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Making green technology work for people and the environment

Professor Andrew Thatcher is the recipient of the 2022/2023 NSTF-South32 Green Economy award in recognition of his work on extending our understanding of human factors and ergonomics to consider the entire Earth system, which included theoretical investigations, empirical investigations, and systematic reviews of the impact of these activities leading to mutually supportive human–natural environment systems.

Significance:

While many technologies exist to address the wide variety of sustainability challenges facing humanity, many technologies are not adopted at sufficient scale or are used incorrectly, negating the positive impacts. This commentary introduces the discipline of human factors and ergonomics, demonstrating four features that facilitate the effective design and implementation of eco-socio-technical systems for sustainability. An example of the URBWAT research project, which implemented a nature-based solution in an informal settlement to collect and treat greywater, is given to illustrate how these four features operate in practice.

Introduction

It is widely recognised that humanity's current activities are leading us on an unsustainable path.[1] Not only are we facing a human-induced climate crisis, but human activities are also contributing to significant biodiversity loss, unsustainable consumption of natural resources, degradation of land and ecosystems, rapid urbanisation without sufficient supportive infrastructure, and massive social and economic inequalities[2], and we face the threat of pandemics that can severely disrupt our global economic, health, and social systems[3]. We are not a world in equilibrium, but a world in denial about our negative impact on our life-supporting systems. South Africa's sustainability issues match these global trends with a particular emphasis on high susceptibility to climate change such as drought, heat, and localised weather events such as flooding.[4] For South Africa, climate change also creates risks for biodiversity loss, health issues from the spread of infectious diseases, and reduced food security.[5] However, South Africa, like many other vulnerable Global South countries, also faces an 'adaptation deficit' with regard to sustainability challenges because we have many other socio-economic development needs that require attention.[6]

Sustainability is fundamentally a human problem. Certainly, humans have contributed to biodiversity and ecosystem loss and biophysical disruptions[2], but the underlying issue of sustainability refers to whether humans can live tolerable, healthy, and dignified lives in synergy with natural systems that provide the life-sustaining resources for our survival (including air, food, water, shelter, and materials). Few would argue that there are millions (if not billions) of people living in informal settlements, cities, war zones, and in environments with degraded access to nature who would not meet these criteria. However, we must also bear in mind that while natural systems and the planet will carry on in some form even in the absence of humans, the opposite is not true. This is essentially what we mean by sustainability.

Of course, there are many technological solutions that have been developed (and will continue to be developed) to address these sustainability issues. One problem is that many of these technological solutions are seldom adopted[7], are adopted at a low level, or are used incorrectly (e.g. electric vehicles[8]). A reason for this slow rate of adoption or poor use is not only because of availability, financial, or political reasons (although these are pertinent drivers of success or failure), but because their integration with human users is poor or ineffective.[9] The discipline that considers the interaction between humans and technology within the context of their environment is known as human factors and ergonomics (HFE). The International Ergonomics Association[10] defines HFE as:

> *the scientific discipline concerned with the understanding of interactions among humans and other elements of a system, and the profession that applies theory, principles, data, and methods to design in order to optimise human well-being and overall system performance.*

One of HFE's roots is in sociotechnical systems, originally developed by the Tavistock Institute[11], as a means of understanding the interactions between the social system (the humans), the technology, and the manufacturing system (the interactions between humans and technology). However, finding solutions that address sustainability concerns requires more than the consideration of sociotechnical systems. To move forward, it is necessary to recognise the importance of understanding the human–environment–technology interactions. In HFE terms, this means moving beyond sociotechnical systems to look at 'ecosociotechnical' systems. But what can HFE bring to our understanding of workable interventions, technologies, and solutions for a sustainable future?

HFE principles that help achieve sustainability in design

HFE's general approach is to apply human-centred systems-thinking to enable resilient systems. When considered in the context of sustainability, this encapsulates what the European Commission[12] refers to as Industry 5.0: work that is sustainable, human-centred, and resilient. For HFE, this sustainable future is achieved through the core features of the discipline being human-centred, transdisciplinary, resilient, and adopting a systems approach.

