International Journal of Engineering Education Vol. 38, No. 1, pp. 110–116, 2022
Printed in Great Britain

0949-149X/91 $3.00+0.00

Phenomenon- and Project-Based Learning Through the Lens of Sustainability*

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To embed the phenomenon of sustainability in engineering education, there are few practices to think about and put into implementation. This article attempts to address this pedagogical challenge by developing a teaching and learning practice for knowledge creation and competence. To realize this practice, the notion of the intelligent building has been addressed within the sustainability domain by piloting systems thinking pedagogy that incorporates learning tasks like cases, design modules, projects and is facilitated by guidance, feedback, and critique. The process utilizes the University of Ottawa (uOttawa) campus buildings as a "real-space sustainability lab" for developing learning content and collecting data for engineering design projects as part of teaching four related undergraduate courses. Gathered data from the questionnaires, interviews and observation clearly show that unleashing engaging activities into phenomena- and project-based learning may significantly improve student analytical thinking, reflective judgment, and self-efficacy.

Keywords: phenomenon- and project-based learning; sustainability; engineering design; intelligent buildings; systems thinking; knowledge creation; reflective practice

1. Phenomenon-Based Learning (PhenoBL)

Design is a creative process and a strong tool to pioneer change in engineering education. Given the growing scope of sustainability challenges ahead and the complexity and diversity of the technologies, creativity will grow in importance in engineering learning. Creativity can be stimulated by taking students far out of their comfort zone, bombarding them with things they have never encountered before, and challenging them in design projects. This entails whole-brain thinking: "right-brain" thinking for creativity, imagination, and holistic systems thinking; and "left-brain" thinking for logical reasoning, analytical reasoning, and planning [1–3]. The process requires a transdisciplinary education to combine tools, techniques, and methods from various disciplines [4] as well as a simultaneous collaboration by sharing ideas between and across disciplines, and beyond a discipline [5].

In 1781, Immanuel Kant argued that cognitive agents ignored the underlying structure of their world (noumenal reality), and could only know phenomenal reality (the world "as it appears" through experience) [6]. A phenomenon is an observable happening or event as it appears in our environments or experiences like a building. By contrast, a noumenon is a non-observable force whose existence is indirectly established like wired and wireless electricity [7], artificial intelligence (AI), and machine learning (ML). Throughout the curriculum, the central feature of the two complementary terms "phenomenon/noumenon" is their transdisciplinary focus which can be explored. Is this feature related to engineering? Well, the practice of designing and constructing the building system, for example, involves both visible and invisible experiences. It refers to the sensible and intelligible world, where if something is known about the phenomenon, then this entails something about the noumenon.

Finland's Phenomenal Institute says that in PhenoBL, "holistic real-world phenomenon provides the starting point for learning. The phenomena are studied as complete entities, in their real context, and the information and skills related to them are studied by crossing the boundaries between subjects" [8]. PhenoBL is a pedagogy that aims to teach subject areas concurrently rather than separately, in a holistic approach rather than teaching subjects in silos. The content is learned through an exercise that implies students undergo integration of experiences with an element of ambiguity, which educators need to be ready to face. PhenoBL also provides the students with opportunities to investigate a topic in detail with deeper knowledge and awareness. This invites learners to break the boundaries of traditional subject teaching and move toward explorations of topics [9]. In engineering design, the concept of PhenoBL is not commonly encountered in the literature, however, it provides an interesting framework for encouraging creativity and self-directed active learning.

A transdisciplinary integration of topics allows comprehending whole systems in their complexity, as well as the interplay between natural and man-

* Accepted 30 August 2021.

made determinants as is evident in the physical notion of intelligent buildings (IB) incorporated within the phenomenon of sustainability in its ecological, economical, safety, and social dimensions. This integration may be realized through a lens of systems thinking pedagogy where sustainability is conceptualized and actualized as a driver for knowledge creation aided by active learning approaches as shown in Fig. 1. It is a unique practice in terms of assimilating engineering education within the PhenoBL and project-based learning (PBL). An emphasis on sustainability narrows the lens through which to view design literacy and ensure that scientific knowledge is not the only driver but all aspects of knowledge, particularly economic and social are required. Narrowing down, the process combines knowledge and blends various skills and tools from design thinking, collaboration, professionalism, and reflective practice. This combination calls for a strong alliance between instructors, learners, and institutions to develop an approach for intellectualizing real-life applications supported by resources, guidance, feedback, and critique.

