A REVERSE ORDER LIFE CYCLE APPROACH TO ENHANCE SYSTEMS ENGINEERING EDUCATION AT UNDERGRADUATE LEVEL

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ABSTRACT – The advances of Industry 4.0 lead the transition into the era of complex systems, requiring systems solutions for complex problems, increasing the interest in the development of systems engineers. However, traditional systems thinking may lose its effectiveness in this new context, which leads to a challenge in systems engineering education. This research aims to better prepare systems engineers of the future by addressing the disconnect which exist between systems engineering education at undergraduate level, and the real-life complex systems seen in society today though the implementation of a reverse order life cycle approach.

By following the reverse order life cycle approach with a familiar electrical appliance, such as the electric kettle, in the classroom, undergraduate systems engineering students were able to gain the necessary insight and understanding regarding the dynamics of complex systems the underlying systems engineering concepts.

Keywords: Engineering education, Industry 4.0, Reverse Life Cycle, Systems Engineering

INTRODUCTION AND BACKGROUND

The advances stemming from Industry 4.0 created unprecedented complexity of technological development and social interaction. Industry 4.0 can be defined as the utilization of new digitized and connected industrial systems, which are expected to yield extensive industry-spanning opportunities (Kiel, 2017). These connected systems will be challenged by the advances in technology, proliferation of connected sensors, increased computational ability, massive data storage availability and the progress in machine learning or artificial intelligence (Gershwin, 2017). As industry and government become more dependent on systems solutions for complex problems and as procurement agencies increasingly promote systems engineering, there is increasing interest in the development of systems engineers (Davidz, Nightingale & Rhodes, 2005).

Systems Engineering (SE) is defined by the International Council on Systems Engineering (INCOSE) as “an engineering discipline whose responsibility is creating and executing an interdisciplinary process to ensure that the customer and stakeholder's needs are satisfied in a high quality, trustworthy, cost efficient and schedule compliant manner throughout a system's entire life cycle” (INCOSE, 2017). In the light of Industry 4.0, industry and academia have expressed concern that systems engineers may not be prepared for the complexity and interconnectivity which new Industry 4.0–driven systems present. The fundamental changes within systems posts one of the biggest challenges for engineering design and also for SE engineering education (Hester & Adams, 2015); Motyl et al, 2017; Von Solms & Marnewick, 2017) to increase (Seymour & Luman, 2011), and be accelerated (Davidz et al, 2005).

The necessity for a SE orientation in electrical engineering education was expressed by Sage as early as 1979 (Sage, 1979). The needs associated with SE education are challenging, as undergraduate engineering students rarely have the insight and understanding in the underlying system dynamics of these complex systems. Students generally have limited engineering exposure to and experience in the complexity of systems and advanced technology as prevalent in society today (Subramanian & Dubey, 2012). These challenges facing undergraduate SE education can be summarized as follows:

- Limited experience in systems thinking of undergraduate engineering students;
- Complexity of even simple technological devices;
- Monetary cost of following the complete SE model to cover the whole product lifecycle;
- Limited time availability for a course in Systems Engineering;
- Large undergraduate class size of typically more than 100 students.

Wasson (2004) comments in his book entitled "System Engineering, Analysis, Design, and Development" that the focus of SE courses at many universities globally are lacking, as students are taught the activities of SE, such as writing specifications, developing designs and performing system integration and testing, but no multi-discipline problem-solving and solution development methodologies that can be applied to the system. He further comments that academic instructors "often lack industry SE experience to be cognizant of the problem." And that they teach a methodology which is "congruent with academic research and scientific inquiry methodologies" which are not consistent with proper SE activities (Wasson, 2004, p.34).

Due to the abovementioned challenges of SE education universities, not all academic institutions have coped with the SE educational challenges, resulting in an under supported industry facing a severe lack of professionals who have mastered the fundamentals of SE (Bougaa et al, 2017). This paper aims to address some of the challenges associated with SE education by proposing reverse order life cycle (ROCL) approach in an undergraduate electrical engineering programme. The layout of the paper is as follows: the next section presents the methodology followed in this research. Thereafter, an overview on the SE course is presented, followed by the assessment of learning as well as a conclusion.

