Delivering Sustainable, Safe and Healthy Buildings for a Net Zero Future: Educational Challenges and Opportunities

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Abstract

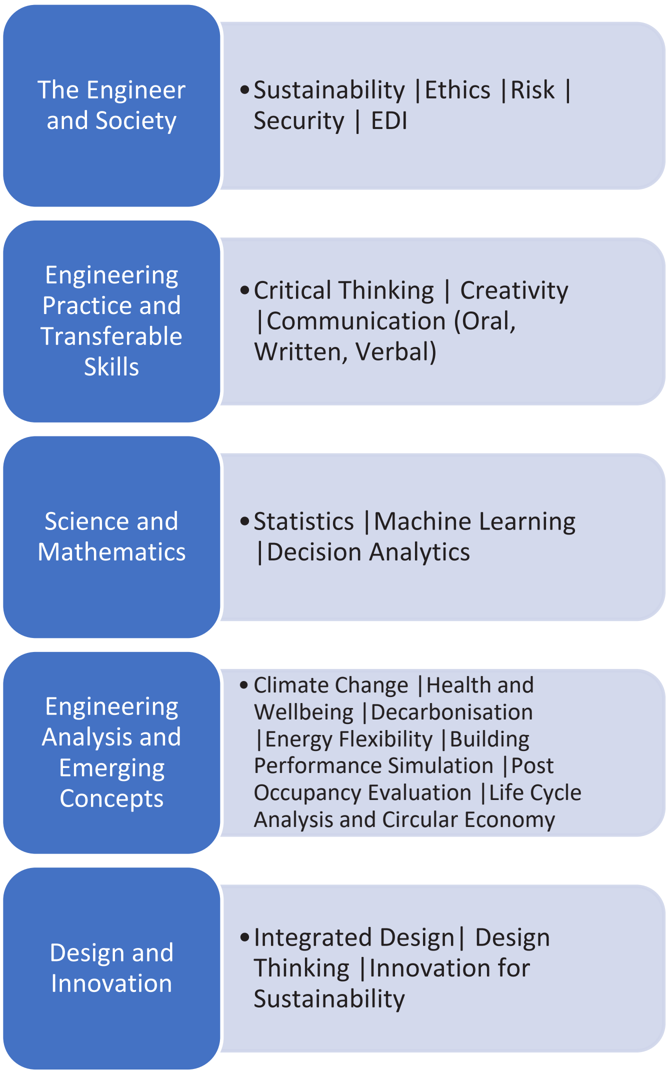
It has been 120 years since the first electrical air conditioning unit was designed and tested by Willis Carrier in the USA as an "apparatus for treating air" by humidifying or dehumidifying. Ever since, especially after the second World War, engineering courses across Europe have traditionally focussed on design of such heating, ventilation and air conditioning (HVAC) systems as deemed critical by industry partners. However, the role of buildings in humankind's transition to net zero carbon emissions and the wellbeing of human society has increased significantly in importance since the turn of the century. This has meant an increasingly holistic view being shone on the role HVAC systems in the delivery of sustainable, safe, and healthy buildings for a net zero future.

This major challenge the humankind is facing in the 21st century has created a number of challenges and opportunities for the transformation of our educational programmes. For the first time, the experiences and observations of course leaders across Europe have been recorded to reflect on the proposed strategy for transformation of the content and delivery of programmes. This paper is aligned with common learning outcomes of national engineering councils across Europe: (a) Science and Mathematics, (b) Engineering Analysis, (c) Design and Innovation, (d) The Engineer and Society, and (e) Engineering Practice. Through an online questionnaire across European member states, we evaluate the extent to which climate change, health and wellbeing, decarbonisation and energy flexibility have been integrated into accredited university courses. The paper finishes with a call for "revolutionary evolution" of our undergraduate HVAC programmes in defining the changing role of HVAC engineers in industry and society.

Introduction

The drive to reach net zero carbon emissions by 2050 is a key pledge of many European countries (European Commission, 2021), with buildings responsible for around 40% of EU energy consumption. The use of Heating, Ventilation and Air Conditioning (HVAC) systems in buildings remains a key component of energy use in buildings (Ürge-Vorsatz et al., 2015), due to the need to cool and ventilate building under an increasingly warming climate.

To address this challenge, European academic institutions teaching a curriculum on HVAC systems must adapt their courses to better prepare graduates for a career in designing HVAC systems. Considerations for such preparation can be split into five sets of themes, as shown in **Figure 1**. Our discussion is aligned with international standards for learning objectives for engineering courses including the Washington and Sydney Accords, EUR-ACE® Framework Standards (EUR-ACE 2006) and Guidelines (EAFSG) and the Accreditation of Higher Education Programmes (AHEP) in UK (Engineering Council, 2020).