2. Building as a System

Building science considers the building as a "system" that requires effective solutions for the comfort of its occupants. The primary elements of this system include a façade (envelope), inhabitants (humans, animals, and/or plants), technical systems (electrical/mechanical/electronic), a site with its landscape and infrastructure, and the external environment (weather and micro-climate) [10]. There are two major meanings to the notion of "intelligence" in a building system: the façade and the technical systems. Façade is a partial aspect of the wider significance of an IB. It is the interface between interior space and the exterior environment [11], with a significant impact on a building's overall performance. Technical systems include the various types of power-operated machines such as electricity, water, information and communication technologies (ICT), heating, ventilation, air conditioning (HVAC), security, safety, and privacy together with automation, embedded sensors, and other high-tech systems [12].

Today, what does it implies to be a conventional, high-performance, smart or intelligent building? They are all colloquial terms describing ever-growing opportunities to improve upon building with lots of overlap [13]. High-performance design equally focuses on the building form and its capacity for efficient use of energy. Leadership in Energy and Environment Design (LEED) and other green rating systems are examples of the standard-bearers of high-performance buildings to evaluate sustainability based on factors such as design, construction, maintenance, operation as well as occupant health and comfort [14].

"Smart" and "intelligence" are challenging terms to define and measure. Smart means common sense and awareness of the environment. Within the design disciplines, smart has most frequently been used around materials and surfaces [15]. Fundamentally, a smart building uses ICTs and automation to gather, analyze, and share information about what happens in the building to optimize the building's performance while enhancing occupants' comfort and using less energy than a conventional building.

The Intelligent Building Institute (IBI) Foundation in 1989 defined an IB as "one which provides a productive and cost-effective environment through optimization of its four basic elements including structures, systems, services, and management as well as the interrelationships between them" [16]. In

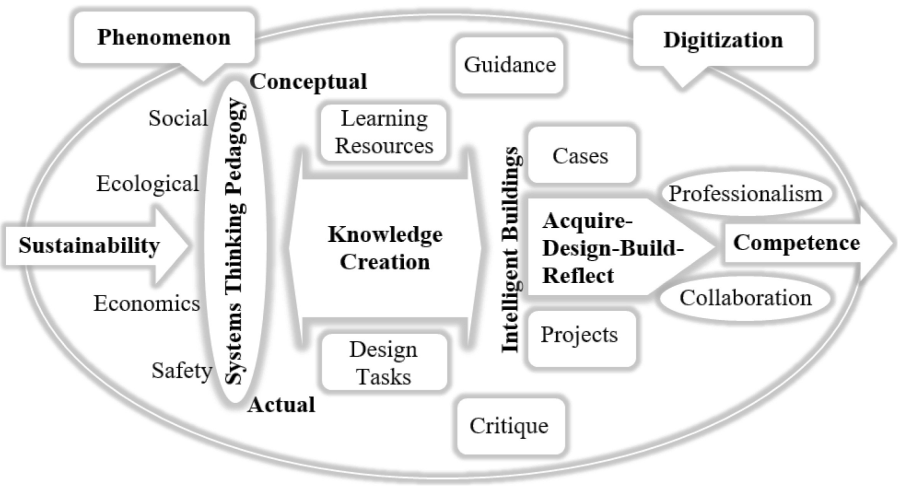

Fig. 1. Phenomenon- and project-based learning practice.

recent years, AI and ML have been proposed for forecasting building performance. It is emphasized that AI when combined with Big Data and building information modeling (BIM), can tremendously increase the energy efficiency and cost-effectiveness of buildings that are designed to provide occupants with a comfortable indoor living environment. BIM is an integrating technology that supports developing an information backbone to transcend organizational boundaries within projects [17]. Although these disruptive technologies come with challenges, the prospect is there for facilitating solutions.