Human-centred

By definition[10], HFE puts humans at the centre of the design and intervention process. HFE traditionally considers the physiological, anatomical, and psychological attributes and capabilities of humans in their interactions with other elements of the system. Historically, from a physical perspective, this has included aspects such as whether the human could effectively and efficiently see, hear, touch, fit into, reach, or manipulate other physical elements of the system under the expected variety of environmental conditions (e.g. lighting, ambient temperature, and vibratory conditions). With the development of psychological cognitive models in the 1960s, this was expanded to include issues such as being able to recognise, understand, make decisions, and problem solve under conditions of ambiguity and uncertainty. More importantly though, the HFE approach has always been about first trying to understand human needs, interests, and motivations in order to design systems that improve human efficiency, effectiveness, and safety.

Transdisciplinary

As should be evident from its definition[10], HFE has strong multidisciplinary roots drawing theory and methods liberally from anatomy, physiology, biokinetics, cognitive psychology, organisational psychology, as well as applications from numerous engineering and design disciplines. HFE does not just borrow from these disciplines, but actively contributes to the development of new theory, novel methods of analysis, while also making additional contributions to design from a human-centred perspective. HFE can therefore be considered as transdisciplinary, embracing the type of transdisciplinary work that regularly includes users of technologies and systems as well as other community actors that Lang et al.[13] argue are necessary for effective sustainability work. HFE calls this approach ‘participatory design’, which is well embedded in the field generally and strongly endorsed for work involved in resolving societal problems typical of sustainability.[14] Participatory design adheres to the principle that the users’ lived experiences make them ideal partners in the design process as they have direct experience with the surrounding systems (e.g. the environment, the work, and the social structures) and they have to live with the consequences of any design interventions.[15]

Resilience

For decades within HFE, humans (and sometimes other biological entities) were considered to be the sole components of systems that enabled system resilience. However, a central component of HFE design for complex technological systems over the last two decades has been the concept of resilience engineering, popularised by Hollnagel et al.[16] The resilience engineering design approach recognises that complex systems need to be adaptive to uncertain, sometimes chaotic, environments in order to persist and that resilience must also be embedded in non-biological agents, including technology. For HFE, there are two important components for resilience engineering: adaptive capacity[17] (i.e. the potential to adapt to future challenges) and graceful extensiblity[17] (i.e. being able to continue having adaptive capacity). In HFE, resilience engineering has typically been applied to the design of complex engineered systems like nuclear power plants and spacecraft, but, more recently, applications can be seen in the design of infrastructure (e.g. electricity grids) and cybersecurity.[18] Applying the concepts to address sustainability issues is an easy step to make, one that has already been made by Thatcher and Yeow[19] in their sustainable systems-of-systems framework described under the systems approach.

Systems approach

HFE considers itself a systems discipline[10,20], usually viewing humans as integrated physiological, psychological, and anatomical systems that interact within a context (i.e. an environment or organisation) that includes other systems. Wilson[20] went so far as to suggest that HFE approaches that do not take a systems view cannot be considered HFE at all. Moray[21] encapsulates this thinking as a nested set of systems that include physical, psychological, and technological considerations at the centre, with increasingly complex systemic factors surrounding these central systems, from team and organisational factors through legal and regulatory frameworks to societal and cultural pressures. The HFE systems approach embraces all these external and internal factors as contributory towards whether a technological system is adopted (or not). Building from this systemic understanding, HFE has developed numerous systems analysis tools to help unpack complex scenarios such as accidents and nuclear power plant design in order to identify possible places to intervene and improve design.[22] However, these existing HFE complex systems analysis tools lack important attributes (such as coping with emergence, adaptations, and transitions) making them ineffective in handling sustainability problems.[22] In contrast, Thatcher and Yeow’s[19] sustainable systems-of-systems (SSoS) framework might help HFE conceptualise the relevant factors for the design of sustainable systems that include humans and technology.

The SSoS framework merges HFE design thinking with ecological models of systems: SSoS adopts the concept of natural nested hierarchies of complex ecological systems from Costanza and Patten’s[23] and Gunderson and Holling’s[24] concepts of complex adaptive cycles and panarchies. Natural systems can be represented as a nested hierarchy of increasing complexity and size[23] (e.g. an individual, a family, a community, and society). Complex adaptive cycles demonstrate how ecological systems naturally pass through predictable phases during their life cycle, while panarchies show how complex adaptive systems interact to inhibit or enable change across adjacent levels of a nested hierarchy of systems.[24] The SSoS framework[19] uses Wilson’s[20] nomenclature of target system (the system of interest to the intervenors), sibling systems (at the same level in the nested hierarchy), child systems (at smaller, less complex levels in the nested hierarchy), and parent systems (at larger, more complex levels in the nested hierarchy) to define the related systems that might influence the design intervention. Recent applications of the SSoS framework have been applied to identify design solutions for several sustainability problems including designing post-pandemic work-from-home strategies after COVID-19[25], enabling organic farming methods to permeate through France[26], designing a nature-based sanitation solution in South Africa[27], and identifying decarbonisation strategies in China[28].