The Engineer and Society	• Sustainability |Ethics |Risk | Security | EDI
Engineering Practice and Transferable Skills	• Critical Thinking | Creativity |Communication (Oral, Written, Verbal)
Science and Mathematics	• Statistics |Machine Learning |Decision Analytics
Engineering Analysis and Emerging Concepts	• Climate Change |Health and Wellbeing |Decarbonisation |Energy Flexibility |Building Performance Simulation |Post Occupancy Evaluation |Life Cycle Analysis and Circular Economy
Design and Innovation	• Integrated Design| Design Thinking |Innovation for Sustainability

Figure 1. Key inputs into modern building engineering academic courses.

The last two themes, 'Engineering Analysis and Emerging Concepts' and 'Design & Innovation', represent many of the greatest challenges that the building stock will have to overcome due to greater recent clarity on how building performance could be affected by changes in the environment, building design, regulatory requirements, and improvements in materials.

(a) The effects of **climate change** on occupants and key processes within buildings have largely been defined (de Wilde & Coley, 2012). However, engineers will be required to design HVAC systems to account for "future proofing" (Georgiadou et al., 2012) and increased energy usage (Berardi & Jafarpur, 2020).

(b) **Health and wellbeing** of building occupants is influenced by indoor environmental quality (IEQ) (Chatzidiakou et al., 2014), a key concept covering thermal, noise and lighting quality as well as indoor air quality and moisture. Air flow generated through HVAC systems can mitigate (Leyten & Kurvers, 2006) as well as exacerbate (Betterman & Burge, 1995) health problems such as asthma and allergen related issues.

(c) **Decarbonisation:** The decarbonisation of current building stock – the need for buildings to themselves meet net zero emissions and the awareness of the role of HVAC systems in meeting those targets. It is possible to investigate the role and influence of HVAC systems on energy demand across entire countries using top-down models. However, concerns have been raised regarding the skills gap for a bottom-up approach (Stanes et al., 2022).

(d) **Energy flexibility**: Within demand-response energy systems, there is an awareness of future needs for HVAC systems to be able to operate flexibly depending on the availability and pricing of electricity (Jensen et al., 2017). It was previously found that model predictive control could outperform the use of conventional control systems in terms of energy conservation (Afram & Janabi-Sharifi, 2014). Advances in machine learning (ML) and artificial intelligence (AI) could allow the further expansion and refinement of variables used in such models.

(e) **Building Performance Simulation** allows for a transition to *performance*-based building regulations.

(f) **Post-occupancy evaluation** first originated as a method for observing behaviour within a living or working environment (Zimring & Reizenstein, 1980). However, in the specific context of building control systems, it has evolved into a dual analysis of whether such existing environments both satisfy occupants' needs for comfort as well as better understand their energy consumption requirements using surveys, onsite inspections, and monitoring to inform future "planning and practice" (Meir et al., 2009).

Several questions are raised by these emerging 21st century building engineering challenges:

- Are the key learning outcomes required to address these challenges already incorporated in our undergraduate programmes?
- Can we redefine the role of HVAC engineers in the context of these challenges?
- What are the key challenges and opportunities?

The following sections describe the approach taken to elucidate the answers to these questions and an examination of the findings.

Methodology

An online questionnaire was created to gather the attitudes of both academic and industry professionals on the four sets of factors influencing the design and delivery of European undergraduate courses in HVAC systems. The questionnaire was circulated to REHVA's Standing Committees: a) Technology and Research Committee (TRC), b) Education and Training Committee (ETC), and c) Publishing and Marketing Committee (PMC).

The total of 46 respondents comprised 11 non-academic and 35 university staff from 14 European countries. The breakdown per country: a) UK (9), b) Turkey (6), c) Italy (5), d) Spain (4), e) Netherlands (4), f) France (3), g) Poland (3), h) Denmark (2), i) Estonia (2), j) Romania (2), k) Slovakia (2), l) Finland (1), m) Hungary (1), n) Ireland (1). Two of the respondents from Turkey and one from Slovakia were from non-accredited courses.

Results

Findings have been organised into themes based about the specific challenges or opportunities identified through the surveys. These themes include recruitment challenges and rebranding, the engineer and society, engineering practice and transferable skills, science and mathematics, Engineering Analysis & Emerging Concepts, and Design and Innovation & Emerging Concepts.

Recruitment Challenges and Rebranding

Recruitment on undergraduate courses differed widely and is, in part, a function of national HEI characteristics, as well as the composition of local industry. The image of HVAC/building services engineering as staid and uninspiring was reported to contribute to declining numbers in high-quality applicants in some programmes. In recognition of this misconception, ASHRAE is no longer an acronym, but is part of ASHRAE Engineering and the Built Environment. Despite this acknowledgement and name change by a major professional body, only 31% of the respondents from universities agreed that renaming their programme is needed to better reflect the changing role of HVAC engineers.