3. Knowledge Creation Across and Beyond Disciplines

As part of multiple coursework for creating knowledge upon PhenoBL and PBL combined, four undergraduate courses taught by the first author make the case of this investigation. These include two electrical engineering courses: "Electric Power Transmission, Distribution and Utilization Systems (ELG4125-Fall)" and "Power Electronics (ELG4139-Fall)"; and two mechanical engineering courses: "Electronics for Mechanical Engineering (ELG3336-Fall)" and "Electric Circuits and Machines for Mechanical Engineering (ELG2336-Winter)".

The transdisciplinary topic of IBs was chosen as a teaching medium for the 10-week lab project for each course. This multi-task project as a whole makes the learning process worthy of reflection, technically and pedagogically. The project narrative is accompanied by supporting information and scaffolding tools that facilitate knowledge creation through hands-on and digital media experiences. The idea requires students to explicitly consider the interaction between the basics of electrical and mechanical engineering, building science, sustainability and health, and skills of design, simulation, and prototype development. The first author collaborates with the Office of Campus Sustainability in providing information and data about the uOttawa campus buildings. A local consulting firm specialized in transformers and other technical equipment collaborates in supplying the students with information and guidance in terms of equipment specifications and Canadian code requirements.

The first author taught in Finland for three years and is largely interested in the Finnish concept of PhenoBL [18]. It is significant to note that the starting point of PhenoBL is constructivism, in which students are viewed as active learners, knowledge creators. The information is seen as being constructed as a result of problem defining and solving constructed out of little pieces into a whole that suits the situation in which it is used at the time [8]. A design paradigm that focuses on the system's stream of connected experiences was adopted in teaching the four undergraduate courses. This design paradigm does not contradict traditional teaching but is a compliment. Yet, it was found that it facilitated the conception and the explanation of a holistic system. Systems thinking is an important part of PhenoBL and PBL because it helps simplify various problems by classifying them according to their root disciplines and subjects. PhenoBL, especially when applied to engineering projects, is about crossing boundaries between disciplines and proving their interrelated nature, basing them in the world around us to spark interest and ingenuity.

The whole project work involves five tasks based on the hierarchy shown in Fig. 2. Each course is allocated certain tasks according to the content knowledge. Teaching these courses is based on both direct instruction and learner-controlled knowledge principle where the flow is a steady move from lectures and tutorials, to the hands-on lab, to self-controlled experiences. Each course project is introduced at the beginning of the semester where students can select the work that is most meaningful to them within the phenomena of IB. Each group of two students is expected to write a proposal and proceed throughout the semester. Small group work leads to better retention of information. The proposal must be prepared by Week 5, which concludes the conceptual design phase. Upon approval, the group proceeds towards detailed design work (ELG4125 and ELG2336) and prototyping (ELG4139 and ELG3336). The project is based on an authentic open-ended problem with clear success criteria by breaking down the task into meaningful, achievable pieces that relate directly to the project objectives. It aims at learning on a "need to know" basis where students become researchers who gather knowledge, then decide from among the best solutions.

The ELG4125 class performs Tasks 1, 2, 4, and 5 with emphasis on electrical system design. The ELG2336 class performs Tasks 1 and 2 with emphasis on mechanical system design, mainly the HVAC system. The ELG4139 class performs Task 3 which involves developing a smart testbed with a focus on data acquisition integrated with BIM simulation software. However, the ELG3336 class performs Tasks 3 and 5 with a focus on mechatronics. The instructors (professor, teaching assistants, and invited speakers) facilitate discussion at the class level and critique at the group level to validate the proposed solutions. The projects are mostly focused on on-campus buildings as a part of actualizing its organizational sustainability culture. The uOttawa is determined to adopt a culture that

