

MEETING THE CHALLENGES OF ENGINEERING A SUSTAINABLE FUTURE

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ABSTRACT: Engineers have a significant role in the sustainable development and management of resources. This responsibility encompasses the three generally accepted dimensions of sustainability – environment, economic and social - and applies to engineering projects throughout their life cycle. Sustainable engineering practice is supported by professional engineering associations, such as Engineers Australia, which includes the promotion of sustainability as a principle of its Code of Ethics. It has also been given impetus by the recent Paris Agreement on climate change. However, while there has been considerable progress in this field, there is much work required to achieve a truly sustainable future. While the industry has a major role in promoting and encouraging sustainable practices in engineering projects, educators also have a significant role in this process, through developing and fostering the knowledge and skills of sustainability in engineers. At the undergraduate level, this task is normally undertaken through courses that teach the principles of sustainable engineering practice. A major challenge for educators, however, is the ongoing development of the knowledge and skills of sustainable engineering taught in such courses. While postgraduate courses can achieve this objective, the majority of practicing engineers are unlikely to be able to undertake the detailed formal study. Meeting this gap between sustainable engineering knowledge and its implementation, therefore, presents challenges to educators. Possible options proposed include an ongoing commitment by government and society to sustainability in engineering projects, ongoing implementation of innovative sustainable engineering practices, and lifelong learning in sustainable engineering practices by professional engineers.

Keywords: Sustainability, lifecycle management, resilience, education, professional development

1. INTRODUCTION

Professional engineers are responsible for planning, designing, delivering and maintaining significant public and private works. Increasingly, in undertaking this role, they are expected to undertake sustainable engineering practices and adhere to sustainable management principles. Such practices are supported by professional engineering organizations, such as Engineers Australia [1] [2].

Sustainable management practices have increasingly gained acceptance by both the community and the corporate sector, resulting in a number of global initiatives with respect to sustainability, including the United Nations Paris Agreement of 2015, which recognizes the urgency of managing climate change, a task that requires wide cooperation and participation by all countries in a global response aimed at accelerating the reduction of global greenhouse gas emissions, with a goal of containing the increase in global average temperatures to below 2 °C, and preferably to no more than 1.5 °C [3].

While there is increasing commitment to sustainable engineering practices, both locally and globally, there are significant challenges in developing engineering and other professionals

who have the requisite knowledge, skills, and commitment to implement such practices. While some of this work can be accomplished by the University sector, much of its success relies on continued acceptance of the need for sustainability, implementation of sustainable practices by industry, and a commitment to practicing sustainability by individual professionals such as engineers and scientists.

One approach to addressing these challenges is to engineer the future in a sustainable manner. This task will require a commitment by all parties in major engineering and other projects to exercising and implementing sustainable practices and understand the issues involved. This paper discusses the issues and challenges in this process through a review of the principles of sustainability, discussing approaches to managing the future sustainably, providing examples of current sustainability initiatives, discussing the development of a sustainable future, outlining the role of professional engineers in sustainable practices, discussing the development of sustainability skills in professional engineers, providing examples of teaching sustainable engineering skills and discussing the opportunities for meeting the challenges of engineering a sustainable future.

2. THE PRINCIPLES OF SUSTAINABILITY

2.1 Sustainable Development and Practices

Sustainable development, on which the principles of sustainable practices are based, is normally defined as “development that meets the needs of the present, yet does not compromise future generations from having the ability to meet their own needs” [4]. It is commonly described as balancing economic development, social equity, and environmental protection. Some views of sustainable development add the political dimension. For example, the United Nations Educational, Scientific and Cultural Organization (UNESCO) views sustainable development as having natural, economic, social and political dimensions [5].

The United Nations has developed a list of 17 sustainable goals to be achieved by 2030, These goals relate to social areas (for example, poverty, hunger, health, education, gender equality, reducing inequality, safe cities); resources (such as water, energy, sustainable consumption and production, the marine environment), resilience, climate change, sustainable ecosystems and building global partnerships for sustainable development [6].

