From Concept to Reality: Sharing Insights and Pathways for Enabling Experiential Learning in Real-time Sensing

Sanam Aghdamy[a], Cheryl J. Desha[a], Dominic Ong[a], Shanmuganathan Gunalan[a], Hong Guan[a], Andy Nguyen[b], David Rowlands[a]
School of Engineering and Built Environment, Griffith University[a], School of Civil Engineering and Surveying, University of Southern Queensland[b]
Corresponding Author's Email: s.aghdamy@griffith.edu.au

CONTEXT

21st Century engineering demands competency in data retrieval, storage and management, where possible in real or near-real time. From design through to operation, maintenance and disassembly, it is critical for engineers to harness the power of data analytics, towards achieving crucial infrastructure and development targets within many of the 17 United Nations Sustainable Development Goals. However, engineering curriculum is still deficient in teaching how to gather, analyse and interpret data, and communicate the resultant knowledge for decision-makers. This is beginning to be addressed within higher education as there are emergent examples of 'living buildings' where students access and work with real time or near-real time building data to develop such knowledge and skills. However, this remains a relative 'novelty' in Australia, in several niche learning environments.

PURPOSE

This paper documents the authors' journey in 'Phase 1', namely integrating real-time sensing features within a new building to address data information and knowledge literacy. Efforts have been guided by CDIO (Cognitive, Design, Implement and Operate) as a member of this community of practice and insights into sustainability transitions provided by Multi-Level Perspective MLP Theory. The paper presents a narrative on the resultant pathway experienced by the authors in enabling CDIO outcomes through establishing on-campus real-time sensing. The authors intend for the paper to share lessons-learned, to support other colleagues attempting to use living laboratories to equip students with knowledge and skills for 21st Century engineering. It will complement a future 'Phase 2' paper that evaluates the curriculum renewal efforts that engage with the living building once it is in operation.

APPROACH

The authors reflect on navigating organisational and technical challenges to a successful outcome. Using language from MLP, this included: addressing factors within the 'socio-technical regime' through identifying the diversity of stakeholders and establishing partnerships early-on, and upfront consideration of the market availability of sensors and establishing best value for curriculum integration. It also included addressing the 'socio-technical landscape' through evaluating emergent end-user interests, spanning student learning and academic research interests, and obtaining broad support through involving CDIO and disciplines already engaged in data curation.

RESULTS

The paper documents the outcomes in producing the "living laboratory". Organisational outcomes included the established relationship between the School and Facilities Management, more than $150,000 of University funding (cash: $130,000 and Industry in-kind: $20,000). Technical outcomes included the integration of sensors that produce data suitable for use in various core and advanced engineering curricula, across several disciplines, with future-readiness for a graphical user interface. Pedagogical outcomes include the creation of a working group to embark on 'Phase 2' of the journey, to embed the living laboratory within coursework, research supervision, and evaluate the results.

CONCLUSIONS

The paper concludes the benefits of using MLP Theory to guide the initiative, and the necessity of 'Phase 2' data to evaluate students' experience of learning, and benefits towards a 21st Century curriculum.

KEYWORDS

Experiential learning, real-time sensing, living laboratory

Introduction: Informing the ‘Why’ and ‘How’ Phase 1

This paper documents the authors’ journey in integrating real-time sensing features within a proposed new building to address data information and knowledge literacy. Prompted by calls to action within the CDIO - Cognitive, Design, Implement and Operate - community of practice, the authors reflect on navigating organisational and technical challenges to a successful outcome in ‘Phase 1’ of a 2-Phase journey, where the second phase will involve embedding the data within curriculum and evaluating the shift in data literacy. Using language from Multi-Level Perspective Theory (Geels, 2011), the authors address factors within the ‘socio-technical regime’ through identifying the diversity of stakeholders and establishing partnerships early-on, and upfront consideration of the market availability of sensors and establishing best value for curriculum integration. They also address the ‘socio-technical landscape’ through evaluating emergent end-user interests, spanning student learning and academic research interests, and obtaining broad support through involving CDIO and disciplines already engaged in data curation.