University staff (n=35) were asked for details about their courses and the recruitment process. Roughly half (18 out of 35, 51.4%) reported problems in attracting high quality applicants. Of the remainder, which did report successes, 11 provided some feedback on the measures they had implemented to improve recruitment. In the majority of cases (7 of 11 respondents, 63.6%), it was found that better links to industry in some form had been beneficial. These links included scholarships (3), technical meetings and collaboration (2) and the crowdfunding of a marketing campaign (1). Renaming the course was found to have been beneficial in 2 cases. Other administrative changes which were found to improve the quality of applicants were school visits (3), accreditation (2), open days (2) and mixed mode attendance (2). Other respondents pointed to climate change, and its associated activism, as inspiration for young people to engage. Additionally, the broadening role of building services engineers within the architectural domain or resource economics could increase the number and type of applicants.

The Engineer and Society

Five socially relevant themes were identified, and participants were asked to rate them in terms of importance in engineering education from of no importance to most important: Sustainability, ethics, risk, security, and equity, diversity and inclusion (EDI). Of these, sustainability was the most consistently regarded as the most or very important amongst both academics and non-academics (**Figure 2**). Whilst for non-academics, respondents rated ethics as most important more often than sustainability. EDI, in contrast, was the most contested theme with almost equal responses between most important and of no importance for academics. Although EDI was as likely to be list as most important as not by academics, it was also reported to be the most challenging concept to deliver. A comment made by one of the respondents provides insights into the perceived difficulties:

> *"I would say the most difficult criterion to incorporate into the delivery of any engineering-focused educational program is ED&I. Within the framework of management, PM, and 'soft skills' related modules or delivery components this is relatively straightforward. However, when it comes to the more 'technically focused' elements it becomes more problematic, particularly referencing or incorporating the 9 protected characteristics from the Equality Act 2010. Some are easier to incorporate than others e.g., persons with specific disabilities would come under the remit of Approved Document M of the Building regulations. Characteristics such as 'gender reassignment' or 'belief system' need some significant creativity and strategic design of assessments and delivery to create a relevant and appropriate focus without resorting to 'lip service'. It can be done but can be problematic." – UK*

