the real world* (Sterman, 2000). It combines theory, methods, and philosophy to analyse the behaviour of systems not only in management, but also in environmental change, politics, economic behaviour, medicine, engineering, and other fields (Forrester, 1961, 2009).

Modelling and simulation of complex interactions among various components/objects in dynamic systems occur through a formalised methodology and process comprising problem identification, and definition, formulating a dynamic hypothesis about the problem behaviour, initiating simulations and policy analysis to understand and manage complex and dynamic systems. An overview of the ST and SD modelling methodology is shown in Figure 2, highlighting two main aspects: firstly, it is a cyclic and iterative process, from defining a problem to designing a learning strategy/infrastructure; and secondly, it explicitly presents the key products of the intermediate processes as integral parts of understanding the model/problem/system (Richardson & Pugh, 1981).

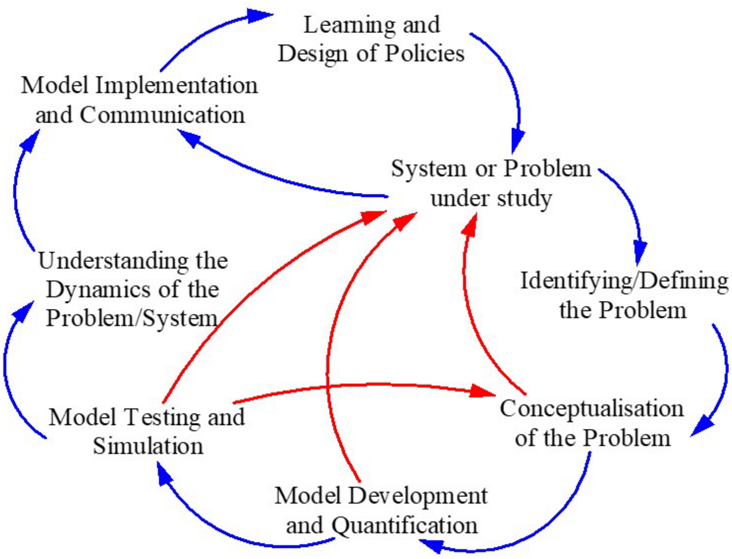

Figure 2. Overview of the ST and SD modelling approach (Richardson & Pugh, 1981)

ST methods are constantly evolving and SD models have been employed to foster communication among various stakeholders to facilitate a common understanding of complex real-world problems (Midgley, 2000). Students are often not taught the feedback effects in their own disciplines, especially the effects of the causal relationships and linkages they study on the variables studied by other disciplines or systems. From this view, Senge (2006) defines ST as a discipline which integrates the other disciplines. Thus, despite the institutional and cultural limitations which exist across universities, this kind of integration of disciplines can be implemented in trans-, multi-, or interdisciplinary teaching and research (Newell, 2001; Repko, 2012).

METHODOLOGY

Sample size and data collection

In order to explore how project-based learning in a course about energy systems based on ST and SD modelling facilitated students' interdisciplinary learning, a survey was conducted at the end of the course, with 17 students from the course participating in it. One of the survey questions, as given below, was pertinent to exploring their interdisciplinary learning aspects. Students' responses were collected anonymously on the university's learning management system, Luminus:

> Do you think the systems thinking (ST) and system dynamics (SD) approach is interdisciplinary in nature, OR
>
> Elaborate how the systems thinking (ST) and system dynamics (SD) modelling project facilitated your learning in an interdisciplinary way?

Implementation of project-based learning

One of the main pedagogical strategies in an ST course involves a combination of problem- and project-based learning to deal with complex real-world problems. It also involves active and collaborative learning by students in small groups to produce artefacts and models, computer simulations, policy analysis, as well as reports that align with the intended assessment and learning outcomes (Mathews & Jones, 2008; Nagarajan, 2019; Sterman, 2002). The courses on energy systems were offered by the author of this paper, at Residential College 4 in the National University of Singapore (NUS), intended for students to learn and apply ST and SD modelling concepts/tools to develop models in order to holistically understand how energy systems/problems maintain complex interdependencies with various economic, political, social, technological, and environmental systems/factors. The teaching involves a project-based approach to facilitate collaborative learning in small groups comprising students from different disciplines, as it allows for active and engaged learning which can also lead to in-depth insights while modelling real-world problems.