To demonstrate how these different HFE features can contribute to producing improved, sustainable solutions, a summary of the design and implementation of a nature-based sanitation solution for dealing with greywater collection and treatment in an informal settlement[27,29] is given as an example.

URBWAT as an example of HFE design thinking

The URBWAT research project was an interdisciplinary research initiative that looked at finding solutions to greywater collection and treatment in an urban informal settlement. The study site was Setswetla, an urban informal settlement in Johannesburg, South Africa, on the northern edge of Alexandra township, wedged between Marlboro Gardens Cemetery to the west, the Jukskei River to the east, and Marlboro Drive to the north. The URBWAT project worked in a small section of Setswetla called Silvertown. The original inhabitants of Silvertown were settled there in early 2006 by the local government which provided zinc-sheet accommodation (hence the name ‘Silvertown’). In this context, local government provided potable water available from community standpipes, a limited number of chemical toilets, limited electricity connections, and solid waste removal from a single skip bin which was removed once a month. However, in Silvertown (as is the case elsewhere in Setswetla and in many other South African informal settlements) there is nowhere to dispose of wastewater from cooking, cleaning, and bathing activities. Instead, residents have created informal channels and ad hoc disposal points for this wastewater which then travels through the community and into the Jukskei River without any treatment.

The URBWAT research project’s aim was to work with the community to find nature-based solutions for the collection and treatment of this wastewater before it contaminated the community and the river. The nature-based solution that was chosen by the community was small, sub-surface horizontal constructed wetlands. In nature, wetlands serve as important cleaning mechanisms for surface water, among other ecological benefits. More details of the URBWAT research project can be found in Thatcher et al.[27] and Davy et al.[29] By applying the core features of human-centred, participatory, resilient, and systemic approaches, it is possible to show how HFE was involved in applying this thinking to the design and implementation of these constructed wetlands so that they would be used effectively by the community.

Human-centred design

A key component of any successful design intervention is to understand the needs of the people who will be impacted. In the URBWAT research project, this involved establishing the needs of various stakeholders, including local government representatives, community leaders, the URBWAT project team, and community residents themselves. The needs analysis was conducted before any design solutions were developed and was revisited multiple times during the project to identify possibilities in which multiple needs might be met simultaneously. For example, at the start of the project, it was evident that while greywater contamination of the community was a relevant issue requiring attention, there were other needs that were perceived as more important, such as job creation, stormwater and floodwater protection, sanitation solutions, and reducing violent crimes. During the URBWAT research project, the HFE team worked to establish if any of these other needs could also be met. By the end of the URBWAT research project, we had partially succeeded in creating temporary jobs during the construction and design planning stages and had designed the constructed wetlands so that they provided protection from stormwater and sewerage spills.

Other needs were emergent and were only identified when earlier design issues of the constructed wetlands had been addressed. An example of an emergent need was the exaggerated stooping posture adopted by community residents when engaging in water collection and washing activities. The stooping resulted in acute (and chronic) back pain during a variety of washing and water collection tasks. The community residents did not initially identify this as an important need due to the relative importance of other needs. However, during observational user evaluations of the early design iterations, it became evident that excessive stooping during these activities was contributing to physical pain and (in the case of women, children, and the elderly) prevented them from carrying out many water-based tasks effectively. Integrating a raised washing area into the design of the constructed wetlands, not only improved the intake of wastewater into the constructed wetlands but also reduced the physical demands (and therefore back pain) while performing these tasks.

Participatory design

A key component in the early design thinking for URBWAT was to involve end-users (community residents) in developing possible solutions. This was achieved through six design workshops and an iterative design process that enabled community residents to define the initial design and then to participate in identifying refinements and extensions to earlier design iterations. In this way, community residents were not only the initiators of design ideas, but through regular interviews and feedback sessions, they were also primary contributors throughout the research project, identifying design flaws, suggesting improvements, and showing how the interventions could integrate with existing behavioural habits and infrastructure. A second way in which community residents were involved in the design was through being employed as construction workers and project managers. Their local knowledge was invaluable in fine-tuning the designs, bearing in mind the local availability and costs of materials and skills, the physical layout of available space, and the power dynamics between various community residents.