Sustainability affects all engineering projects and processes. For example, energy efficiency is important in any engineering undertaking that uses power, such as in transportation activities and the lighting and air-conditioning in buildings. Similarly, it is increasingly necessary to consider recycling, and the use of recycled products, in the design and implementation of infrastructure and building projects. Project development using lean principles that save waste will be less wasteful of natural resources. Using extensive community consultation with respect to the planning of engineering projects and considering the views of the community in the final implementation decision is likely to positively impact on the social aspects of projects. Sustainable practices are important in both smaller engineering projects and processes, and larger systems (such as energy delivery) that affect significant populations.

2.2 Resilience

A related concept to sustainability is resilience, which can be described in terms of systems thinking. The resilience of the socio-ecological-economic system, which is the focus of this discussion, is largely underpinned by the following concepts

- We live within socio-ecological systems in which changes in one domain of the system

impact other domains.

- Socio-economic systems are complex adaptive systems that do not change in a predictable way and can be driven across a threshold into a different regime
- Resilience can be defined as “the capacity of a system to absorb disturbance, to undergo change and still retain essentially the same function, structure, and feedbacks” or “the capacity to undergo some change without crossing a threshold to a different system regime—a system with a different identity” [7].

A resilient system, therefore, can be subject to significant change, such as in natural disasters, and return to its previous function, provided that it does not cross a threshold. From this point of view, resilience can be considered as being defined by the characteristics of the amount of disturbance that a system can absorb and still remain within the same state, the degree to which the system can self-organize and the ability to build and increase its capacity for learning and adaptation. This characteristic of persistence connects resilience with sustainability, as sustainable development can also be considered as having the goal of not only creating but also maintaining well-performing social, economic and ecological systems. This persistence is common to both concepts. Resilience thinking can provide a framework for viewing the three components of sustainability as one system operating over linked scales of time and space; and a focus on the change of a system with time and disturbance [8].

Thus, a resilient social-ecological system has a greater capacity to avoid problems as a result of disturbances external to the system, and so has a greater capacity to continue providing us with those goods and services that support our quality of life [9]. A further consideration of this point of view is that if it is accepted that there will be a certain amount of climate change over time as a result of the emissions to date and in the future of greenhouse gases, a resilient engineering installation will be one that is designed and installed in such a way that it will maintain or fairly quickly return to its function should the intensity of a climatic event increase as a result of further climate change. A related argument for a link between sustainability and resilience is that persisting in the achievement of a sustainable world will result in the development of resilient systems of engineering works.

Resilience may also be understood through the concepts of threshold (the magnitude or intensity that must be exceeded for a particular result not to occur), the adaptive cycle (how an ecosystem organizes itself and responds to a changing world) and panarchy (a conceptual framework of systems

and their linkages) [10].

A resilient system will, therefore, have an upper bound to the intensity of a particular event, will be adaptable and be composed of a number of linked sub-systems, or alternatively form part of a larger integrated resilient system. For example, a transportation system of roads could be considered resilient if, during or immediately after a disaster there is a system of key transportation routes (such as roads) available that will enable assistance to be given to a community to evacuate as required, be sustained during the disaster, and return to normal life as quickly as possible after the disaster. These key transportation routes would be supported by sub-systems of other routes that would return to normal service as soon as possible after the disaster and by other transportation facilities such as sea and air transport.

A further perspective on the concept of resilience from an engineering point of view is that of robustness, or “designed resilience,” of an engineering system. This approach assumes bounded uncertainty, in which the types and ranges of uncertainty are known, and the system is designed to be resilient to the shocks from them. This engineering approach to resilience is different from that of other professions, such as psychologists, who deal with the resilience of individuals and societies; ecologists, who consider both the speed at which a system can recover or if it can recover; and military or disaster focused personnel, who also consider speed and ability to recover [11].