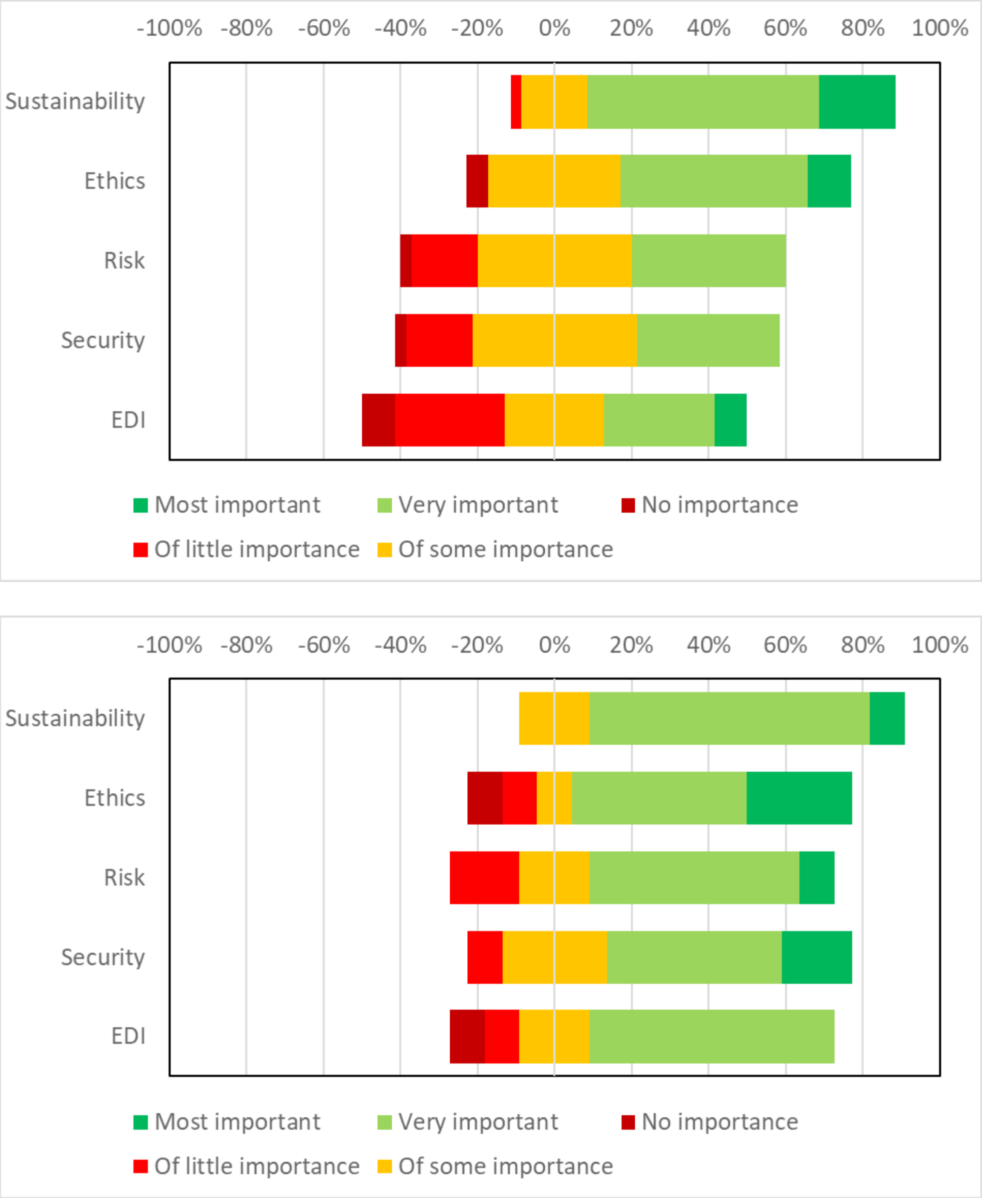


Figure 2. Comparison of societal considerations within academic teaching (above) and importance within industry (below).

Engineering Practice and Transferable Skills

Six practical skills were presented for evaluation including critical thinking, creative thinking, teamwork, oral communication, written communication, and visual communication. A comparison of responses between academic and non-academic respondents is illustrated in **Figure 3**. There is reasonable agreement between the two groups that these skills are all, at least, very important, except for oral communication which approximately 25% of non-academics ranked as only 'slightly important'.

Respondents from academia also provided comments on the innovative methods to incorporate these skills into courses. Primary amongst these techniques were design or project-based approaches which were cited by 10 of the 17 respondents.

"Our modus operandi is to include as many 'real life' project-based scenarios in our teaching, learning, and assessment processes. We structure our learning outcomes on a degree, level, and module basis to incorporate input from industrial partners and representatives to highlight the necessity for the 6 components listed above."- UK