In order to understand complex interdisciplinary connections, students were given a group project to model how *a coal-based energy system interacts and impacts other systems such as* population, the economy, energy production, emissions, and environmental pollution etc. by considering the given variables/factors related to other sub-systems. Please see the Appendix/Supporting Information for more details about the project assigned.

The list of tasks given below to achieve the project's intended learning outcomes align with the steps involved in the ST and SD methodology shown in Figure 2.

1. **Identify the problem/system and map the interconnections and interdependent cause and effect relationships** among the subsystems/variables to develop **a causal loop diagram (CLD)** with reinforcing and balancing feedback loops as a qualitative model.

2. **Develop a quantitative stock and flow diagram (SFD)** based on the causal loop diagram constructed in Task 1. This requires students to gain an interdisciplinary systems level understanding of the problem so as to quantify the model by applying new knowledge and understanding.

3. **Use real-world data** for all the variables/quantities in the stock and flow diagram to **formulate the model** using the Vensim software programme (Ventana Systems Inc., 1990) which is essential to generate model behaviours and **useful insights upon simulation**. This requires students to apply quantitative and mathematical reasoning about the problem based on the different variables/systems involved in the model.

4. **Perform simulations, sensitivity analysis, and propose policies** for sustainable coal usage for electricity production. This requires students to understand the non-linear relationships and dynamic complexity associated with the problem/overall system. They need to interpret behaviour graphs and carry out policy analysis to propose possible holistic solutions.

5. **Integrate the policies and simulate the model to generate the desired model behaviours so as to synthesise a new and overall understanding of the dynamic complexity of the problem to gain more insights**. This enables students to gain an understanding of the overall interdisciplinary nature of the problem and learn from other domains of the systems/disciplines.

Basically, the students are required to work in small groups (three or four students per group) to complete the project. Each small group is formed by having students from different faculties/disciplines facilitate interdisciplinary ideas/perspectives as they work on the project collaboratively. While working in small groups, they need to map the cause and effect relationships among the various subsystems mentioned above, identify the problem, and list the factors that influence the problem to construct CLDs and SFDs as models for simulation. They also need to gather relevant data, perform computer simulations and perform sensitivity analysis (also known as what-if analysis or policy testing) to explain how the policy interventions have impacted the dynamics of the whole energy system as well as the sub-systems connected to it. The following section presents interdisciplinary aspects of students' learning and their perspectives based on the project they have completed.

RESULTS AND DISCUSSION

Systems approach versus interdisciplinarity

Compared to multi- or cross-disciplinary teaching and learning, which involves a simple examination of multiple insights and perspectives, an interdisciplinary framework of teaching and learning requires the synthesis and integration of different perspectives with that framework (Newell, 1990, 2001; Repko, 2012). Basically, such synthesis involves combining two or more concepts or things to create something new. In terms of ST, the goal is also synthesis, rather than analysis, which is the segmentation of a complex problem into parts/components and then integrating them into new models (CLDs, SFDs) for simulation to gain holistic perspectives from different disciplines in order to offer solutions and policy levers (Meadows, 1999).

From the perspective of interdisciplinarity, understanding an energy system and its interdependent nature with other systems or disciplines through systems approach can be shown, in general, as in Figure 3.

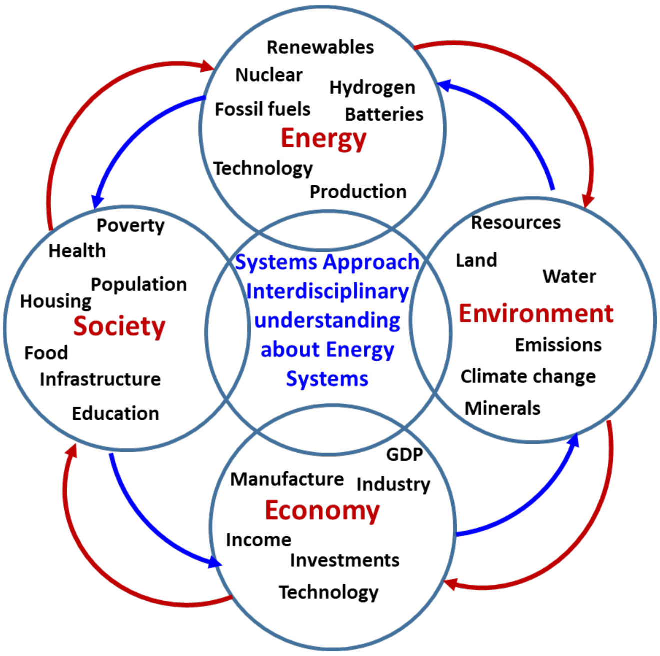

Figure 3. Interdisciplinarity associated with the interdependent nature of an energy system with other domains/systems

