SUSTAINABILITY THINKING IN ENGINEERING EDUCATION: DATA-INTENSIVE RESEARCH, COMPUTATIONAL SUSTAINABILITY AND MULTIDISCIPLINARY RESEARCH

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Abstract: Most universities, and in fact most organizations and government agencies are committed to sustainable development. Sustainability in higher education is also mainstream in the scientific arena with a need for forward looking on how to infuse sustainability across disciplines. Education for sustainable development aims at fostering social, political, economic and ecological issues pertaining sustainable development. The aim of this paper is twofold. The first objective is to introduce Sustainability Thinking as a dedicated program in engineering education for sustainable development, comprising of Data Intensive Research, Computational Sustainability, and Multidisciplinary Research. The second objective is to urge the engineering education community to move towards multidisciplinary research to bear on the pressing global challenges. The paper further expounds on the role of "Big Data" and advanced analytics in engineering research and explores the concepts behind Computational Sustainability: Data Analytics for Sustainability, Computational Thinking, and Systems Thinking. The paper also discusses the role that multidisciplinary research plays in achieving Systems Thinking and finding solutions to many complex sustainability problems. It is further argued that making a paradigm shift in sustainability pedagogy requires a shift in cultures within disciplines of computer science and engineering.

1 INTRODUCTION

Most universities, and in fact most organizations and government agencies are committed to sustainable development. Brundtland Commission of the United Nations (UN) defines sustainable development as a "development that meets the needs of the present without compromising the ability of future generations to meet their own needs" (World Commission on Environment and Development 1987). The UN expanded this definition at the 2005 World Summit to incorporate social, environmental and economic aspects as the three pillars of sustainability (United Nations General Assembly 2005). This definition of sustainability indicates that for our system to be sustainable, it should operate indefinitely into the future. Hence, the role of advanced analytics becomes elevated to optimize the system over time and space.

Sustainability in higher education is also mainstream in the scientific arena with a need for forward looking on how to infuse sustainability across discipline. Education for sustainable development aims at fostering social, political, economic and ecological issues pertaining sustainable development. Engineers are responsible for sustainability performance of all types of enterprises, where socio-environmental properties of products and processes are of prominent importance (Filho 2015).

The aim of this paper is twofold. The first objective is to introduce Sustainability Thinking as a dedicated program in engineering education for sustainable development. The second objective is to urge the engineering education community to move towards multidisciplinary research to bear on the pressing global challenges.

2 SUSTAINABILITY THINKING IN ENGINEERING EDUCATION

There is a need for Sustainability Thinking, topics dedicated on sustainable development for undergraduate and graduate engineering students that addresses the pillars of sustainability in a holistic, synergetic and systematic way. The proposed three topics of Sustainability Thinking in Engineering Education, appropriately developed for undergraduate and graduate level of studies, are as follows:

- Data Intensive Research
- Computational Sustainability
- Multidisciplinary Research

3 DATA INTENSIVE RESEARCH

Global challenges can be mitigated with the help of breakthroughs and new developments in technology. In fact, data and the insight derived from information are critical to tackling sustainability challenges and communicating the results. Information Technology (IT) can be applied to built infrastructure, ecosystems, the environment and sociotechnical systems (The Climate Group 2008). Improvement is seen in sensor technologies (smart planet), communications and human-computer interfaces, data-driven science, modeling and simulation, real-time information and tools, and eco-feedback devices. These improvements in better information collection, analytics and management leads to enhanced policy and decision making (National Research Council 2012).

One of the new challenges of engineering sustainability involves measuring, monitoring, and analyzing the unprecedented amounts of data of our natural and built environment. Sustainability data are particularly heterogeneous, comprising of GIS information, sampled and detailed measurements, images, video and audio files, scanned documents, handwritten notes and comments, and more. The data may be temporal or geospatial in nature, historical (field observations) or real-time (social network forums), with highly variable levels of granularity, completeness and confidence levels. The handling of such a considerable amount of data being hoarded in locations all over the world for sustainability research is currently done in an ad hoc manner (Computing Community Consortium 2011).

Jim Gray (as detailed in Hey et al. 2009) charts the evolution of science through four broad paradigms: A thousand years ago, science was empirical or experimental, describing natural phenomena. For the last hundred years, theoretical branch was formed to use models and make generalizations. During the last millennium, simulation of complex systems was developed. Today, a new and fourth paradigm in computer science has formed: Data Exploration (or eScience), focusing on data-intensive systems and scientific communication (Microsoft Research 2009). Data-intensive science consists of data capture, curation and analysis activities. But, what is so different between computational science and data-intensive science?