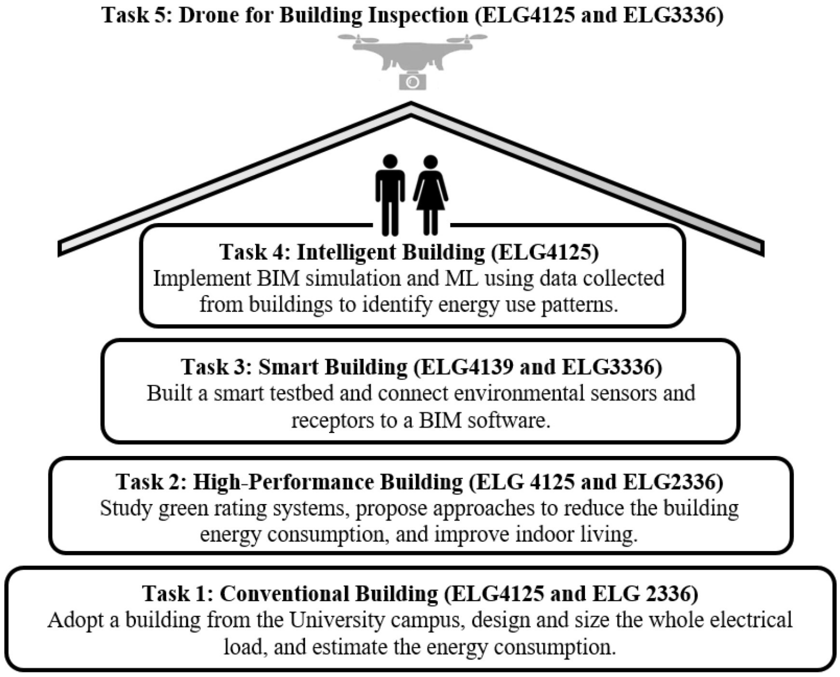

Fig. 2. Project tasks allocated for the four undergraduate courses.

values sustainability and has an enduring commitment to perform in a sustainable and environmentally responsible way. Its Sustainability Policy is reviewed annually and remains a core value, "promoting the principles of sustainability through teaching and research concerning environmental protection and sustainable practices" [19].

The final submission for ELG4125 and ELG2336 is in the form of a design portfolio including a summative one-page e-poster, five-page design details, prototype, and a 2–3-minute video that shines a light on the basics and outcomes of their investigation. However, the final submission for ELG3336 and ELG4139 is in the form of prototypes usually exhibited together to the entire faculty in addition to an e-poster. The portfolio reflects the whole student's progress in self-directed design learning. Videos and prototypes are artifacts that incorporate reflection on what students have learned. Be it in the form of a video or prototype, students prove that they are capable of creating new knowledge by investigating concepts, developing new knowledge, and finally sharing that knowledge with others.

4. Learning and Assessment Practice

At the end of each semester, project presentation sessions are organized to realize the learning outcomes from the entire experience. Students are asked to peer evaluate the projects and take an end-of-class questionnaire. Students in each class are asked to attend the presentations and interact with presenters. In addition to acquiring presentation and listening skills, students complement their knowledge about building designs since the presentations are about different buildings. An important outcome from this process is making students knowledgeable about the campus and connecting them to buildings they study and live in.

By acquiring design skills, the above four courses represent a recruitment hub for a community of several student competition teams at the Faculty of Engineering's Brunsfield Centre for Engineering Student Projects and Entrepreneurship. In 2014, two students from the ELG4125 class collaborated with another two students from the School of Architecture at Carleton University in the design of a net-zero energy building (NZEB). The team competed at the national Evolve Sustainable Design competition and won the first runner-up award [20]. In terms of learning outcomes, Table 1 outlines the microlearning associated with each project task as well as the combined outcomes. Perceived as a whole experience, a new approach emerges, highlighting the importance of integrating the proposed PhenoBL and PBL platform with knowledge and skills from various courses to enhance student teaching and learning.

To assess the process of learning, the authors thought of two major evaluative goals: knowledge creation and reflective practice. For data collection, three brainstorming techniques were used: questionnaire, interview, and observation as an impor-