Thus, any representation of interdisciplinary studies is to relate the specific topic or complex problem to the whole by drawing on multiple disciplinary perspectives that are relevant to the problem, such as modelling a complex issue related to energy systems, water and food security, environmental issues such as global warming, healthcare and infectious diseases, and so on. Such studies, advanced through the systems approach, will facilitate students' ability to synthesise and integrate interdisciplinary perspectives (Mathews & Jones, 2008; Newell, 2001; Repko, 2012). Table 1 shows the similarities and relationship of ST and SD methodology with other interdisciplinary approaches.

Table 1

Matching of ST and SD methodology with other interdisciplinary approaches

ST and SD Modelling Approach/Methodology (Mathews & Jones, 2008; Richardson & Pugh, 1981)	**Interdisciplinary Approaches**	
	Newell's approach (Newell, 2001)	Repko's approach (Repko, 2012)
1. **Problem identification or definition** (a complex issue, question, topic) 2. **System/problem conceptualisation** (deeper understanding of the complex nature of the problem or system); Studying the problem from the perspective of each discipline (mapping interdisciplinary sub-systems connected to the main system or problem); Identifying (non-linear) interdependent linkages between variables mapped from different disciplines. 3. **Model formulation (qualitative)**: Identify key variables/factors to define system boundary; Propose model assumptions and develop causal loop diagrams (CLDs) and feedback structures that will cause dynamic behaviour patterns of the problem or system. **Model formulation (quantitative)**: Construct stock and flow diagram (SFD) from CLD developed in Step 3, and establish quantitative inter-relationships in the model. 4. **Analysis of Model** and evaluation of the behaviour: Simulate the base model and interpret the dynamic behaviour of the key stock variables in model. Establish structure and behaviour relationships in the model. 5. **Model use and implementation** (**Policy analysis**): For constructing a new understanding of the problem from multiple perspectives and analysis of leverage points. Propose new policies by attempting to solve the problem. 6. **Design of learning strategy and infrastructure**: Producing a model with policies incorporated and create a new understanding of the problem through integrated and interdisciplinary perspectives about the problem.	1. Defining the problem/ issue 2. Determining relevant disciplines (including inter-disciplines and schools of thought) 3. Studying the problem from the perspective of each discipline. 4. Evaluate assumptions 5. Identifying (non-linear) linkages between variables studied by different disciplines 6. Constructing a new understanding of the problem 7. Producing a model (metaphor, theme) that captures the new understanding 8. Testing the understanding by attempting to solve the problem.	1. Define the problem or formulate the focus question 2. Justify using an interdisciplinary approach 3. Identify relevant disciplines 4. Conduct a literature search 5. Develop adequacy in each relevant discipline 6. Analyse the problem and evaluate each insight into it. 7. Identify conflicts between insights and their sources 8. Create or discover common ground 9. Integrate insights and produce an interdisciplinary understanding of the problem 10. Test the understanding

Thus, similar to other interdisciplinary approaches as given Table 1, the steps followed in a cyclic and iterative manner through ST and SD methodology will also provide a better conceptualisation of and new understanding about the problem or system through holistic thinking in order to synthesise and integrate new ideas and provide contextualisation from multiple disciplines associated with the problem. The following section presents how project-based learning based on ST and SD modelling facilitated students' interdisciplinary learning and their views about it.