Researchers today are using many different methods to collect or generate data. Data comes in all scales and shapes, from sensors to supercomputers, covering large international experiments to individual observations. Scientists are no longer looking through telescopes; instead, they are visualizing data relayed from large-scale complex instruments into data centres and the information processed by the software on their computers (Microsoft Research 2009). This makes data-intensive science unique. Hence, engineering students must adopt to the new technology and the new way of data-intensive research when dealing with “Big Data”.

“Big Data” is huge in volume, diverse in variety (structured and unstructured), and created in real time at a high velocity (Kitchin 2013). Big Data is also exhaustive in scope striving to capture the entire population or systems, fined-grained in resolution and uniquely indexical in identification, relational in nature, and flexible, holding the traits of extensionality and scalability; i.e. expand in size rapidly (Kitchin 2013; Kitchin 2014).

Big Data is becoming more common and new data analytics more advanced. Hence, as Big Data seeks to be exhaustive, capturing a whole domain and providing full resolution, engineering students and researchers shall reconsider their sustainability research methodologies and take on the innovative induction methods. Induction differs from experimental deductive design because it generates hypotheses and insights “born from the data” rather than “born from theory” (Kitchin 2014). To understand real world sustainability problems, one needs to explore the data generated by our real world rather than making assumptions and experimenting within it. Big data and the advanced analytics would enable such advanced novel research methodologies in the field of sustainability research.

Big data is everywhere and is helping everyone. Big data has improved the online advertising sector’s target marketing by tracking the browsing habits of customers, reduced the cost of healthcare sector by creating unified electronic health records, improved management of electricity consumption for the utilities sector and reduced CO2 emissions through the adoption of “smart-grid” technologies, reduced fuel consumption and congestion in the transport sector by tracking the location of mobile and navigation devices, and benefited the public sector. Such benefits include weather forecasts, traffic management, crime statistics, improved transparency of government functions (e.g. procurement) and educational and cultural knowledge for the wider population (OECD 2013).

4 COMPUTATIONAL SUSTAINABILITY

Computational science is now indispensable to the solution of our world complex problems. In fact, computation is now recognized as the third pillar of science along with theory and experimentation (PITAC 2005). Computational Sustainability is an emerging interdisciplinary field that applies computational science techniques to solve the social, economic, and environmental sustainability challenges of our complex world. Computational Sustainability can further be defined as a combination of:

- Data Analytics for Sustainability,
- Computational Thinking, and
- Systems Thinking.

4.1 Data Analytics for Sustainability

Let us expound the use and value of emerging data analytics in engineering education for sustainable development. The term analytics deals with obtaining, processing, describing, visualizing data as well as making sound decisions under uncertainty. Descriptive, predictive and prescriptive analytics are the three pillars of analytics required to improve decision making under uncertainty (IBM 2013):

- Descriptive Analytics answers the question "What has happened?" Using key metrics and key performance indicators, descriptive analytics explores data to find details such as frequency of events, the cost of operations and the root cause of failures, etc.
- Predictive Analytics answers the question "what could happen?" using statistical models and forecasts. Using time-series data trends and correlations, predictive analytics identifies patterns in data and applies advanced statistical analysis, data mining and sophisticated mathematical modeling to validate assumptions and test hypothesis to make confident conclusions.
- Prescriptive Analytics answers the question "what should be done?" using optimization and simulation. Using rules, constraints and thresholds in combination with advanced optimization and mathematical models prescriptive analytics recommends and justifies actions and suggest potential implications of the actions.

Table 1 from IBM portrays the definitions and the application of analytics in the area of facilities asset management.

Table 1: Definitions and Application of Analytics for Asset and Facilities Management (IBM 2013)