Responding to the call for data literacy

Over the last decade, several key studies have highlighted the critical need to provide students with a deeper understanding of the fundamental concepts and principles of engineering and to equip them with the means to meet the challenges of the 21st Century. As recognised by key bodies including the World Federation of Engineering Organisations (2017) from design through to operation, maintenance and disassembly, it is critical for engineers to harness the power of data analytics, towards achieving crucial infrastructure and development targets within many of the 17 United Nations Sustainable Development Goals (United Nations, 2015).

As concluded by Ridsdale *et al* (2015), there is an urgent need for critical knowledge and skill development in data curation spanning monitoring, collection, analysis, interpretation and communication. Furthermore, there is a need to go beyond data itself, to understand where it has come from. Melsa *et al* (2009) reflect on providing more experience in applying theoretical understanding to real problems. This point was also acknowledged in Sheppard *et al* (2009). However, studies such as Goldsmith *et al* (2011) and Brunhaver *et al* (2018) conclude that the engineering curriculum is still largely deficient in teaching how to discern what data to gather, how to gather, analyse and interpret data, and then how to communicate the resultant knowledge for decision-makers. Within the CDIO community of practice, there has also been a concerted effort over the past 10 years to encourage learners to develop curiosity in the process of manufacturing or design, towards solutions that are better for people and for the planet (Takemata *et al*, 2013; Muñoz Guijosa *et al*, 2016). This includes the need for students to develop a strong sense of purpose in a world of rapidly increasing data availability, to know ‘why’ data is important, ‘how’ to curate the data, ‘what’ should be prioritised and acted upon within iterative design processes, and ‘who’ the data should be communicated to for effective construction/ implementation of the solution.

Studies by Byrne *et al* (2012) and Kershaw *et al* (2017) highlight the potential for ‘living buildings’ to provide such learning environments, where students access and work with historical and real time or near-real time data about the building performance from construction through to operation, to develop such knowledge and skills. However, this remains a relative ‘novelty’ in Australia, in several niche learning environments such as Curtin University and The University of Melbourne.

A new building opportunity through the lens of Multi-Level Perspective Theory

In 2016 the Griffith University Council agreed to add a new building to the Nathan campus, to meet increasing demand for engineering and built environment facilities across programs in engineering, architecture, design and aviation. The “ETA” *Engineering, Technology and*

Aviation building, Building N79, would house innovative learning and teaching facilities for the university's School of Built Environment and Engineering, with design goals emulating the CDIO community of practice aspirations of which Griffith University is a member.

Within this context, the second-author took on the End-User Coordinator role for the 3-year design and construction journey. This included overseeing the embedding of building technology and equipment to enable experiential learning by students across all major engineering disciplines to be taught civil, environmental, mechanical, electrical and electronic, software. End-user consultation amongst the School Executive resulted in a consensus to pursue a 'living building' outcome that could then be used to scaffold digital literacy throughout the curriculum across these disciplines. In considering how to project manage such a request, the second-author built on previous capacity-building research into the role of partnerships for rapid curriculum renewal (Desha, Robinson, & Sproul, 2015), which had identified the need to engage with a diverse set of stakeholders spanning multiple disciplines and multiple levels of hierarchy. Furthermore, innovation diffusion studies by Geels and Schot (2007) and Geels (2012) provided the lens of Multi-Level Perspective Theory, which considers the innovation itself, the socio-technical regime within which it is being deployed, and the socio-technical landscape within which it needs to survive into 'mainstream', integrated application as a normal feature of the curriculum.

The authors also referred to literature by researchers including Nguyen *et al* (2015) on the topic of developing a cost-effective vibration data acquisition system for long-term continuous structural health monitoring, Tschimmel (2012) regarding design thinking models as effective Toolkits for Innovation, and Piironen (2017) regarding multidisciplinary CDIO projects. They subsequently sought to address factors within the 'socio-technical regime' through identifying the diversity of stakeholders and establishing partnerships early-on, and upfront consideration of the market availability of sensors and establishing best value for curriculum integration. They also sought to address the 'socio-technical landscape' through evaluating emergent end-user interests, spanning student learning and academic research interests, and obtaining broad support through involving CDIO and disciplines already engaged in data curation.