2.3 Uncertainty and Risk

The uncertainty in the sustainability and resilience of a system arises because many events affecting the system have limited predictability, and in some cases cannot be anticipated with certainty. Such uncertainty arises from the limited predictability of the events on a global scale, such as weather conditions, the economy, wars, seismic activity and the extent of the rise in sea level as a result of global warming. It is incumbent on the engineering profession to limit the extent of such uncertainty. One approach for working with uncertainty and managing it is managing risk [12]. This process is discussed in the Risk Management Standard AS/NZS ISO 31000:2009, “Risk management- Principles and guidelines.” According to this Standard, the risk may be defined as the “effect of uncertainty on objectives”, where:

- An effect is a deviation from the expected, which may be either positive and/or negative.
- Objectives can have different aspects (such as financial, health and safety, and environmental goals), and can apply at different levels (such

as strategic, organization-wide, project, product and process).

- The risk is often characterized by reference to potential events and consequences, or their combination. It can be positive or negative.
- Uncertainty is the state, even partial, of deficiency of information related to, understanding or knowledge of an event, its consequence, or likelihood.

The risk is often expressed in terms of a combination of the consequences of an event and the associated likelihood of occurrence. It is managed through a system that is based on a number of principles; uses a framework based on mandate and commitment and that uses a continuous improvement approach; and uses a process of seven steps consisting of communication and consultation, establishing the context, risk assessment (risk identification, analysis and evaluation), risk treatment, and monitoring and review [13].

An alternative view of risk is to distinguish unfavorable or favorable outcomes by using the word “risk” for possible unfavorable outcomes and “opportunity” for possible favorable outcomes [14].

This approach to risk management is both rigorous and collaborative. Properly applied, a good risk management approach like that described will assess and make provision to take advantage of the benefits and minimize the adverse effects arising from the sustainability risks in a system. It will, therefore, provide a basis for managing the benefits and issues from the risks in the sustainability and resilience of a given engineering system, and aid in the developing solutions to understanding, designing and implementing measures to manage and improve the sustainability and resilience of the system.

In summary, the concepts of sustainability, resilience and managing uncertainty through a risk management process are closely linked and require consideration at all levels of engineering systems if an ongoing sustainable future is to be achieved.

The relationship between sustainability, uncertainty/risk and resilience is shown in Figure 1, which is based on a similar figure in a paper on food system resilience [15]. In this figure, factors in sustainability, like global warming, lead to uncertainty in the global environment which results in the uncertainty and risk of increased instability in the weather and climate, which in turn may lead to disruption of and damage to the infrastructure and services system. This simplified picture can be extended to a considerable number of events and risks, all of which may jointly interact with the resilience of the world system. Therefore, the management of sustainability is highly desirable if the risk of negative impacts on the global environmental, societal and economic

systems is to successfully managed.

3. MANAGING A SUSTAINABLE FUTURE

The 2015 Paris Agreement recognizes that climate change represents an urgent and potentially irreversible threat to human society and the Earth, which requires cooperation by all countries in an international response aimed at accelerating the reduction of global greenhouse gas emissions, and that significant reductions are required in global emissions to achieve the emissions reduction of the Agreement. It also recognizes that climate change is a common concern of the human race and that parties should, when implementing climate change, respect human rights, health and related matters, including indigenous rights. The need to promote access to sustainable energy in developing countries through the enhanced deployment of renewable energy is acknowledged [3]. As an example of the commitment to climate change by many world governments, the Australian Government has a goal to reduce carbon emissions by 26 percent to 28 percent over 2005 levels by 2030 [16].