"Problem based learning organized in project teams." - Denmark

"Problem based teaching is important."-Denmark

"Case studies and open problems" -Spain

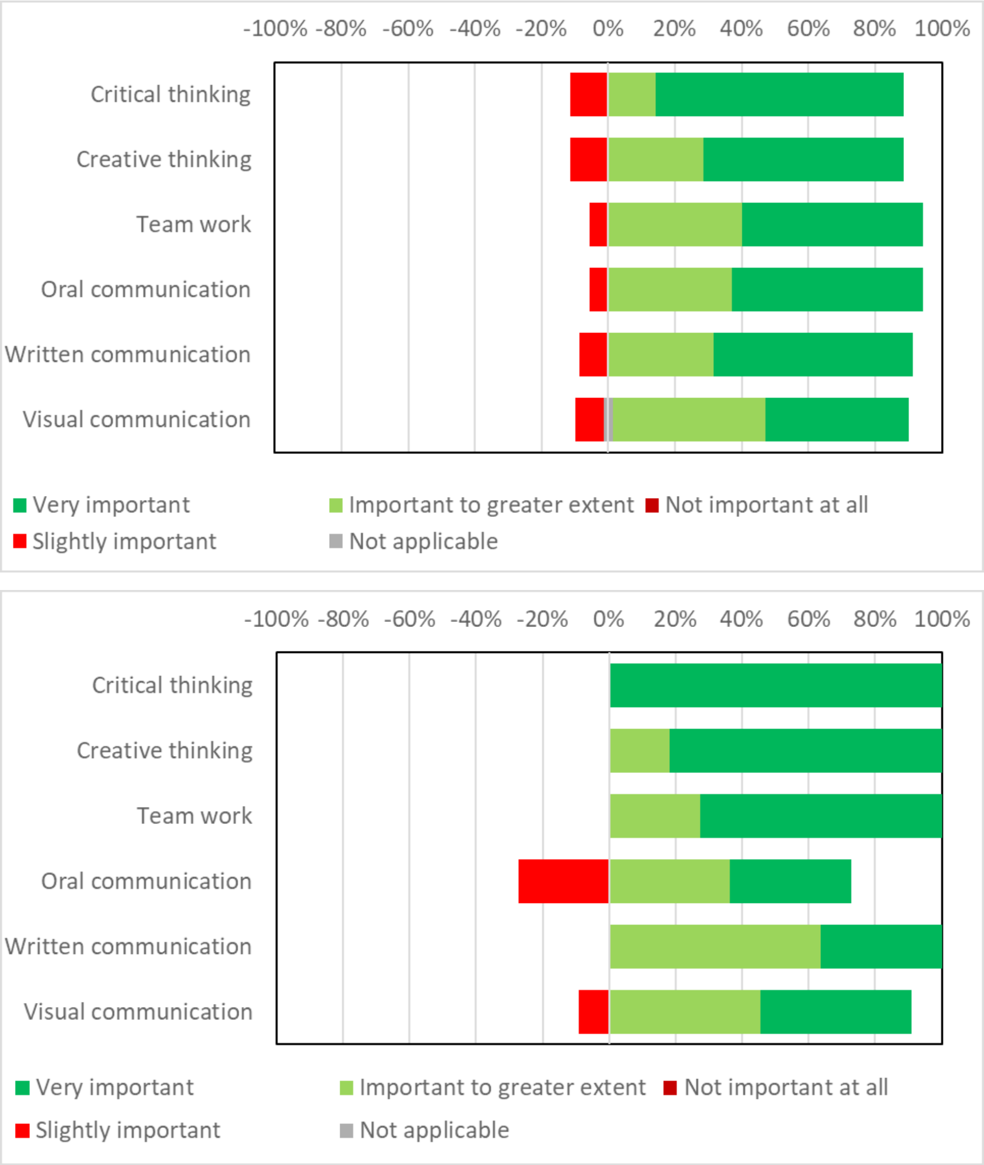


Figure 3. Comparison of importance of skills within academic teaching (above) and for industry professionals (below).

Science and Mathematics

The need for high-level and robust data analytics skills, machine learning, and decision-making analytics, is greater than ever. These skills are required to address increasingly large datasets such as those from smart metering and IoT technologies. Additionally, building controls are becoming essential to deliver on performance use targets and energy flexibility and will become a standard design requirement for buildings. The argument is that we need a step change to equip graduates with these science and mathematics skills to prepare them for a rapidly changing industry. Academics were asked to assess these skills in the applicants to their programmes. The majority (>80%) reported that the statistics foundations were fully presented or presented to a greater extent. However, about the same percentage of respondents reported that, for both machine learning and decision-making analytics skills, applicants were not presented at all or to a small extent, indicating a significant gap in the required skills.

Issues reported by academic respondents:

Amongst the issues reported by the academic responses were a lack of preparedness in high-school mathematics, the need to update curricula, and the importance of programme reaccreditation every 4-5 years that exerts pressure on universities to readdress the needs from industry. These issues point to the conclusion that analytical skills development requires significant attention. The few universities that are following trends are primarily master level programmes (European programmes follow either 3+2 or 4+1 year educational cycles required for engineering programmes, note in England the educational cycle requirements for engineering courses are either 3+1 or 4+0 years, some programmes offer a year in industry).

One comment from an academic respondent from the UK (below) suggests a way forward to place building engineering programmes in the context of emerging concepts of importance to the profession.

> *"With a focus on Intelligent Buildings and Smart Cities, we as a teaching and research-focused organisation have had to adapt our teaching and learning philosophies to incorporate the spread of 'Big Data' and machine learning algorithmics within our delivery. The emphasis needs to be on the use of mathematics as a 'toolbox' to be able to build Model Predictive control systems with a holistic focus on energy efficiency, decarbonisation, and human comfort. With the rise of collaborative working applications within a BIM paradigm, the current cohorts have had to adapt to an ever-increasing exposure to complex data generated from BIM models and the move towards the Digital Twin philosophies from both project planning and delivery to obtain real-time operational data have required a different approach to teaching mathematics and data analysis." - UK*

Engineering Analysis & Emerging Concepts

The level of incorporation of the key concepts, described in the introduction, into engineering analysis is shown and compared for both academic and industry

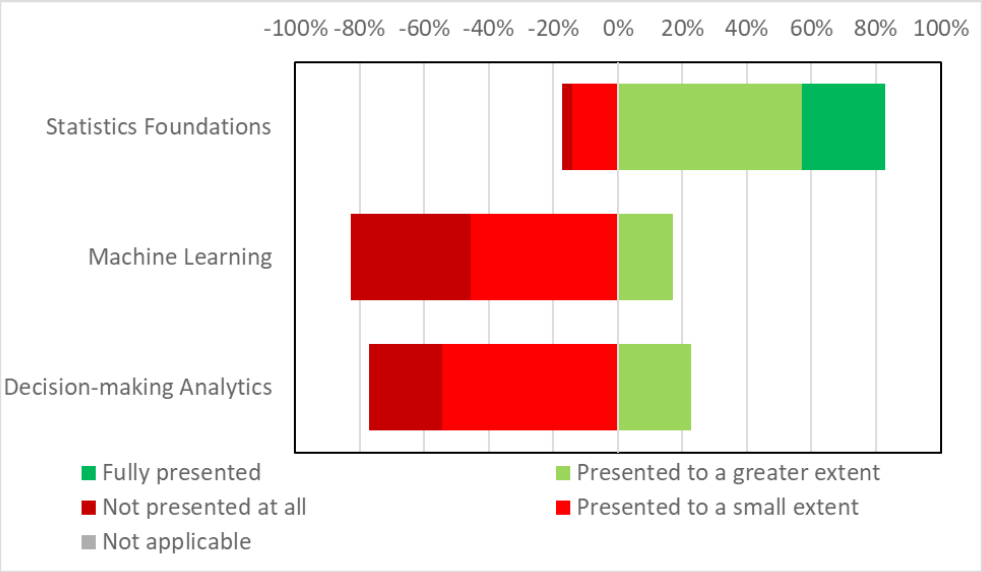


Figure 4. Presentation of skills by applicants to engineering programmes reported by academics.

professionals in **Figure 5** below. There is general agreement with IEQ – health being viewed as fully integrated by more than 80% of both types of respondents. Both groups also see room for improvement in the integration of POE and life cycle performance and circularity into engineering analysis.