Enabling a living laboratory Phase 1

In the following sections, the authors outline the organisational coordination and technical considerations for sub-surface and surface monitoring and the roles the sensors will play in the teaching and understanding of various engineering concepts within the school. Additionally, it shares lessons-learned in developing the building as an interactive teaching tool, support them contemplating similar student engagement with data and sensing through new buildings or substantial building retrofits on their campus. Organisational outcomes included the established relationship between the School and Facilities Management, more than $150,000 of University cash $130,000 and Industry in-kind $20,000 funding. Technical outcomes included the integration of sub-surface and surface sensors that produce data suitable for use in various core and advanced engineering curricula, across several disciplines, with future-readiness for a graphical user interface. Pedagogical outcomes include the creation of a working group to embark on 'Phase 2' of the journey, to embed the living laboratory within coursework and research supervision, and evaluate the results.

Organisational partnerships

Given the complex interactions that happen amongst client, contractor and sub-contractors during building projects, the challenge of integrating a living laboratory within the building was important to address from early in the design phase. It was also critical to track the design phases and then construction to ensure that aspects such as plans for sensing locations, wiring and sequencing of installation were adapted as the design expectations and scope of the building changed. The resultant organisational map is discussed below.

(1) Facilities management (Internal): The relationship between the academic personnel and Facilities Management was crucial to ensure all project team members understood why particular locations were important to install sensors on or in, and why it would be advantageous to install and monitor from early in the construction process. For example, there was considerable coordination effort required to plan out the construction sequence for the main columns of the building, to enable the earth pressure sensors to be installed safely in between concrete pours. There was also considerable planning required to ensure data could be retrieved from the sensors in the period between installation and electricity being connected to the site. This involved extensive consultation with the data team, and also innovation provided by the engineering workshop, to enable robust battery storage in outdoor environments.

(2) University engagement (Internal): On reflection, University leadership was critical to the success of the living laboratory project, enabling pathways for submitting equipment grant funding applications “out of round” to normal acquisition processes due to the timing of the design and planned construction phases. Sciences Group level appreciation of the CDIO community of practice was also key to sharing the vision of a living laboratory for experiential learning, which began a year before the building project commenced. Such long-term agenda-setting by the School Executive enabled alignment of the building project with intentions to enact an experiential curriculum renewal process.

(3) Academic collaborators (External): Drawing on existing relationships with CDIO members and the goodwill within this community to share best practice, this included drawing on previous and current research and scholarship relationships with academics in other universities to discuss priorities for experiential learning, and methods that could work in obtaining relevant building data for various coursework needs in the engineering curriculum. It also included engaging with academics inside the university in other faculties spanning information technology and environmental science, to ensure that the ‘business case’ for creating a living laboratory was larger than ‘just engineering curriculum’, but also included the future potential to harvest data about the outdoor and internal environmental conditions humidity, temperature etc, people movement and room occupancy.

(4) Technical review – expert panel (External): The authors have often reflected to one another that access to technical reviewers and expertise outside the core project team was a critical component in the success of the living laboratory project. This spanned engineers from within the design firms who provided advice on likely locations of interest on the building from a structural perspective, through to industry personnel from sub-surface testing companies, in addition to the product manufacturers.

(5) Architect and design team (External): In the design phase of the project, early scoping of living laboratory needs was critical to enabling some innovative features to be considered in the building. This included for example an extra-long span in a high-use area, which would enable data to be collected showing time-of-day differences. It also included long-spans in the high-bay lab, which required sensors on the ceiling and a strategy for installation and ongoing maintenance of these sensors at-height.

(6) Contractor and sub-contractors (External): In the construction phase of the project, it was important to engage with the new project lead the head contractor to ensure that the living laboratory knowledge generated during the design phase was transferred to the work plans and relevant sub-contractor installation requirements at the right time and in the right place during construction.

Technical components

Electronic sensors were placed at sub-surface level to capture environmental effects including rainfall, temperature and groundwater fluctuations within the design life of the sensors. Additionally, surface level sensors are in the process of being installed to capture how the building will respond to short-term and long-term loading effects construction, wind, shrinkage, creep, laboratory machineries induced vibrations and etc.

Sub-Surface sensors

Two vibrating wire piezometers with capacity limit up to 350kPa and one observation well were installed at a depth of about 6m below the surface of the slope on an easily accessible green-field location immediately across the road from the N79 building. These locations were selected so that the piezometers could measure the actual ground water table fluctuation over different environment / weather conditions. Piezometers were embedded in the ground in pre-drilled holes. The piezometer tips were encapsulated within a section of porous sand. The top and bottom sections of the encapsulation were sealed in-situ by cement-bentonite mix placed around the annulus of the oversized drilled hole to ensure the sensitive tip only measures the water pressure generated by the groundwater table and not from other seepage sources.