METHODOLOGY

Pedagogical Approach

The pedagogical approach followed in the classroom is based on exposing the students to the concepts of SE through traditional teaching methods combined with engaged learning sessions. A single SE topic was covered every week in one theoretical class and a practical session. Carefully constructed, goal-oriented activities relevant to the course material has been proven to challenge students to engage in learning activities through doing, enabling the students to gain the theoretical knowledge of the subject and learn to apply the gained knowledge in real world applications (White, 2001). Goal-directed practice avoids simply transferring factual knowledge from lecturer to learner, but aims to assist in the better understanding, retention and application of new information, improving the quality of learning (Wood, 2003; Ambrose et al, 2010).

The practical sessions were sequenced to allow a natural progression in developing the students' understanding of the systems engineering concepts. All activities and exercises were constructed to cover a single SE topic, where the introduction and integration of new tasks and concepts were incorporated in a staggered manner. Such a staggered approach enables students to become proficient in a task before being overwhelmed by new information and actions, which helps students develop mastery in a subject (Ambrose et al, 2010). The importance of team work in the undergraduate engineering curriculum is enforced by the establishment of small teams, with a maximum of 4 to 5 students per team. Each team collectively were required to participate in the practical aspects of the course. The small team size allowed each student sufficient access to topic matter. An assessment was prepared for each of the practical sessions to test the students' understanding of the relevant SE topic. Assessments included document submissions, group presentations, demonstrations as well as practical activities.

Reverse Order Life Cycle Approach

The Technical Processes definition of the ISO 15288 System Life Cycle standard proposes the Systems Engineering Life Cycle (SELC) to start with Stakeholder Needs and Requirements Definition followed by System Requirements Definition as shown in Figure 1 (ISO/IEC 15288:2008, 2008). In this forward Life Cycle process, component characteristics are deduced from the System Specification in a deterministic process. As students have limited exposure and knowledge relating to design, the progress from system specification to component and system development is difficult to teach.

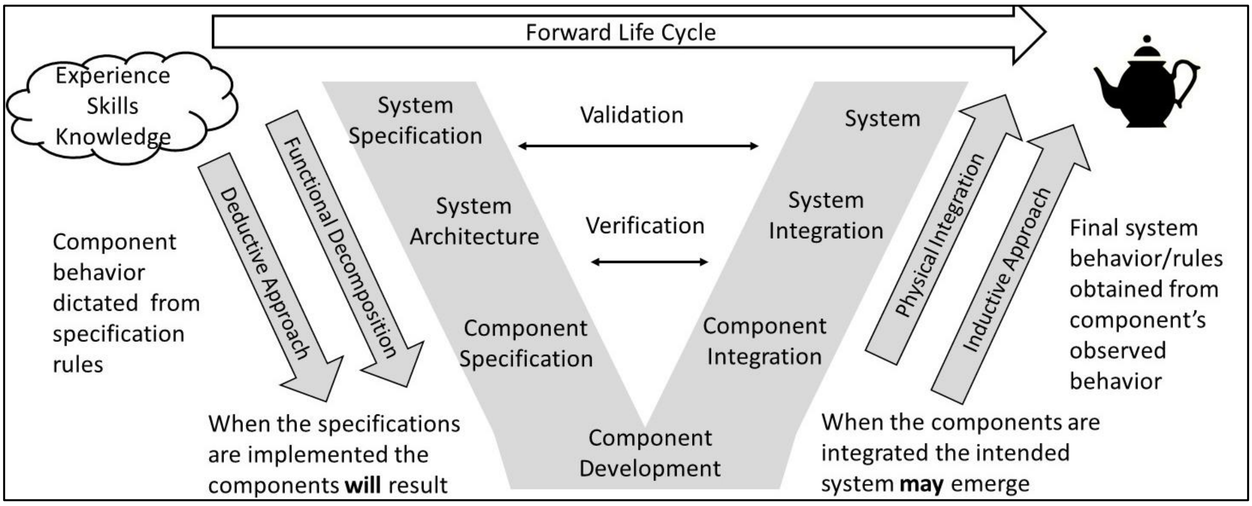

Figure 1: The Systems Engineering V-model for Life Cycle product development.

The teaching of complex engineering can however, be enhanced by following the inductive approach or bottom-up approach to teaching (Meyer & Simpson, 2018). An inductive approach can be used to expose the students to the Reverse Order Life Cycle (ROLC) as shown in Figure 2. The ROLC starts with the already developed and manufactured product from which the underlying components are extracted by physical decomposition.