Students' augmented learning through modelling and computer-based simulations using Vensim

Vensim[1] (Ventana Systems Inc., 1990) is a visual computer modelling tool that allows students to conceptualise, document, simulate, analyse, and optimise models of dynamic systems they develop based on a project or a problem to be modelled. It offers a simple and flexible way of constructing simulation models, from causal loop diagrams (CLDs) to stock and flow diagrams (SFDs). ST involves developing CLDs as qualitative models, whereas SD requires SFDs that can be developed from the corresponding CLDs. Accordingly, Vensim offers tools for constructing CLDs to be shown as feedback loops which will be transformed into their corresponding SFDs for formulation, quantification of variables, and then to perform simulations. As shown in Figure 4, by connecting variables with arrows as links in the SFD, relationships among them are made and recorded as causal connections. Information from these causal connections is used by Vensim's Equation Editor to help students formulate and quantify the information in order to complete the simulation model. Students can improve on their model throughout the building process, observing the causes and effects arising from the variables, and also interpret the dynamic behaviours obtained as graphs after performing the simulation of the model.

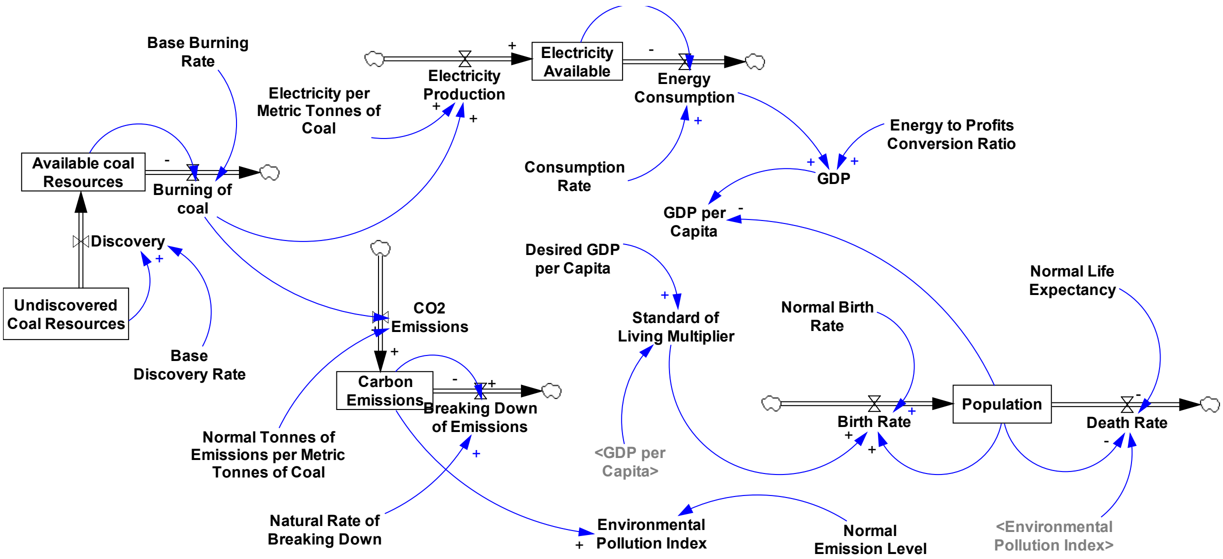

Figure 4. Stock and Flow Diagram (SFD) as a model to show interdependent and interdisciplinary connections among different domains/systems.

STUDENTS' RESPONSES AND INTERDISCIPLINARY NATURE OF THEIR LEARNING

This section presents how project-based learning based on ST and SD modelling facilitated students' interdisciplinary learning and their views about it. Students are able to apply essential concepts and the tools of ST and SD modelling (as shown in Figure 1) that enabled them to perform systems mapping (to develop CLDs) and simulations with formal mathematical models (formulate and quantify SFDs). A sample of the model/system structure (stock and flow diagram, SFD) developed by students showing the interconnected subsystems—energy resources, energy production, quantifying energy conversion, emissions, pollution index, environmental system, population, GDP etc.—is shown in Figure 4. This shows students are able to conceptualise the interdisciplinary connections and model the interdependent interactions of an energy system with other systems.

When students build a model based on the tasks for simulations, Vensim tools such as the output graphs can be used to generate dynamic behaviour patterns of different systems in the model (see Figure 5). These behaviour-over-time-graphs (BOTGs) are further analysed to derive insights and establish quantitative relationships among various key stock variables. Through sensitivity analysis, students will be able to propose better solutions/policies to address the problem.