Seven vibrating wire earth pressure cells with capacity limit up to 1,000kPa were installed underneath five footings of the N79 building to measure the bearing pressure of the founding material soil or rock, whose carrying capacity can be affected by the ground water table fluctuations. Earth pressure cell, measuring about 30cm in diameter with a flat, thin face, was typically embedded in specially prepared soil bedding in between the insitu founding soil or rock and the building's reinforced concrete footing. It was placed face-down on the founding material to maximise contact pressure.

A wireless tipping bucket rain gauge was installed on the rooftop of a nearby building (N44), immediately next to N79, which is still being constructed. The location on the rooftop ensures that the rain gauge is unobstructed and free from tree covers. Once N79 is completed, the rain gauge will be moved from building N44 to the N79 rooftop to collect rainfall data, which would be used to develop understanding of the behaviour of the groundwater fluctuation readings measured by the piezometers.

All the above-mentioned sub-surface sensors were connected respectively to vibrating wire interfaces with radio modules thus enabling wireless communication with the data logger model CR1000X-AN-ST-SW to ensure that the sub-surface data is reliably and efficiently collated.

Surface sensors

There are two types of sensors that are being installed on the structural elements at the surface level above the ground, which are accelerometers and strain gauges. The accelerometers (Bestech Wilcoxson; Model ID. 731-207; Nominal sensitivity of 10V/g) will be used to monitor the health status of the structure. As building N79 is obviously not a slender building, such high-sensitivity (i.e., 10V/g) piezoelectric accelerometers are deemed necessary to pick up small vibration responses generated under ambient excitation conditions. Given the semi-rectangular shape of the building, the accelerometers will be positioned on its three corners (i.e., North-West, North-East, and South-East). There will be one single axis accelerometer on the North-West and South-East corners of the building on the first, third and fifth levels and there will be two single axis accelerometers on North-East corner of the building on the first, third and fifth levels (i.e., 12 accelerometers in total). The use of four accelerometers at three corners in each floor is to ensure that the main vibrational behaviour of whole floor, which can be approximated as a rigid body in horizontal movement, can be captured at a minimum cost. It is worth noting that, as there is a discontinuation of some columns in the sixth level of the building N79, the fifth level was considered as the most appropriate highest level for placing global sensors.

A total of 15 strain gauges PCB Piezotronics (Model ID: 740B02) will be used to measure: (1) concrete creep and shrinkage, (2) structural vibration induced by people movement, (3) structural vibration induced by machineries, (4) gantry beam deflection due to crane roll over, and, and (5) deflection due to wind gusts. The use of piezoelectric strain gauges is to ensure that instantaneous strain under dynamic loads can be captured to enable live monitoring observations. These strain gauges will be installed on level one. Two of these strain gauges will be allocated to measure concrete creep and shrinkage. Each of these will be installed on a column close to the underside of the slab. Given the higher level of axial load on level one compared to upper levels, positioning these sensors on this level would maximize the opportunity to obtain more reliable and meaningful results. Two strain gauges will be allocated to measure the vibration induced by people movement. Each of these will be mounted to the underside bottom face of slab of level two (*i.e.*, ceiling of level one). These sensors will be installed on longer span slabs with larger deflection to maximize the opportunity to obtain pronounced and meaningful results.

There will be two strain gauges to measure structural vibration induced by machineries. These sensors will be mounted underside bottom face of slab of level two, where the material testing laboratory is located. The crane gantry beam is located in the high-bay area of flexi-laboratory on level one. To measure the beam’s deflection due to the gantry crane’s roll over, two strain gauges will be installed underside bottom face of the beam. Whilst one of them will be installed at the mid-span the other one will be installed at one third of the beam span from one of the supports. Two strain gauges will be allocated to measure the deflection of the facades at the high-bay area of flexi-laboratory level one due to the wind gusts. These strain gauges will be mounted on the backside of the aluminium header. Finally, five strain gauges will be mounted on the upper side of the walls on level one to measure the deflection due to the wind loads. Since the other strain gauges will be located on level one, these strain gauges have been chosen to be on the same level for convenience and reducing the installation time and cost.