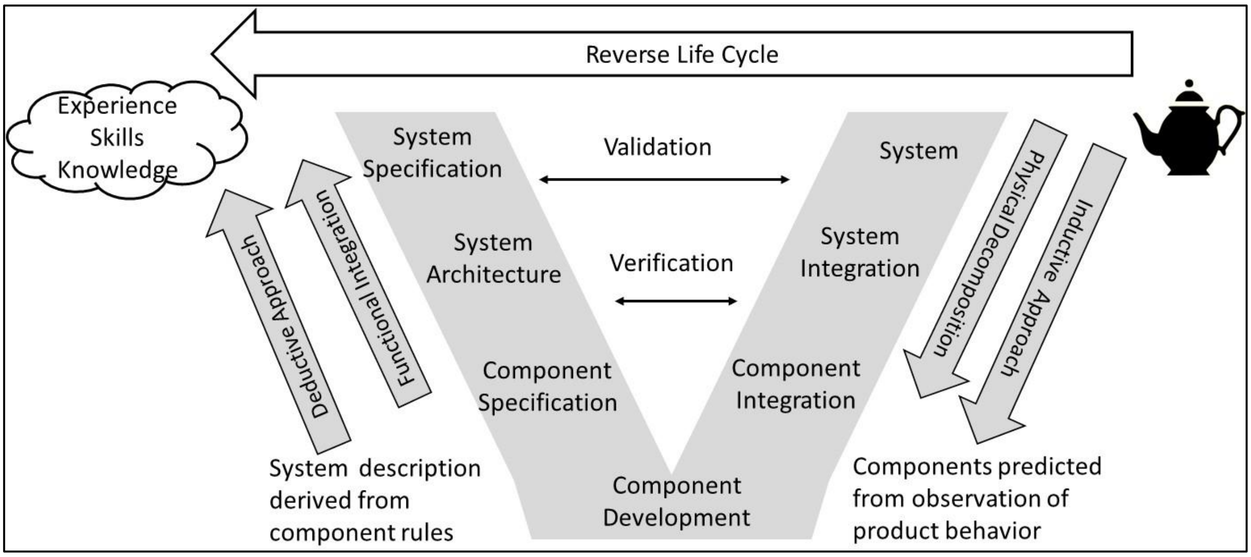

Figure 2: ROLC Systems Engineering V-Model for experience, skills and knowledge extraction.

By following the ROLC engineering V-Model (Forsberg, 2005) approach, students are exposed to an already designed and manufactured product where they are guided to work back to predict the underlying component structure of the product. The System Design Specification is subsequently deduced from the known characteristic or behaviour rules of the components. During this process, the experience, skills and knowledge utilized by the manufacturer during the design and manufacturing of the final product may then be revealed.

In this way undergraduate students with very limited design experience can get exposure to the many facets of engineering knowledge required to design, implement and manufacture products. By guiding the students on this path of discovery, the systems engineering concepts explained in the theory sections of the course are made real to them through the analysis of the already manufactured systems.

Complexity and Budgetary Approach

SE design methodology is well suited for the design of complex systems. However, at undergraduate engineering student level the student's ability to deal with complexity is not fully developed and students struggle to comprehend complex systems (Wasson, 2004). Students are more often than not overwhelmed by the complexity of systems which then blinds them to the teaching of the fundamental underlying Systems Engineering concepts. To overcome this challenge, the course was structured around an everyday used commercial product. The student's familiarity of an everyday product allowed them not to be distracted by the complexity of the product since they already have a thorough understanding of the operating principles of the device. Most modern-day household objects contain sufficient interdisciplinary complexity to allow the development of the Systems Engineering concepts underpinning the development of the product.

The demand for engineering graduates in industry have forced tertiary institutions to have large class sizes, up to and exceeding 100 engineering students. Financial challenges in the higher education sector also contributed to constrained teaching budgets which limits the funding available for teaching and learning resources. The limited funding and the large class sizes pose challenges for courses requiring individual student participation in technology applications. The approach followed was therefore to find suitable technology objects of everyday use which could be procured in reasonable quantities without placing unnecessary demands on the already limited teaching consumables budget.

SYSTEMS ENGINEERING COURSE LAYOUT

The SE course was presented to undergraduate electrical engineering students in the third year of study at a Washington Accord (IEA, 2014) accredited engineering education institution. The course was structured to allow the development of basic SE concepts, including System Validation, Systems Architecture, Systems Requirements and specifications, Systems Modelling and Systems Safety.