One industry professional from Spain commented that there is a gap in the software available for life cycle assessment and the need to perform such analysis and a non-academic from the Netherlands commented that the level of analysis required to make full integration of these key concepts is not rewarded. "HVAC professionals are very often not very motivated to spend more time and effort in their design and installation activities due to the fact that this is not rewarded (lowest price thinking, performance commission is not [paid] for)."

Design and Innovation & Emerging Concepts

Design thinking is the iterative process of creation, assessment, selection, and realisation to address complex problems. Well embedded in architectural education the concept of divergence and convergence forms a double diamond to support students to: (1) discover: research users' needs, (2) define: state users' needs and problems, (3) develop: challenge assumptions, create ideas and start to create solutions, and (4) deliver: try solutions out.

The level of incorporation of these same key concepts described above into analytic tools used in design is shown and compared for both academic and industry professionals in **Figure 6**. As with integration into engineering analysis, academic and non-academic respondents largely agree on the strengths and

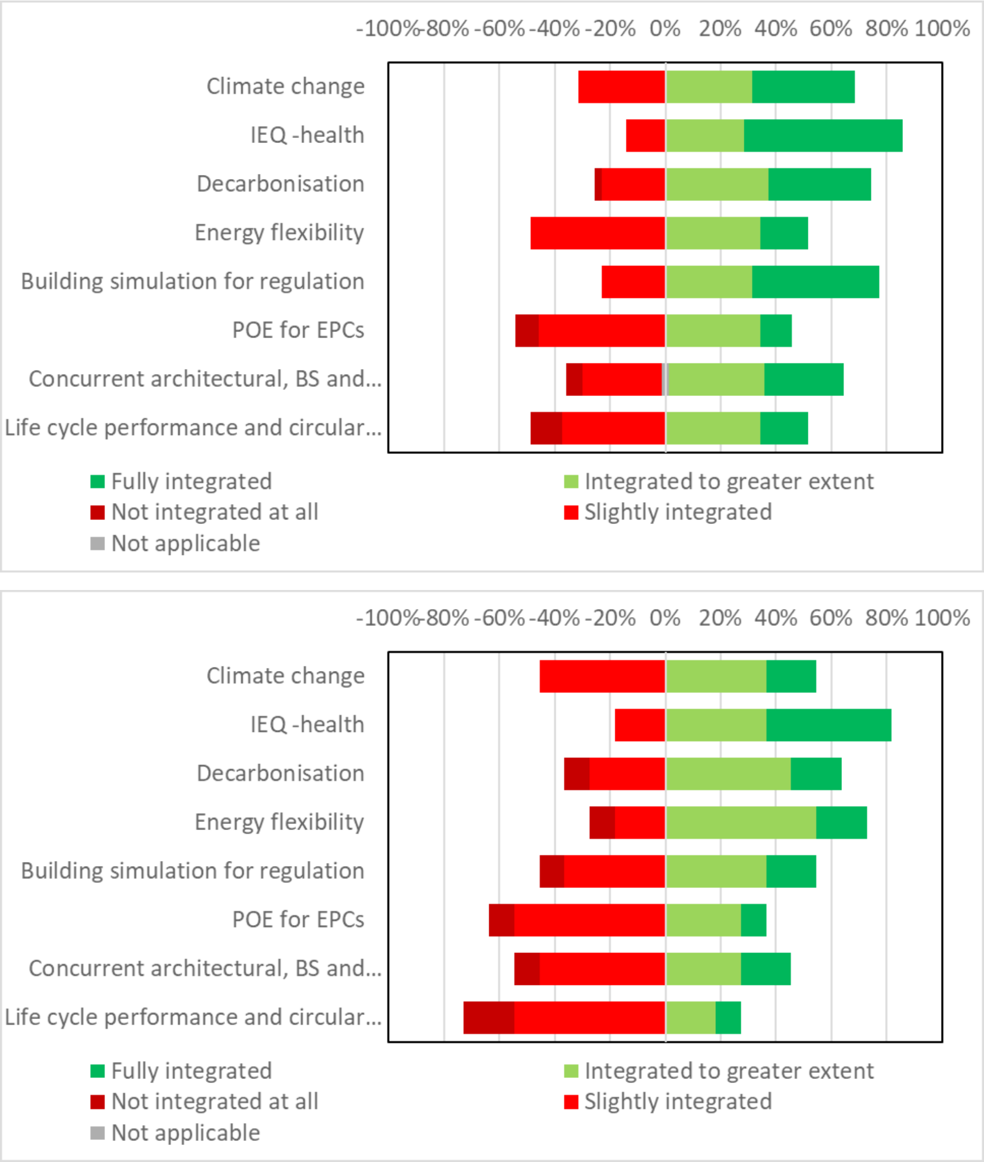


Figure 5. Integration of key concepts into engineering analysis, responses from (35) academics (above) and (11) non-academic (below).