Understanding analytics

Definitions, sample applications and opportunities, and underlying technologies

	Descriptive	Predictive	Prescriptive
	What HAS happened?	What COULD happen?	What SHOULD happen?
What the user needs to DO	• Increase asset reliability • Reduce labor and inventory costs	• Predict infrastructure failures • Forecast facilities space demands	• Increase asset utilization • Optimize resource schedules
What the user needs to KNOW	• The number and types of asset failures • Why maintenance costs are high • The value of the materials inventory	• How to anticipate failures for specific asset types • When to consolidate underutilized facilities • How to determine costs to improve service levels	• How to increase asset production • Where to optimally route service technicians • Which strategic facilities plan provides the highest long-term utilization
How analytics gets ANSWERS	• Standard reporting - What happened? • Query/drill down - Where exactly is the problem? • Ad hoc reporting - How many, how often, where?	• Predictive modeling - What will happen next? • Forecasting - What if these trends continue? • Simulation - What could happen? • Alerts - What actions are needed?	• Optimization - What is the best possible outcome? • Random variable optimization - What is the best outcome given the variability in specified areas?
What makes this analysis POSSIBLE	• Alerts, reports, dashboards, business intelligence	• Predictive models, forecasts, statistical analysis, scoring	• Business rules, organization models, comparisons, optimization

Business value →

Furthermore, analytics provides insights from past and real-time data to predict future trends and mitigate risks, manage uncertainty, identify gaps and opportunities, and accelerate the pace of sustainability innovations. Furthermore, fact-based decision making and optimization can be improved by data analytics. Analytics can bring positive influence on achieving sustainable development outcomes, balancing economic interests against social and environmental concerns through integration and analysis of data, as information is vital to understanding key sustainability issues and their impact. Analytics can be the solution to many complex problems.

What's apparent is that the amount of data being stored in digital databases is astounding fast and growing beyond the capabilities of experts to manage and use the data efficiently. In order to deprive insights from these massive, dynamic, and possibly unstructured data (Big Data), and to not only find the expected but to discover the unexpected, advanced visual analytics helps with synthesizing information using interactive, exploratory, visualisation tools. Rapid technological advancements in hardware, as well as Big Data simulation techniques, have made it possible to capture the changing characteristics of high-dimensional and continuous streams of data of our increasingly complex world in order to take suitable measures in the multi-disciplinary multi-policy areas of sustainable development.

Furthermore, engineers require formal education to advance their analytics skills by gaining capabilities to effectively manage initiatives with a consistent, accurate view of information, integrating forecasting to predict future performance, cost, risk, carbon footprint, GHG emissions, and energy consumption of alternative sustainability initiatives and their resource and capacity needs. With the help of analytics, engineers can model alternative sustainability projects, quantify and simulate their effects on achieving the sustainability goals, make optimal decisions, and propose changes to stakeholders based on data and not merely their intuition.

4.2 Computational Thinking

The idea of Computational Thinking was first introduced by Jeannette Wing. Computational Thinking is a universal skill set for everyone and not just computer scientists (Wing 2006). Wing defines Computational Thinking as “the thought processes involved in formulating problems and their solutions so that the solutions are represented in a form that can be effectively carried out by an information-processing agent” (Wing 2011). Wing further outlines the benefits of Computational Thinking for scientists, engineers and other professionals as follows:

- Apply new computational methods to their problems,
- Reformulate problems to be amenable to computational strategies,
- Discover new science through analysis of large data,
- Ask new questions that were not thought of or dared to ask because of scale, but which are easily addressed computationally, and
- Explain problems and solutions in computational terms.

Computational Thinking is spreading nationally and internationally into education, industries and government (PITAC 2005). Campuses in North America and abroad are revisiting their curriculum to incorporate Computational Thinking. For example, founding Google investor, Dr. David Cheriton, has donated $7.5 million to the University of British Columbia to create a new chair in computational science and a first-year course in Computational Thinking accessible to students outside of computer science. Dr. Cheriton regards the computer science discipline “as key to a 21st century education” (UBC News 2014).

4.3 Systems Thinking

Systems Thinking provides the “necessary bridge from Computational Thinking to sustainability practice” (Easterbrook 2014). Sustainability demands systemic approach to acknowledge that “technology, human behaviour and environmental impacts are tightly interrelated” and that Systems Thinking is “an essential component of any attempt to bring about transformational change to a sustainable society” (Easterbrook 2014).

Piero Mella provides his own view of the 5 rules of Systems Thinking set out in Peter Senge’s book *The Fifth Discipline* (Mella 2012): 1) developing the capacity to zoom from the whole to the parts and vice versa, 2) searching for the variables and not constants, 3) understand the cause of the variations and form chains of causal relationships among the connected variables, 4) search for systemic interconnections among variables of interest, and 5) always specify the boundaries of the system we wish to investigate.