Sensor data acquisition system

As the sub-surface sensors were installed and commissioned, they were calibrated and deemed to be measuring in the range expected. This data was then collected and stored in a central repository so that it can be accessed at any time anywhere on the campus. Griffith University already had the infrastructure available to collect and store large amounts of data from many different sources as it already monitors power usage and temperatures on campus. The new building N79 has a data aggregator which collects the building sensor data and then sends it to the Griffith University server. It was realised that if the data and system were to be accessed by students then it may be problematic to give the students access to the actual archived data. Therefore, a secondary repository was set up to exactly mirror the main repository that students could access.

Pilot, integration and evaluation Phase 2

In the following paragraphs the authors present the next phase of the initiative, which includes summarising findings of a pilot student project that used initial data feeds from some of the sensors to create a way of collating, viewing and visualising the data. The authors then project forward with regard to next steps in integrating the data into coursework and research studies, and evaluating the living laboratory initiative.

Pilot student project: Interactive tool and dashboard

A key part of the living laboratory is the interface between the data itself and the students and staff accessing the data. Since some sub-surface data was available early in the construction, an opportunity was identified to enable a final year Software Engineering student to attempt a visualisation and data collation protocol, within the student’s final year project.

This involved (1) designing and developing a kiosk-style visualisation dashboard and (2) creating a data extraction tool that would allow access to the building's historical sensor data as well the latest live data. The dashboard system consists of a main display that opens the Chromium web browser in the full screen mode. The dashboard used different ad-hoc screen views for each sensor with its background image that would show the location of the sensor in the N79 building. The dashboard cycles through all the sensors individually, highlighting the particular sensor's location on the building floorplan/map and indicating that particular sensor's data. The data extraction tool is a web page that allows the student to request the data for either all the sensors or for a particular sensor in the given time range. It queries the main data repository using those keys, generates a CSV file which can be saved on the user's computer. The saved file can be imported into whatever software the course requires. The data can also be displayed on the screen in a textual format or as a graph.

Integration into coursework and research studies

Data measuring the rainfall, temperature, groundwater fluctuations and movements due to various loadings on the building will be gathered and used to embed into the relevant engineering courses. In order to ensure the ongoing collaboration and connections required as discussed by Geels (2011), the first-author has taken on a formal Teaching and Learning Living Laboratory leadership role within the School. This includes liaising with the listed courses' convenors to connect them with teaching and learning support as needed, enabling the update of course content and assessment to accommodate the living laboratory components.

Evaluation of living laboratory initiative

Evaluation will be undertaken in Phase 2 as curriculum initiatives are undertaken, including:

- "Plus, Minus, Interesting" survey: an informal, formative appraisal of the student experience of the course, conducted at early stage of each trimester. The feedback will allow educators and courses' conveners to understand impacts on students' curiosity and motivation.
- Students' Experience of Course (SEC) survey: a standardised survey conducted at the end of each trimester. The feedback from students will help educators and courses' conveners to understand the link between the curriculum efforts and attained learning outcomes.
- Assessment results: results of assessment where living laboratory data is integrated, will help educators and courses' conveners to understand how well students have learned the associated concepts and/or applications. It will also allow them to 'see' into where the sensors could be contributing to learning, effectively.
- Focus Group: feedback from students from the courses embedding the living laboratory data at the end of each trimester would help educators and courses' conveners to understand students' perceptions and interests.

Conclusions

The paper has documented Phase 1 of the journey in producing the "living laboratory" at Nathan campus of Griffith University, which will now be rolled-out into curriculum and evaluated in Phase 2 of the project. It presents the organisational, technical and pedagogical outcomes in producing the "living laboratory". Organisational outcomes included the established relationship between the School and Facilities Management. Technical outcomes included the integration of sub-surface and surface sensors that produce data suitable for use in various core and advanced engineering curricula, across several disciplines, with future-readiness for a graphical user interface. Pedagogical outcomes include the creation of a working group to embark on 'Phase 2' of the journey, to embed the living laboratory within coursework and research supervision, and evaluate the results. This paper concludes the benefits of using MLP Theory to guide the initiative, and the necessity of 'Phase 2' data to evaluate students' subsequent experience of learning, and benefits towards a 21st Century curriculum.

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