Systems-thinking in design

To help understand the project and how the constructed wetlands were integrating into the community, to identify stumbling blocks in the implementation processes, and to identify possible opportunities for improving the design, we applied the SSoS framework.[19] This involved creating a nested hierarchy diagram of the relevant systems, stakeholder goal analysis, and more detailed systems diagrams of the parent, sibling, and child systems. Mapping how these systems evolved over time also enabled the HFE members of the URBWAT project team to identify the stages in the complex adaptive cycles within the panarchy of adaptive cycles. From this analysis, it was evident that a number of parent systems were cycling through their natural stages at a faster rate than expected, creating disruptions in their respective child systems, including the target system (i.e. the constructed wetlands) and some of the important sibling systems to the constructed wetlands. For example, the community residency parent system had a relatively short lifespan, with many residents leaving (and new residents arriving) on an almost constant basis. This meant that there were always new residents that were not involved in the design of the constructed wetlands and did not understand what the constructed wetlands were or how to use them properly. Similarly, ward councillors were expected to be in their positions for at least 5 years, but over 2 years, the ward councillor changed three times, each time shifting priorities with regard to the residents' needs and their willingness to support the research project.

These faster-than-expected life cycles of the parent systems forced the sibling systems (and their respective child systems) to adapt faster. For example, rapidly changing residency systems resulted in dwellings being built closer to the constructed wetlands (in one instance, even incorporating the walls of a constructed wetland into their own dwelling). Building new dwellings also created disruptions to related systems, such as taps without sufficient water pressure. This meant that residents had to find another communal tap and their cleaning activities took place at a different location, which either overburdened the constructed wetland (if the working tap had a constructed wetland) or meant that the constructed wetland was not receiving wastewater for treatment. Similarly, building new dwellings meant new ad hoc electricity connections being installed over, around, or even under the constructed wetlands. Some of these issues could be addressed during the iterative design process. For example, a mural was painted by a community resident on the wall of a dwelling adjacent to one of the constructed wetlands to depict the purpose of the constructed wetlands and how to use them properly in order to address the issue of the fast turnover of community residency.

Resilience in design

What does it mean to design a system that is resilient to these changes? It is important to note that resilience in this context does not mean that we can design a system that can maintain its shape and form despite these chaotic external perturbations. The key in a context such as this was to make iterative design a fundamental part of the design thinking. An iterative approach to the design allows one to keep innovating with the way in which the system, people, and the environment interact while still maintaining the underlying mechanisms (in this case, greywater collection and treatment). Adopting a nature-based solution was essential to maintaining a resilient interface by incorporating the natural adaptive qualities of biological entities. In this instance, constructed wetlands needed to be seeded with a variety of wetland plants so that they could adapt to the different effluent and water loads. Humans could also act as agents of resilience by imbuing sufficient scope in the basic design of the constructed wetlands for the human users to customise the design to fit different physical spaces, different treatment loads, and different water collection and washing behaviours. Finally, resilience in design meant ensuring the efficient integration of the constructed wetlands with related sibling systems, as system interconnectedness facilitates resilience. For example, the constructed wetlands were designed with elevated walls. This design protected dwellings from stormwater and sewerage spills. The raised walls also provided elevated walkways, so people did not have to walk in sewerage or mud.

Conclusion

Throughout the discussion on how HFE can be used to facilitate better integration of interventions aimed at sustainability, it is important to note that HFE is not doing this alone. HFE acts as a support to the biochemists, physicists, engineers, architects, climate scientists, ecologists, botanists, zoologists, and other specialists who use their own scientific knowledge to develop solutions. However, HFE is an important conduit between the scientific development of solutions and how they will integrate with the people who will use them. Of course, there are many other disciplines that can also provide their own disciplinary perspectives, including anthropology, psychology, sociology, political science, ethics, and philosophy. However, it is the HFE discipline whose specific expertise lies in tying technological development with human use. It is important to note that nothing lasts forever, particularly in a highly dynamic environment such as the URBWAT example. Instead, we should be designing systems and implementation strategies that can rapidly change depending on the environmental influences, including those of other humans. For example, even though the initial URBWAT research project has ended, it is evident that further iterations are still required. What is important to emphasise is that understanding the systemic influences on a particular technological artefact within a given context is important to ensure the effectiveness, efficiency, and sustainability of an intervention.[19]

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Competing interests

I have no competing interests to declare.

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