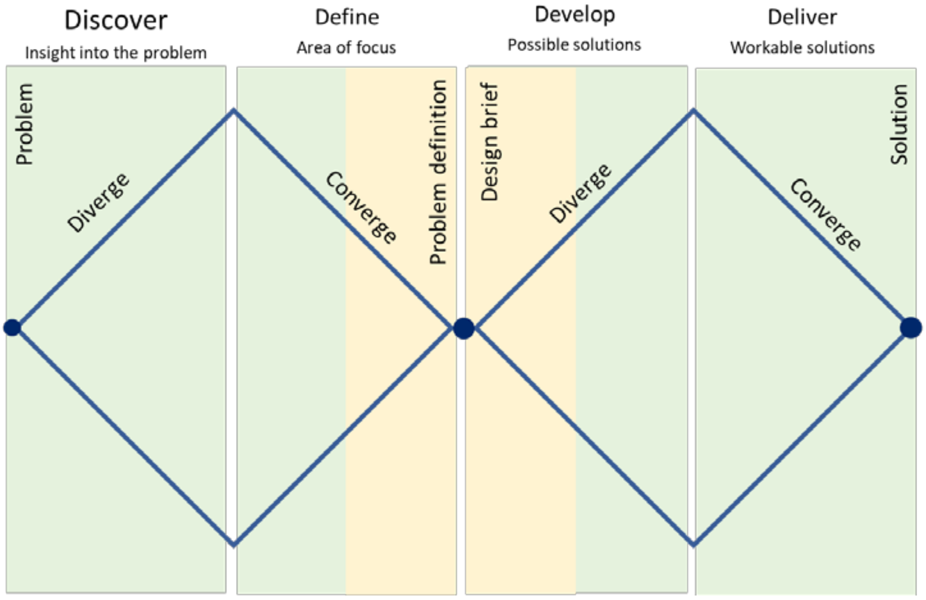


Figure 6. Diagram of the convergence and divergence typical of the design thinking process.