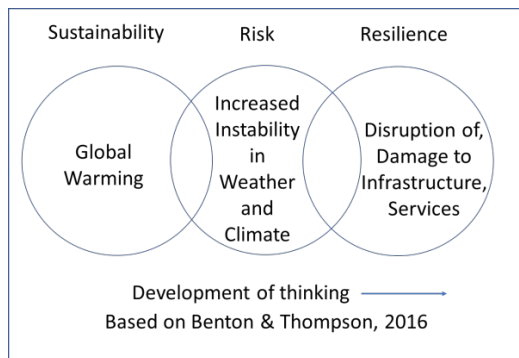


Fig 1 Sustainability, Resilience, Uncertainty

The importance of managing climate change is underscored by the significant increase in greenhouse gas emissions and other climate indicators. Data from the World Bank indicates that world greenhouse gas emissions rose by 40 percent from 1990 to 2012 [17], with the main industry sectors responsible for carbon dioxide emissions in 2013 being electricity and heat production (49.4 percent), manufacturing industries and construction (19.7 percent) and transport (20.2 percent) [18]. Overall, the World Bank estimated that total world carbon dioxide emissions in 2013 were 35,848.6 million metric tonnes [19]. This position is complemented by the United Nations Environment Programme (UNEP) Sustainable Buildings & Climate Initiative (SBCI), which have stated that the building sector, which would span a number of industry sectors, contributes up to 30 percent of global greenhouse

gas emissions per year and consumes up to 40 percent of all energy, a figure which between 1971 and 2004 had been growing at 2.5 percent per year for commercial buildings and 1.7 percent per year for residential buildings [20].

The Paris Agreement is complemented by the United Nations' 17 sustainable development goals to be achieved by 2030 [6].

The Paris Agreement of 2015 also has a number of technological goals and notes the role of technology research, development and demonstration; and the development and enhancement of endogenous capacities and technologies. It also establishes a process for technology development and transfers to support its long-term vision. Some of the technology initiatives include technology needs assessments and their implementation, technology action plans and project ideas; provision of financial and technical support for the implementation of the results of the technology needs assessments; the assessment of technologies that are ready for transfer; and enabling environments for addressing barriers to the development and transfer of technologies that meet social and environmental requirements [21].

The above requirements recognize the role of engineering in the sustainable development process. Examples of such initiatives could include, as well as the initiatives of energy efficiency, recycling, and waste management, other initiatives like the use of advanced materials, nanotechnology, management of the natural environment including less dependence on non-renewable resources and a range of other initiatives. Sustainable processes might include smart design for sustainability and resilience, sustainable asset management, recycling, lean manufacturing and construction that reduces waste, rehabilitation rather than replacement, the design of materials to match the expected product life cycle, and reuse of waste materials in other applications and products. Further insight into some of these processes are provided by Allwood and Cullen, who have discussed, in addition to energy efficiency, ways to achieve efficiency in the use of material, including re-using metal components, longer life products and achieving a sustainable material future through business activity evaluation, the influence of policy and the actions of individuals [22].

In summary, there is a global recognition of the existing and potential future consequences of climate change and other components of a sustainable future, and a commitment by many governments to address these issues, and in particular global warming. The challenge that now faces the world, and the engineering profession, in particular, is how to address the positively and sustainably manage climate change and other

sustainability initiatives through the positive management of emissions, waste, resources and global infrastructure. Achieving this goal will achieve a more livable future world, conserve our resources for the future, improve global resilience to the effects of climate change by infrastructure and buildings and, through positive risk management, reduce the uncertainty of the future. This process should also deliver global social and economic benefits. Engineers have a significant role in planning, designing, developing and managing this sustainable future.

4. SUSTAINABILITY INITIATIVES

Engineering a sustainable future presents many challenges to the engineering profession. It also provides many opportunities. Areas in which engineers can play an active role in developing a sustainable future include planning and designing infrastructure and other installations that not only meet the needs of society, but also use sustainable materials and methods, waste minimization, developing and implementing systems and processes to minimize greenhouse gas emissions, undertaking renewable energy projects, improving the manufacture and use of engineering material including developing and implementing advanced and green materials, minimizing waste, recycling and designing installations to maximize resilience and minimize the adverse impacts of climate change.

These challenges and opportunities can be illustrated through considering three areas of engineering practice – the use of advanced design and development including material reuse, the development and use of advanced engineering and construction materials, and the challenges in the energy sector.