An ordinary household electric kettle was selected as the technology object of which the underlying systems engineering concepts were studied. The kettle is an everyday object with which all the students were familiar with the operation and function thereof and the costs associated with a standard electric kettle fell within the budgetary requirements of the higher education institution. The kettle is the culmination of different engineering disciplines such as mechanical, electrical and industrial engineering with fundamental electrical and thermodynamic science foundation. Being an everyday object, the kettle must comply with safety and regulatory standards of which the introduction to the students are of importance. The design of the kettle also considers aspects of esthetical design, design for mass production and design for usability.

System Validation

Following the ROLC approach, the first task the students had to perform was system validation. The students had to follow the validation methods of Inspection, Demonstration, Analysis and Test. Each group was given a kettle in the original manufacturer's packaging. The method of packaging and any instructions regarding the operation and specifications of the kettle had to be identified and captured to be used in the verification process:

- Inspection: A visual inspection of the kettle was undertaken to identifying functions, interfaces (electrical, mechanical, human) as well as manufacturing constraints.
- Demonstration: System functionality were determined by demonstration as students were required to use the kettle as instructed in the manual.
- Analysis: A physical configuration audit was performed on the kettle to establish the design parameters of the kettle, such as water capacity, electrical power consumption and physical characteristics.
- Test: The performance of the kettle was validated through testing. The tests conducted included measuring the temperature versus time performance for the heating and cooling cycle of the kettle using a predetermined quantity of water.

All student groups were comfortable to operate the kettle and perform validation tests. Students performed the standard required heating and cooling tests, but also conducted various safety validation tests, for example switching the kettle on without the minimum required amount of water. Results included students realizing that the kW rating of the electric element is not exactly as stipulated on the box and that small variation in the test setup may influence results (different placements of temperature probe, water levels etc).

System Architecture

The second task was to determine the system architecture by identification of the system boundaries and the various sub-systems. Each sub-system's border was identified, examined for energy, material and information crossings to establish the interface specification for that applicable sub-system. A functional architecture diagram was drawn showing how the system is constituted from the sub-systems with the relevant interfaces of the system and sub-systems shown. After the subsystems were determined, the kettles were disassembled into its smallest components. The students had to identify and capture the components in a bill of materials. The relationships between the components and the sub-systems had to be determined. The students then proceeded with the drawing of the wiring schematic of the kettle, where all electrical components in the bill of materials had to be included. The wiring diagram of the kettle was used to demonstrate to the students the relationship between the functional architecture and the implemented architecture.

Students struggled to distinguish between functional subsystems and physical subsections of the kettle. For example, when considering the electric element of the kettle, students struggled to understand the difference between the type of component (electrical) and its functionality (heating). Students wanted to put all electric components into the electrical subsystem (responsible for providing electric power) but failed to realize that some were responsible for heating (element).

With the creation of the sub-systems diagram and the wiring schematic, the students learned that the same type of components may have different functionalities. For example, in the wiring diagram there exists two resistors (element and resistor for the LED), where the element belonged to the "heating sub-system" and the LED with its resistor belonged to the "power indication system".

System Requirements

The third task was to introduce the students to systems requirements. Requirement Management topics such as requirement types, requirement language, attributes of good requirements and requirement specifications were presented to the students. From the System Validation and System Architecture experience the students had gained enough knowledge to derive the System Requirement Specification. The design requirements for the kettle had to be presented in a kettle design requirement specification.

As the students understood the functionality, performance, safety and other aspects of the kettle due to previous practical sessions, the technical aspects of the requirements were not difficult for the students to understand. The theoretical session could focus on the structure of requirement and specification writing and not burdened with technical aspects.

System Modelling

The fourth task required the students to develop a mathematical model to predict and simulate the physical operation of the kettle. The motivation behind the modelling of the kettle was for students to gain a better understanding of the factors at play in the system and how various parameters influence the operation of the kettle. A comprehensive model of a physical system allowed the students to:

- Determine whether the desired performance is attainable;
- Determine under what bounds the system operates;
- Determine the most cost-effective means of achieving a desired level of performance;
- Control the system to achieve a desired objective.

The basic steps followed to model the system were:

- Research of the underlying physics;
- Development of a mathematical model describing the system;
- Fit the model to the experimental data;
- Validate the model by determining the acceptability of the modelling errors;
- Perform sensitivity analysis on the primary design parameters.