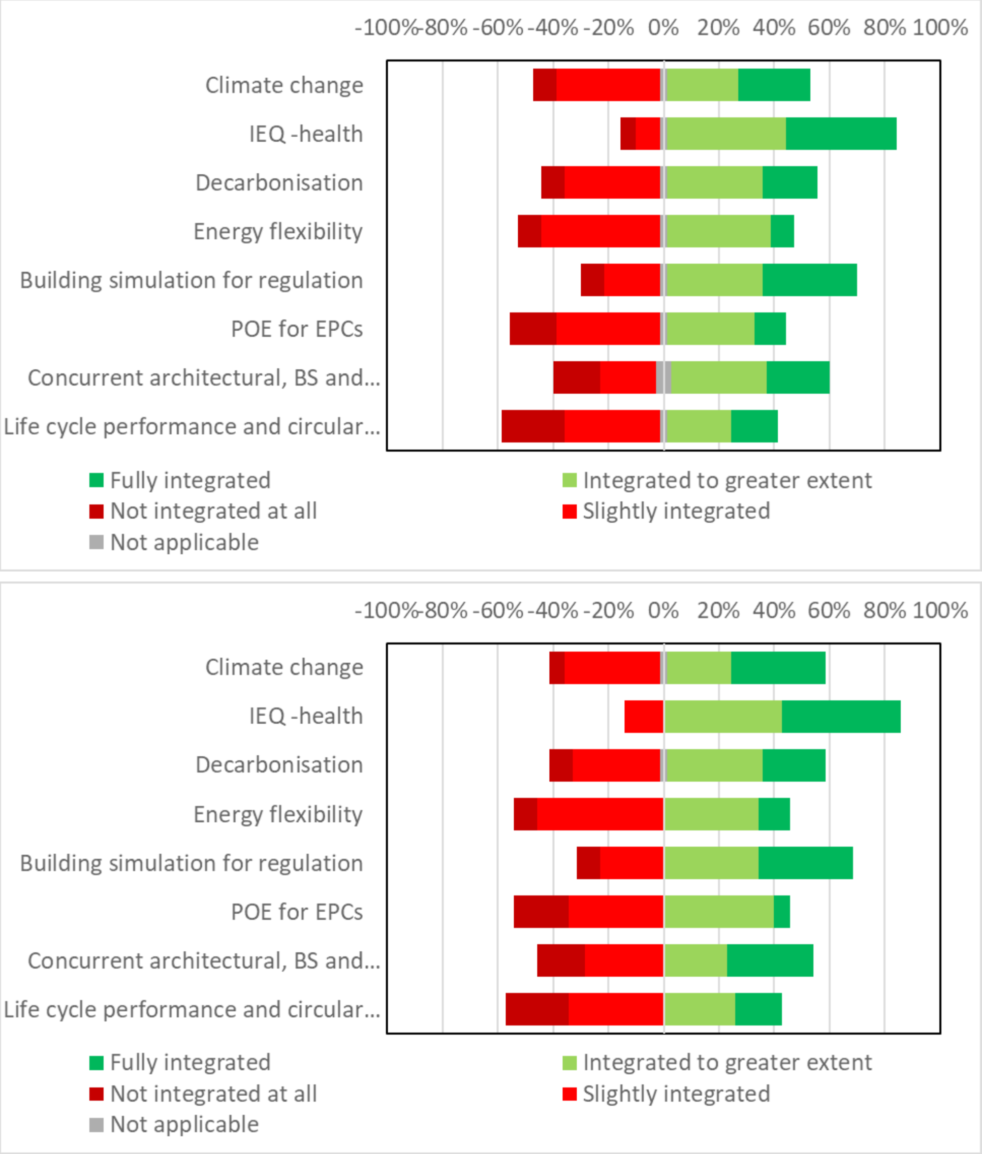


Figure 7. Integration of key concepts into analytic tools, responses from (35) academics (above) and (11) non-academic (below).

opportunities for incorporation of the key concepts into analytic tools. Once again IEQ – health is viewed as fully or largely integrated into the tools by greater than 80% of respondents. POE and life cycle performance were, once again, perceived to be falling behind in integration into available analytic tools.

Insights from academics about the integration of the key concepts, especially of IEQ – health, include using 'real cases' for analysis, and the development of new modules that introduce complex building simulation software. One respondent from Turkey commented, "Over the last two years, students are encouraged to use analytical tools such as software packages and services. Anysys Fluent, Thermoflow, Homer, etc. are widely used in design projects…".

Academics also provided insights into how well integrated the eight key concepts are in design process of HVAC systems in the courses. Respondents reported that design studios provided a platform for integration in engineering specific courses. A comment from the UK suggested that a dual-accredited programme provided opportunities for the integration of concepts.

> *"A dual architecture and engineering accredited programme has helped all students to gain skills in co-ordination and integrations skills for the building services, as well as appreciation for the early design concept and site analysis stages of a project, and its role in driving low carbon designs."*
> *-UK*

Conclusion

The findings from the work presented here demonstrate that both challenges and opportunities exist within engineering education in Europe, and that these are largely centred within five key concepts, the engineer and society, engineering practice and transferable skills, science and mathematics, engineering analysis and emerging concepts, and design and innovation. Specific challenges and opportunities are listed below.

Educational Challenges:

- The science underpinning our understanding of climate change and health and wellbeing in the built environment, as well as the role of our profession in the society, is rapidly changing. The implication of this rapid change is that our building engineering design must consider: Biodiversity and Environment, Circular Economy, Decarbonisation, Resilience and Adaptation, Social Value / Equity and Sustainability.

- New design requirements such as climate resilience, net zero, and health and wellbeing are all based on a "performance in use" concept that expands the liability of design teams. This expanded liability necessitates that the mechanical and electrical designers be involved in decision making in early design phase.

- With a growing number of design requirements, which sometimes conflict, and rapid development of smart metering and sensors, there is a pressure for greater data analytical skills and the introduction of machine learning and decision-making analytics.

Educational Opportunities:

- Motivations for the next generation to enter the profession are more salient than ever due issues such as climate change. The profession and programmes in HVAC engineering will appeal through the positive impacts they can have in the world in meaningful ways on climate change and health and wellbeing. Additionally, the skills required by the profession, such as data analytics and digital engineering design, are areas of interest to this generation and can motivate them to enter the field.

- A new professional will redefine the role of HVAC engineer into Building Design and Engineering as 'performance in use' becomes the norm in the context of net zero and health and wellbeing. The new definition will extend the role of traditional HVAC engineers to building engineering designers being involved in all RIBA stages (Stage 1 preparation and briefing, Stage 2 concept design, Stage 3 spatial coordination, Stage 4 technical design, Stage 5 manufacturing and construction, Stage 6 handover, Stage 7 use).

Undergraduate HVAC programmes play a critical part in defining the changing role of HVAC engineers in industry and society. The challenges and opportunities described here make a case for a "revolutionary evolution" of the way we educate tomorrow's engineering professionals. ■

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