4.1 Advanced design and development

Advanced engineering design and development processes, including the application of advanced software, can be a significant contributor to sustainable and resilient engineering practices.

One example of using advanced engineering to improve efficiency in material usage, by Allwood and Cullen, has previously been discussed [22]. A further example is a research into the use of bioclimatic design principles, which tend to mimic natural approaches and aim to both enable buildings to function satisfactorily in existing and future climatic conditions and reduce building energy use and greenhouse gas emissions. Such principles aim at minimizing energy consumption in mining and manufacturing, minimizing transportation; optimizing resource use through material reuse and recycling, and maximizing the

use of renewable energy [23].

The use of lean design and construction principles, which aim at reducing waste throughout the production or construction process [24], similarly aim to optimize the use of both materials and energy in these processes.

Recycling is also used in a range of engineering processes. For example, achieving sustainability in road design, construction and management requires the use of not only sound environmental management, but also practices like water sensitive urban design, use of advanced and recycled materials, and environmentally responsible project management and construction, subject to precautions being taken to ensure that recycled materials are free from contaminants. An alternative approach in roadworks is to stabilize existing materials rather than obtain new materials, using materials like cement, lime, or powdered polymers [25].

4.2 Developments in engineering materials

Modern Engineering uses a range of traditional and new materials. Such materials are used across the engineering spectrum and in buildings, infrastructure, machinery and electrical applications. In the construction area, for example, there has been considerable research in low carbon concrete applications in buildings and other engineering projects.

There have been enhancements to the physical and mechanical properties of concrete, a stronger focus on the more efficient use of resources and the use of smart concretes in building energy efficiency [26]. For example, geopolymers, which result from the reaction of amorphous aluminosilicates with alkali hydroxide and silicate solutions, have been claimed to be used in the concrete of up to 70 MPa compressive strength and have been used in applications like retaining walls, water tanks, precast bridge decks and precast beams [27].

Alternative materials may have both advantages and disadvantages over traditional materials. Thus, while cement made with fly ash cementitious additives uses waste from coal-fired power stations and can have useful properties fitting it for a range of uses like mass structures its relatively slow rate of strength development can make it not suitable for high early strength applications. Similarly, concrete made from recycled aggregate may have lower densities than concrete made from naturally occurring aggregate because some mortar remains attached to it and resulting larger water absorption than naturally occurring material [28]. There is also the risk that fly ash may become less readily available as the world moves away from coal-fired power stations.

Finally, research into the use of advanced and green materials by the small and medium sector of the industry has indicated that there may be challenges in using some building materials, such as advanced concrete materials, materials using native earth such as adobe and rammed earth, advanced timber products, green roof and pervious concrete. These challenges included whether the firm had previously had experience with using the material, cost of the material and the availability of standards and codes of practice [29].

In summary, while there will continue to be considerable research into the development and application of both advanced and sustainable engineering materials, there are likely to be some challenges with their acceptance by the broader engineering and construction community. It is probable that a number of these challenges arise from the novelty of some of the material, and the reluctance of industry to use new materials until they are proven to be reliable, durable, safe and cost-effective. This may take time, given the innovation-decision process of knowledge of the innovation, persuasion of its use through its perceived characteristics, a decision to use it, implementation of the innovation and confirmation of its value or otherwise [30].

4.3 Energy production and management

The figures estimated by the World Bank in its 2017 World Development Indicators publication included a global electricity production figure in 2014 of 23,869.3 billion kilowatt-hours, and an energy use per capita of 1,929 watts [19]. Given this ongoing demand for energy, and an increasing demand for energy, one area in which to improve the total carbon emissions is through improved management of energy, such as electricity, both through managing demand and moving away from fossil fuel production.

In Australia, a review of the future security of the national electricity market was undertaken by Chief Scientist Alan Finkel. In summary, the report on the review recommended increased security, future reliability, rewarding consumers and lower emissions. [31].