With the estimated parameters of the kettle and the mathematical model of the kettle the students were required to make predictions of the power consumption and time duration for heating and cooling different quantities of water. Design decision regarding the acceptable performance of the kettle versus electrical power consumption and thermal insulation could be demonstrated by the modelling of the kettle.

This exercise gave students exposure to the importance of systems modelling, but also working across engineering disciplinary boundaries. Students were surprised to incorporate techniques and knowledge from other subjects, such as mathematics and modelling, into the systems engineering subject.

System Safety

The final task aimed to expose students to the risk management processes associated with systems engineering involving the identification, quantifying and handling of risk. From the disassembly of the kettle into its lowest components, the students had to analyse each component according to its purpose and how the manufacturer mitigated risk in the design and utilization of that component and subsequently the subsystem and system as a whole. From this analysis the students had to perform a preliminary hazard analysis by identifying all possible hazards of the system. Each identified hazard was recorded, and an associated severity and probability of occurrence classification assigned.

For each hazard, the risk index was determined from the product of the hazard severity index and the hazard probability of occurrence index as dictated by a standard risk matrix. For each identified risk the students had to analyse the design decisions made by the manufacturer to mitigate the risk. As example: the risk of electrical shock to the user of the kettle was identified with a high-risk index. The manufacturer mitigated the risk by using electric isolation of the kettle element, an earth wire, electrically isolated material for the manufacturing of the kettle handle, which effectively reduced the risk index to a low level.

The students followed this method to produce a Risk Analysis document containing the list of identified hazards with its associated risk index and the mitigation procedures the designer and manufacturer have followed to reduce the risk of each hazard to an acceptable level.

RESULTS: ASSESSMENT OF LEARNING

After the conclusion of the five learning sessions, students were asked to complete a survey relating to the implementation of the ROLC in the systems engineering module. The survey contained ten Likert scale questions, with possible responses on a 5-point scale ranging from “strongly disagree” to “strongly agree”. The researchers and lecturers of the class structured the questions in the survey in order to determine if the ROLC approach helped the students to understand complex systems engineering concepts and included the following:

- Investigating the kettle helped me to understand the principles of SE.
- The analysis of a commercial product enabled me to understand and implement the SE process.
- The practical sessions enhanced my understanding of the theoretical concepts taught in class.
- The small group enabled me to gain hands-on experience which helped me to understand SE concepts.

All the 3rd year undergraduate electrical engineering students registered for the module were asked to complete the survey. In total, 89 students were registered for the course and 40 students completed the survey. The survey was conducted in class after the conclusion of the final practical session. The results from the 10 questions are provided in Figure 3 below.