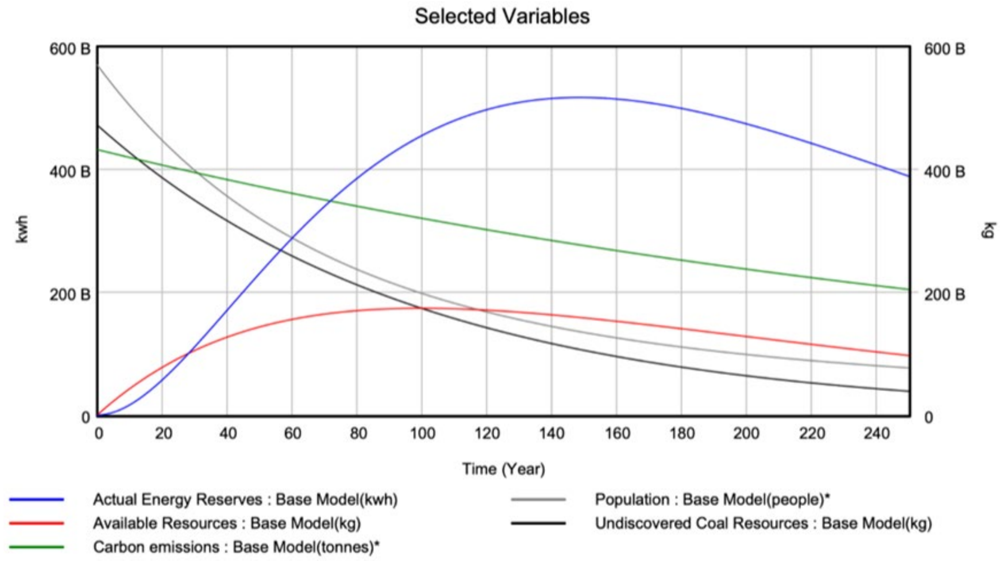

Figure 5. Behaviour-over-time graphs (BOTGs) simulations in Vensim showing the complex interconnectedness of an energy system interacting with other systems

Thus, when it comes to building a systems maps and modelling it, it requires the disciplinary skills of ST as well as the interdisciplinary skill of making connections across disciplines and being able to simulate the interconnected behaviour of the whole system (see Figure 5). What students viewed about their learning from this course and the activities, and sample comments/reflections (collected anonymously through a survey) indicating how it augmented their understanding of emerging interdisciplinary aspects of learning are given in Table 2.

Table 2

Students' responses and emerging interdisciplinary aspects of learning

Sample of Students' Responses (to the question**:** *Do you think the ST and SD approach is interdisciplinary in nature OR* *Elaborate how the ST and SD modelling project facilitated your learning in an interdisciplinary way?)*	**Mapping Emerging Interdisciplinary Aspects of Learning**
• *"Yes. This course offers an interdisciplinary setting for students to discuss real-world problems which are interdisciplinary on their own. By having students with different academic interests and backgrounds, they can share with one another, different perspectives they have on a problem. This allows students to broaden their horizons and understand that problems can be viewed and solved differently. Using sensitivity analysis, students can then visualise the impact of different aspects of one problem and come up with different policy proposals. This allows students to develop more holistically and ensure that they are not restricted to only knowledge taught within their academic domain".* • *"Yes. The ST and SD approach does not only apply to a single discipline, as systems are very well interconnected as a whole with subsystems and structures. It helped me to think out of the box in my assumptions towards matters I thought I already knew. For example, for an energy system, as we think about how to delay Hubbert's peak extraction, I thought that we could just implement policies to curb the use of coal; however, if we just curb use of coal, then what replaces that? We need to find a better alternative; however, another alternative may cost more, deterring them from approaching that method; and the list goes on - that it is not just one way of looking, we have to look at it from the society, economy and environment's point of view to fully address a problem"!* • *"Agree. ST and SD have inculcated a mindset to approach situations with the consideration of the interdependencies and interrelations of variables. Because of it, I believe that ST and SD is not just limited to energy systems but also applicable to other industries such as healthcare and business. Hence, it is interdisciplinary and has taught me to approach problems in a holistic manner."* • *"ST is not restricted to certain fields but requires profound analysis from multiple sources. In the modelling experience, I applied concepts in mathematics and joined them together with knowledge in basic environmental science."* • *"ST and SD is definitely interdisciplinary in nature. While we may learnt about the environment or about energy in this course, there are vastly different topics that ST and SD can be applied to, such as politics. I have definitely used ST and SD*	Based on these responses, the following aspects of interdisciplinary learning can be observed While working in small groups comprising group mates from different disciplines, students are able to apply ST concepts and modelling methodology to gain a holistic understanding of the interdependent interactions among natural resources, society, economy, and the environment, etc. This requires them to integrate their knowledge and understanding of other systems or disciplines, and how they interact with an energy system. Some students are even able to think of extending the connection of energy system to other systems like healthcare, industries, business etc. They also sounded confident about applying ST knowledge to model problems related to political systems. They are able to construct a new understanding of the problem through modelling and simulations. Ability to integrate insights and produce an interdisciplinary understanding of the problem. Re-evaluate their prior assumptions based on a new understanding of the problem