The Engineers Australia organization, which represents professional engineers in Australia, has recently released an energy position paper, which discusses energy productivity, transport energy, and electricity generation. Among its recommendations are that the Australian government adopts an energy efficiency target of 30 percent by 2030 as the means to drive progress under the Australian Government National Energy Productivity Plan, that the Australian government introduces policies and programs that lead to energy efficiency in the transport sector, including

active integration of more efficient transport modal mixes, and that all levels of government proactively develop plans to restructure electricity generation in Australia [2].

5. TOWARDS A SUSTAINABLE FUTURE

Developing a sustainable, resilient future is a challenging task. It is a process subject to considerable uncertainty, which requires the management of the negative risks involved and presents many opportunities. The goal of this task is to develop a rewarding and livable future for both ourselves and our descendants, in which global warming is contained and cities and other infrastructure quickly recover from disasters. Achieving this target requires assessment of the current position and balance of the environmental, economic and social state of the world; evaluation of the options in managing climate change and the ongoing use of resources; and development of solutions that not only achieve a sustainable future but also ensures resilience of key infrastructure and productive facilities in times of challenges and disasters.

Fundamental to this process is an understanding of the options and initiatives that can result in the much more sustainable world. Examples have been given of such initiatives in engineering design and development, improved and new engineering and construction materials and significant advances in energy production and management. These developments can be considered as part of a much wider focus on building a sustainable future, and linking us, through the lens of resilience, with a wider systems approach in understanding not only the immediate impact of sustainability but also its longer-term evaluation.

Because of the increasing role of sustainable practices in the engineering profession, the effectiveness of teaching these practices to engineering students, and of the use of these practices in professional engineering, is developing with the passage of time. Such teaching should not only encourage students to understand the principles of sustainable development but also should provide them with the understanding, knowledge, and skills in this area to motivate them to make sustainable engineering practices a significant component of their professional career. The first step in discussing this process is to review the role of the professional engineer in these practices.

6. ROLE OF PROFESSIONAL ENGINEERS IN SUSTAINABLE PRACTICES

Professional engineers have a significant role

in providing a sustainable, resilient future. As an example of the recognition of this role by professional engineering member organizations, Engineers Australia, of which many Australian professional engineers are members, states that professional Engineers are “responsible for bringing knowledge to bear from multiple sources to develop solutions to complex problems and issues, for ensuring that technical and non-technical considerations are properly integrated, and for managing risk as well as sustainability issues.” Engineers Australia prescribes two levels of engineering practice competency. Stage 1 competencies qualify students as graduate engineers, at which they are expected to understand sustainable engineering practice in their discipline and demonstrate a commitment to sustainable engineering practices and the achievement of sustainable outcomes [32]. The second stage of competencies, Stage 2 competencies, is the Chartered Professional Engineer level, for which graduates must have a minimum of at least three years of professional experience and are required to show competencies in personal commitment, the obligation to the community, the value in the workplace and technical proficiency. These competencies include the sustainability-related skills of developing safe and sustainable solutions; engaging with community and stakeholders; communication and risk assessment [33].

These competencies are supported by the Code of Ethics of Engineers Australia, which contains guidelines for professional conduct that is based on ethical engineering practice that requires judgment, interpretation and balanced decision-making in context. Engineers in their course of professional practice are required to demonstrate integrity, practice competently, exercise leadership and promote sustainability. As part of promoting sustainability, professional engineers are required to engage responsibly with the community and other stakeholders; practice engineering to foster the health, safety, and well-being of the community and the environment; and balance the needs of the present with the needs of future generations [1].

These ethics, combined with required engineering competencies, provide a strong focus on sustainable practice within the engineering profession. At the same time, there are some engineering-related disciplines, such as construction, which do not rate sustainable management skills as highly as some other skills. For example, a survey of recruiters for over 100 construction companies located in the eastern United States of America found that they rated environmental awareness, along with communication skills, lowest among 14 key

competencies, while other skills like ethical issues, problem-solving skills, and interpersonal skills were rated highly [34]. On the other hand, an Australian survey noted both the connections and differences between educational and professional employment requirements with respect to education for sustainability [35].