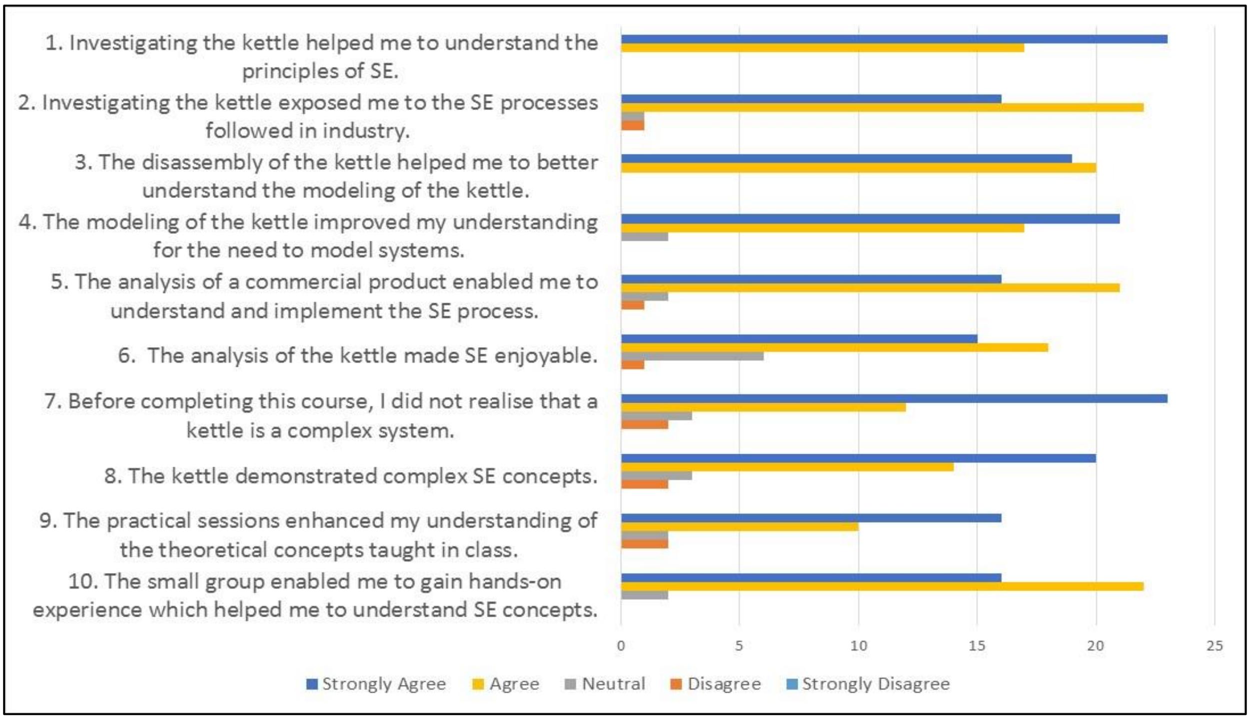

Figure 3: Survey results

The results obtained from the survey were favourable for the use of the ROLC approach to teach core systems engineering concepts. The students indicated that the small groups and the utilization of the kettle assisted them to understand systems engineering concepts better.

In addition to the 10 questions, students were asked to provide additional feedback if willing. In the open feedback section three main themes could be determined:

(1) The utilization of the kettle as a system
(2) The method of group work
(3) The importance of safety standards in projects

Many students commented on their surprise to discover the complexities of the kettle. One student stated that "(u)sing the kettle had a good standing in terms of simplicity and had just enough complexities to give (them) a good idea of how different system interact…". A second indicated that he/she "didn't know a kettle was this complicated" and that the "lessons really taught (them) how to think like an engineer". Other students stated that "(t)he kettle is a simple device with a complicated design behind it. It was good that to be taught the systems engineering principles using it because one can realise the importance of design and manufacture in engineering" and that the "kettle simplicity helped with gaining the knowledge of system engineering and taught me how it can be applied to more complex systems."

Students also commented on the group activities. A student stated that he/she "learnt that engineering is a group activity, you need to work together in order to learn new things". Another commented on learning the "ability to analyse and apply the strengths of team members". A third student stated that an important lesson learnt was "(t)he importance of team work and communication when doing an engineering project".

Lastly, students commented on learning more about the importance of safety standards when designing. Students stated that "safety needs to be considered with a project/product because the first duty of an engineer is the health and safety of the public" and that it is important to "apply safety standard to the project / product(s)".

Results from this study show that the students' familiarity of the everyday product allowed students not to be distracted by the complexity of the product since they already have a thorough understanding of the operating principles of the device. The electric kettle contained enough interdisciplinary complexity to enable the student to develop and understand the systems engineering concepts underpinning the development of the product. Overall, most of the students indicated that the method of instruction assisted them in learning systems engineering concepts and gave them a fair understanding of how complex systems interact and function.

CONCLUSION

This paper presented a reverse order life cycle approach for enhancing systems engineering education in an undergraduate programme in electrical engineering. An ordinary electric kettle was selected as the technology object of which the underlying systems engineering concepts were studied. Utilising the reverse order life cycle process, students used inductive reasoning by observing the final product (electric kettle) first and predicting the underlying component structure of the product. The learning experiences of the students were captured through individual reflection reports as well as group feedback.

The study indicates that the use of the reverse order life cycle process enabled the students to grasp and understand the concepts of systems engineering in a real complex system. Through inductive reasoning by observing the final product, students could see the experience, skills and knowledge utilized by the manufacturer during the design and manufacturing of the final product.

As industry and government become more dependent on systems solutions for complex problems due to the advancement of Industry 4.0 technologies, the students' understanding of complex systems and the systems engineering concepts underlying these systems are critical. The utilisation of an electric kettle, where the technical functions are well known, enabled the engineering lecturer to provide expert insight and guidance regarding the SE concepts are they were taught to the students. As the studied system was familiar, the students could gain the necessary insight and understanding regarding the dynamics of a complex system and the underlying systems engineering concepts.

The results of this work show that the use of the ROLC process and a familiar electrical appliance, such as an electric kettle, can better prepare students for future SE jobs as it improves undergraduate students' understanding of real-life complex systems seen in society today.

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