However, Systems thinking have had minimal impacts in most academic disciplines because either “the university does not encourage teaching and research into inter-disciplinary ideas” or “the ideas are often too abstract to be useful” (Easterbrook 2014). To address this issue, other approaches of introducing Systems Thinking in engineering curriculum have been explored including hands on experience of the non-linear dynamics of complex systems, understanding social implications of design, full lifecycle analysis, simulation of complex systems, as well as running interdisciplinary courses in Systems Thinking and climate change (Easterbrook 2014). We discuss in the next section, however, that in order to be successful in Systems Thinking and find solutions to many complex sustainability problems, universities need to adopt to multidisciplinary research.

5 MULTIDISCIPLINARY RESEARCH

Sustainability science is an emerging academic field linking and providing a holistic view on global, social and human systems with the aim to examine and repair such systems and linkages. Sustainability science spans multiple disciplines, ranging from humanities to sciences and engineering needing experts who have a broad grasp of the larger picture of sustainability-related issues outside their domain expertise (Komiyama et al. 2011).

Sustainability problems often share challenges of a broad range of domains, heterogeneity of decision variables, interconnection of complex systems, optimization of multi, often conflicting, objectives, and human interaction. This type of work would require a team of multidisciplinary experts and approaches. Research institutions should encourage multidisciplinary research with experts in various fields of sustainability, engineering and computational science.

Research on global issues requires multidisciplinary and integrated approach across disciplines. Obstacles that encumbers dealing with multifaceted concept of sustainability-related issues are the complex nature of the problems and the specialization of the research to address such problems (Komiyama et al. 2011). Although many researches related to science may be appropriate to be performed in silos, engineering researches with sustainability context are not. Scholars specialize to obtain deeper scientific understanding of their subject matter; however, the flood of information and data and the resulting specialization hinders the ability to obtain a comprehensive perspective on both their own and others' research topics. Furthermore, mono-disciplinary work limits the capacity of science to address problems that span multiple disciplines. As well, sustainability science should not be an agglomeration of mono-disciplinary work (Komiyama et al. 2011).

This traditional approach in science research puts the onus on a sole engineering student to learn about all topics relevant to their research in such a short duration of their studies. This is an ineffective engineering research approach especially when the research shall be aimed at sustainable development requiring a multidisciplinary approach in tackling world problems.

A team formed from various disciplines shall be involved in any particular applied engineering sustainability research. For example, for an engineering sustainability problem addressing decision support systems for sustainable operations and management of infrastructure assets, the civil engineering student would research the decision making framework and should be allowed to research and define processes for other team members. Other team members may include a mathematics and statistics student to research probability and statistical analytics techniques, a computer science student to research structured and unstructured databases and computational techniques, an industrial engineering student to research reliability and stochastic optimization techniques, a mechanical engineering student to research performance tools and condition assessment technics, a socio-economics student to research socio-economic impact assessment techniques, and an environmental engineering student to research environmental impact assessment techniques related to such decision support system. This holistic approach across disciplines would lead us towards sustainable development.

Nonetheless, most graduate students are reluctant to work on multidisciplinary and applied sustainability problems due to the time and effort needed to become familiar with other domains. Others are reluctant due to the limited time of their studies. Some computer science students also fear of becoming "coders" for other scientists (National Research Council 2012). We can overcome these challenges by effective research management and task division, academic recognition, adequate funding for extended research and change in culture.

We must establish multidisciplinary research centres devoted to the pursuit of sustainability goals. Such infusion will help grow a next generation of engineering professionals who are motivated and capable of taking more challenging sustainability problems. Computer science students need to be educated in the field of engineering sustainability and engineering students in the field of computational sustainability to find gaps and opportunities exist in each of the disciplines. A team from various disciplines shall be formed to tackle sustainability challenges that are likely to persist for generations. Champions of sustainability education shall bring innovation and sustained commitments of this multi-disciplinary research in support of meeting sustainability challenges.

6 CONCLUSION

Making a paradigm shift in sustainability pedagogy requires a shift in cultures within disciplines of computer science and engineering. Only through collaborations we can change the world and only collaboratively-minded researchers can make it a success. Sustainability research, engineering research and computing research should all be infused through forward-thinking sustainable development management. To succeed in a sustainable data-driven economy, engineers need to be trained in systems thinking, computational sustainability and data-intensive research. These skills include an appropriate mixture of Sustainability Thinking and advanced skills in information and communication technology and statistics in addition the specific knowledge of the engineering discipline. Furthermore demand for “data scientists” has increased in the last couple of years and is likely to intensify as data analytics proliferate (OECD 2013). Data science skills are not merely obtained from formal degrees in data science; the skills need to be acquired in specific engineering study programmes.

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