In summary, sustainable management skills are increasingly recognized by professional engineering and other organizations and are increasingly required by industry. There is, however, a challenge to develop the skills in engineering students by both educational institutions and industry so that they become not only part of their undergraduate education, but are also embedded in their professional practice.

7. DEVELOPMENT OF SUSTAINABILITY SKILLS IN PROFESSIONAL ENGINEERS

The support of sustainable engineering practices by professional engineering organizations, government, and industry have resulted in sustainable engineering practice is increasingly being taught to engineering students. Such teaching would be likely to consider the principles of the United Nations Scientific and Cultural Organization (UNESCO) in the education of sustainable development (ESD) These competencies include that such education:

- is based on the principles and values that underlie sustainable development
- promotes life-long learning
- is locally relevant and culturally appropriate
- is based on local needs but acknowledges their international consequences
- engages formal, non-formal and informal education
- accommodates the evolving nature of sustainability addresses content
- builds civil capacity
- is interdisciplinary and promotes participatory learning and higher-order thinking skills [36].

In engineering, sustainability teaching tends to follow one of three models – integration of sustainability into traditional courses, stand-alone sustainable engineering, and embedding sustainable engineering modules within the framework of existing courses. Challenges in sustainable engineering education include a full curriculum, the engineering educational structure and a focus on the environmental aspects of sustainability, with less emphasis on its social and cultural aspects [37]. Thus, there is an opportunity to improve the learning of engineering students in the social dimension of sustainability [38]. This need for a seamless interface between engineering and society has been reinforced by other studies, one of which considered the link between science,

technology and society courses and engineering, and which highlighted the three categories of participation, politics and policy, and citizenship, which were reflected themes that were not discussed often in engineering curricula, but were significant in science, technology and society [39].

In conclusion, while teaching in sustainable engineering practices is undertaken in universities, there is still a gap in teaching the social and cultural aspects of sustainability as outlined in the UNESCO competencies for sustainable education.

8. EXAMPLES - TEACHING SUSTAINABLE ENGINEERING SKILLS

One of the main expected outcomes of teaching sustainable engineering skills is the development of engineers who can practice, on an ongoing basis, the sustainable design and management of engineering projects and processes as expected by society and professional engineering organizations. As an example of such teaching, the University of Cambridge, in recognition of the increasing recognition by the United Kingdom construction and civil engineering industries, and their professional bodies, of sustainable engineering practice, engaged with sustainable development issues.

This approach recognized that many sustainability problems require a systems view of the world that accounted for complexity, interdisciplinary understanding and a broader view of system performance. This process requires not only the use of mathematics but also making judgments and understanding of differences.

As a result, a number of initiatives were undertaken in the Cambridge University Engineering Department. Such initiatives focused on embedding sustainable development within the Department. Initiatives have included:

- introduction of sustainable development thinking into undergraduate teaching
- the development of a Master of Philosophy in Engineering for Sustainable Development
- formalizing sharing of sustainable development
- developing sustainable development as a key theme of departmental strategy.

This approach required achieving a quantitative and qualitative balance, dealing with pedagogical issues, and initiating change. It has been successful. Lessons were also learned in managing change [40].

It is also noted that the Engineering Department of Cambridge University is undertaking research in modeling, simulation, and analysis of complex systems. This research is aimed at better managing their uncertainties through absorbing variations naturally. Part of this

research is in developing a new understanding of uncertainty and risk [41].

The University of Southern Queensland offers the *Technology, Sustainability, and Society* course, an example of a stand-alone sustainable engineering course, to all Engineering and Built Environment students studying a three or four-year undergraduate degree program. This course, which discusses topics like the history of technology, sustainability including environmental impact management, politics and power, the economy, models of society, cultural impacts, law and regulation and management concepts, has been successful [42].