modelling casually when reading or learning about politics."	
• *"Yes. ST is definitely interdisciplinary. When we think of systems, there are so many factors that come into mind. For example, when engineering a race car team, there are human- and machine-oriented aspects along with so many others. I feel that it gave me a greater understanding of the world around me and allowed me to appreciate not just the systems themselves, but also the connections and relationships between objects. Through this, I feel like I am able to now look through a systems-perspectives' "eye" and learn about the world from a different perspective."* • *"ST and SD facilitated my learning in multiple aspects of my life. In a non-academic way, ST can be applied to observe any issues I encounter from many different perspectives in order to understand the problem better and come up with a holistic solution, as opposed to simply considering the problem from my own perspective. In an academic way, I have learnt to apply ST to view my computing problems from different angles in order to write the best programme to solve the problem.*	These comments indicate students are able to see the world around them from multidisciplinary systems perspectives and thinking. They are also able to think how to apply ST in everyday life, in both academic and non-academic scenarios. Developing multidisciplinary perspectives about the world around them and understanding to solve the problem. Identify relevant disciplines associated with the given problem from a systems approach.
• *"I believe they are interdisciplinary in nature. ST and SD modelling can help me understand abstract concepts that I may not be well-acquainted with based on my disciplinary background by reducing them into a system with its components and performing SD modelling, both of which can be universally understood via ST."* • *"Yes. As ST by nature has to do with the modelling of various systems that may come from different disciplines, I was able to learn about different energy systems, which broadened my perspectives and allowed me to better understand the world through the lens of SD modelling.*	Students perceived interdisciplinarity as one of the major advantages of working on projects based on ST and computer-based dynamic modelling, and enhanced their interdisciplinary understanding of the interconnectedness of the energy resources-production-economy-society-environment systems. Producing a model (metaphor, theme) enabled them to form a new understanding of various interconnected systems and how they work. Identify relevant disciplines associated with the given problem from a systems approach.

While critical thinking is frequently experienced as a by-product of the above interdisciplinary learning approaches, ST and SD modelling methodology also requires students to critically examine, evaluate, and validate the models developed. According to the OECD definition (Berger, 1972), 'interdisciplinarity' is an adjective describing the interaction among two or more different disciplines (pp. 23-26). This interaction may range from simple communication of ideas to the mutual integration of organising concepts, methodology, procedures, epistemology, terminology, data, and organisation of research and education in a fairly large field. An interdisciplinary group comprises "persons trained in different fields of knowledge (disciplines) with different concepts, methods, and data and terms organised into a common effort on a common problem with continuous intercommunication among the participants from different disciplines" (Berger, 1972). Thus, it is important to note what students experienced and viewed about their learning through the project work, which also aligns well with this other definition of interdisciplinary learning.

Furthermore, the interdisciplinary nature of ST fostered effective communication skills and the ability to work in small groups collaboratively with peers from different disciplines/fields. Students are also found to appreciate the interdisciplinary learning and preferred to study real-world contemporary issues through modelling.

IMPLICATIONS FOR TEACHING AND LEARNING

The findings based on this study suggest that the ST and SD curriculum facilitates integration of knowledge from different disciplines including geosciences, maths, biology, engineering, business, and behavioural sciences for better problem-solving abilities among students. Some of the essential implications for teaching and learning are provided below:

- **Interdisciplinary teaching and learning at university level through ST and SD modelling.** The main function of implementing the ST and SD curriculum is essentially to enable both the instructors and students to recognise the nature of its inherent interdisciplinarity and its great potential for equipping students with the capacity to address global challenges holistically. Hence, it is essential to introduce the ST curriculum at university level so that both instructors and students learn about real-world complex problems from multidisciplinary perspectives.