Table 1. Major learning outcomes

Task 1: Conventional Buildings (ELG4125 and ELG2336)
• Realize the building as a system and learn how to size electrical loads. • Recognize building model simplifications and likely impacts on simulation predictions. • Learn about transformers, panels, loads, standards, and codes.
Task 2: High-Performance Buildings (ELG4125 and ELG2336)
• Explore major standards and rating systems (e.g., LEED and WELL) that promote sustainability in building practices. • Realize electrification and decarbonization in the built environment.
Task 3: Smart Buildings (ELG4139 and ELG3336)
• Design and build a smart testbed using a microcontroller and various environmental sensors and actuators integrated with BIM simulation software.
Task 4: Intelligent Buildings (ELG4125)
• Obtain the annual gathered data samples from various buildings of the uOttawa campus for training and testing. • Learn how AI, ML, and databases can be applied in energy conservation and indoor living environment.
Task 5: Drone for Building Inspection (ELG4125 and ELG3336)
• Design a drone and size the various components that will enable it to fly continuously for 30 minutes around a tall building carrying the needed equipment for inspecting possible envelope failures.
Combined Outcomes
• Realize the importance of knowledge creation within the PhenoPL in the learning process. • Realize the uOttawa campus as a "Real-life Sustainability Lab" where students learn about the operation of the main power plant, electricity grid, data center, sports facility, and corresponding systems. • Conceptualize modeling and design solutions to solve problems related to energy efficiency and healthy living. • Recognize the impact of transdisciplinary education and the integration of disciplines and subjects.

tant complement due to its directness. The questionnaires were given anonymously and in recent years throughout BrightSpace. Collected data from the questionnaires for ELG3336, ELG4125, and ELG4139 showed that about 60% of students strongly agree with the learning approach. About 30% of students just agreed with the approach, while about 7% disagreed for various reasons including mainly the demanding process and the additional digital tools to acquire. Collected data from interviews and observation support the need for more reflection by linking course content knowledge to the design project on an ongoing basis throughout the entirety of each course not just at the end of the project tasks. It is observed that reflection becomes more meaningful when it leads to action, critique, and revision. However, weaknesses existed especially during the start of the project where students needed support in terms of literature review as well as acquiring simulation tools. The situation is sometimes difficult and frustrating to some students, this allows instructors to proactively drive the motivation of the students toward research and inquiry.

For ELG2336 in particular, student perspectives when choosing the IBs were encouraging but urge for future improvement, although few students see it as demanding or early for their level of knowledge, being in their second year of study. One promising approach to meet the challenge is to link building electrical load design to circuit theory, mainly Ohm's and Kirchhoff's laws. The following are several of ELG2336 students' feedback:

> "The project is interesting, it involves taking knowledge learned in the classroom and applying it on a large scale in real-life application." "Interesting to learn about real-life situations." "Real-life implementations, teamwork is the key, punctuality is important, I believe this will add to my experience for the future, improvements are always possible but can't think of any right now." "It is certainly useful and is unique. Many things in this world are educated guesses." "I don't like it, for an intro course to electricity/circuits/components, the project is a lot of work, maybe hold off with this until the next course."

Finally, we have found student interviews as a supplemental assessment technique. These are interactions that students and teachers value and learn from. While providing critique and feedback, the authors had an opportunity to better understand the process of learning by forming connections, proactively drive the motivation of students, and develop their graduate attributes.

5. Conclusion

This article is an attempt to answer a question about knowledge (beyond scientific) creation practice and skill base by connecting the duality "PhenoBL and PBL" and sustainability with its social, ecology, economic, and safety dimensions. To obtain an answer, the notion of an IB has been adopted and addressed by piloting systems thinking pedagogy that utilizes the uOttawa campus buildings as a "real-space sustainability lab" for developing teaching content and collecting data for engineering design projects as part of teaching four related undergraduate courses. Based on the given interconnected tasks, a learning process of how students can simultaneously reinforce their knowledge is established. By-products of this cycle include both a greater awareness of the significances of student decisions and a more vital understanding of the limitations inherent in the process. Collected data from the questionnaires, interviews, and observation clearly show that unleashing engaging activities into PhenoBL and PBL paradigms may significantly improve student analytical thinking, reflective judgment, and self-efficacy. In addition to acquiring knowledge and design skills, the pedagogy aims to empower designers of future buildings to address the challenges of digitization, energy efficiency, healthy living, and the human social dimension. The authors recommend that engineering educators may use the "PhenoBL and PBL" pedagogy in teaching since this instructional approach engages students in learning that is more focused on real-life applications. This pedagogy applies knowledge and skills from various subjects and enriches competencies like creativity, problem-solving, professionalism, and collaboration. Intervention in this regard should include consideration for sustainability and health determinants as a step forward.

Acknowledgments – We would like to acknowledge the large number of students who have taken the courses over the past several years for trialing this learning approach, and would especially like to thank them for their many productive suggestions.

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