The University also incorporates sustainable engineering management principles included as part of other courses, including postgraduate study up to Doctor of Professional Engineering level. For example, *Technological Impact and its Management* is a stand-alone sustainable management focused course that reviews current technological development and evaluates its impact on the world on we live. There are also courses offered at the University postgraduate level that integrate sustainability with the course material. Such courses include:

- *Asset Management in an Engineering Environment*, which discusses the strategic lifecycle management of engineering asset systems
- *Advanced Engineering Project Management*, which is designed to teach higher level project and program management knowledge and skills
- *The whole of Life Facilities Management*, which teaches the life cycle operations, maintenance and renewal of engineering facilities [43].

In addition, the University offers a postgraduate courses *Management of Technological Risk* course [43]. This course teaches risk management principles based on the Australian Standard for Risk Management [13], and the applications of risk management principles in engineering projects and processes. A text on managing project opportunity and risk [14] supports the course.

These courses place a strong emphasis on assignments that are designed to challenge students to demonstrate their competencies in problems similar to those of professional practice, and which are assessed using the principles of authentic assessment [44]. Similarly, students are also encouraged to apply experiential learning principles [45] through applying practical examples in examinations in those courses with examinations and applying marking feedback from a first assignment to a second, more complex assignment in those courses, like *Advanced*

Engineering Project Management, that are assessed solely by assignments. There is also an increasing use of guest lecturers from industry.

9. OPPORTUNITIES FOR MEETING THE CHALLENGES

As shown above, there is a developing emphasis on teaching sustainable engineering practices in both undergraduate and postgraduate engineering programs. Such teaching tends, however, not to be a large component of the engineering curriculum. It is therefore desirable that graduate engineers further develop the knowledge and skill of sustainability during their professional practice. One way in which such ongoing development could be addressed would be for industry to lead this development through initiatives like providing environments in which these skills can be enhanced. Further formal education in sustainable engineering practice is also desirable. Because most professionals are very busy, this approach may only be suitable for those engineers who have the time to undertake the additional study.

Another possible opportunity for both the tertiary education sector and industry to have a role in developing sustainable engineering knowledge and skills this area is for the industry to develop links with universities with respect to teaching sustainable engineering practice. This approach would benefit those industries that are becoming more sustainable in their outlook and practices, and would, therefore, benefit by having a positive role to play in sustainable engineering education. This process has the potential to elevate the profile of sustainability to engineering students. A further option could be for universities to develop links with industry partners and professional associations in encouraging sustainable practices and offering short courses in them, along with the related areas of risk and resilience, to both students and practicing professionals.

The amount of teaching in sustainable engineering at an undergraduate level could be reviewed to see if it can be better incorporated into the engineering curriculum, perhaps by incorporating an increased number of components of it in selected courses in each year of the engineering curriculum. Engineering teaching could also benefit from more emphasis on the social aspects of sustainability.

There is also an opportunity for further understanding between sustainability, the risks of not using sustainable practices, and the impact at a systems-wide level on resilience, or the ability to better withstand and more quickly recover from the impacts of more extreme and frequent events in areas like the weather, or economic or social

conditions resulting from increased risk.

10. CONCLUSION

While there has been considerable progress in the teaching and practice of sustainability in engineering, there is still much work to be undertaken to make it a part of day to day professional practice and thereby minimize the impacts of climate change, as well as to optimize the social and economic aspects of a sustainable future. In particular, there should be a better understanding of the effect, on the resilience of the built environment, of not managing this future well.

Engineers have a significant role in the sustainable management and in designing, developing, operating and maintaining infrastructure sustainably and with the resilience to minimize the effect of negative climatic and other impacts on the functioning of infrastructure and services, and which can quickly be restored to functionality following such events. While current engineering education would be expected to should provide them with a basic understanding of these principles, it is considered that such education is further reinforced through government and industry support of sustainable practices, postgraduate education, and training.

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