- **What instructors can do (role of instructors and pedagogy).** In terms of the instructor's role, it is essential to design learner-centred activities such as project-based collaborative learning in small groups—students should be learning actively to create qualitative models with causal loop diagrams, quantitative system dynamics models to simulate their behaviour, explore how problems/systems are being modelled to represent real-world complexities and gain interdisciplinary knowledge about the problem or system in order to propose holistic solutions. The Vensim Personal Learning Edition (PLE) programme is effective and supportive as a visual computer modelling and simulation tool that allows students to conceptualise, document, simulate, analyse, and optimise models of dynamic systems that they develop based on a project or a problem to be modelled.

- **Designing innovative curriculum (role of the content to promote interdisciplinarity).** To achieve sustainable development goals (United Nations, 2015), a holistic and interdisciplinary curriculum, and holistic approaches to problem solving are essential when it comes to considering a wider range of factors/systems from multiple perspectives. An ST and SD curriculum and methodological framework within different disciplines can also serve as an instructional model to facilitate a holistic and interdisciplinary understanding about sustainability goals in order to address complex real-world problems and new challenges that may arise (Reynolds *et al.,* 2018; Zuin & Kümmerer, 2021). Hence, one of the possible approaches can be to re-imagine and reconstruct the curriculum of various traditional domains of disciplines by integrating them with the ST and SD curriculum. It can also promote critical thinking as a subset of skills, since students are prompted to examine model assumptions and consider their conclusions through evidence and data.

LIMITATIONS

The results of this study are constrained by the following limitations:

(a) Students' perspectives about aspects of interdisciplinary learning and the insights documented are restricted only to the cohort/sample of students who attended the course.

(b) This is an exploratory study, and more empirical studies at university level are essential in order to extrapolate the research, including the fact that instructors also need additional guidance on exactly what an ST curriculum entails and specific training on how to best integrate it into instruction.

CONCLUSIONS

Based on the survey about interdisciplinary learning and students' perceptions discussed in this paper, it can be suggested that the implementation of the ST and SD modelling curriculum through project-based learning facilitates interdisciplinary teaching and learning. It allows students to learn to explore the relevance of the problem they solve in terms of other subjects and real-world applications, and to integrate their interdisciplinary learning in order to synthesise new knowledge about a problem to propose policies/solutions. Driven by the complex structure and dynamic behaviour of real-world problems, the interdisciplinary teaching/instruction necessitates the design and integration of pedagogical methods/frameworks and the integration of content from different academic disciplines. Systems thinking (ST), in combination with system dynamics (SD) modelling offers a methodology of integrative interdisciplinarity, in which some of the concepts and insights of one discipline contribute to the problems and theories of others.

In order to facilitate augmented learning, computer-based modelling and simulations on Vensim PLE programme can be employed. It can also be realised that teaching and learning through ST and SD modelling promotes the development of multidisciplinary thinking skills that may otherwise not be fostered when thinking purely based on one particular discipline. To address the most pressing global challenges and real world problems which are inherently interdisciplinary, it is appropriate that the ST and SD modelling curriculum is incorporated into sustainability education such that the scientists, sociologists, engineers, medical professionals, economists, policymakers etc. are equipped with the tools to facilitate the transition towards a sustainable society. Thus, it is important to rethink university education and curriculum due to the increasing complexity of societal and environmental challenges, for which initiatives such as implementing an ST curriculum in an inclusive way may be considered as a means of boosting interdisciplinary skills among university students.

In summary, ST and computer-assisted SD modelling courses can also be designed to be learner-centred and inquiry-based to include interdisciplinary perspectives, holistic thinking, and policy simulations and testing.

ENDNOTE

1. Besides Vensim, there are various other simulation programmes available such as Stella, PowerSim, InsightMaker, Dynamo, and more. However, the Vensim Personal Learning Edition (PLE) is a freely available version for educational purposes.

APPENDIX/SUPPORTING INFORMATION. Sample Project Assignment for Modelling

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