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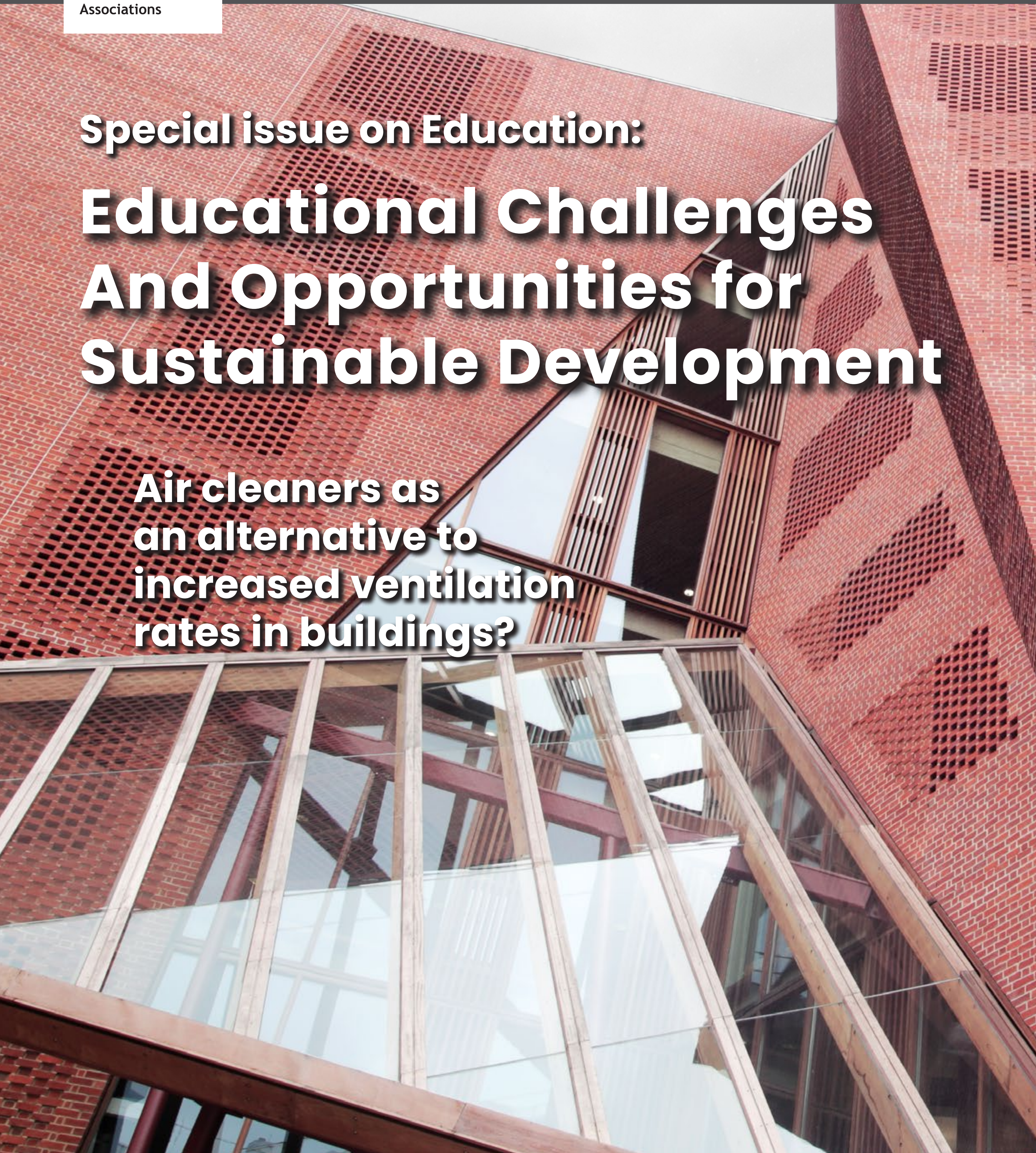

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Inspiring and Preparing the Next Generations of the Built Environment Professionals for a Net Zero Future: Revolutionary Evolution

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. Transcending multiple disciplinary boundaries is becoming increasingly important for devising solutions to these pressing issues. These issues have extended the role of traditional HVAC engineers to all stages of buildings' life from preparation and briefing, concept design, spatial coordination, technical design, manufacturing and construction, handover, and finally use including circularity. Undergraduate HVAC programmes play a critical part in developing new competencies and attributes of future built environment professionals. The challenges, opportunities, best practices described in this special issue make a case for a "revolutionary evolution" of the way we educate tomorrow's engineering professionals.

The total of 46 respondents from 14 European countries provided their views on competencies and attributes of future built environment professionals. In addition, colleagues from Canada, Scotland, Netherlands, and Romania provided set of educational approaches covering key aspects of engineering education from building performance simulation, sustainable development, integrated and net zero carbon design. This special issue ends with insights on transdisciplinary architecture and engineering education in England.

If you are interested to co-create vision for future built environment professionals, please get in touch. This work continues. ■

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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).

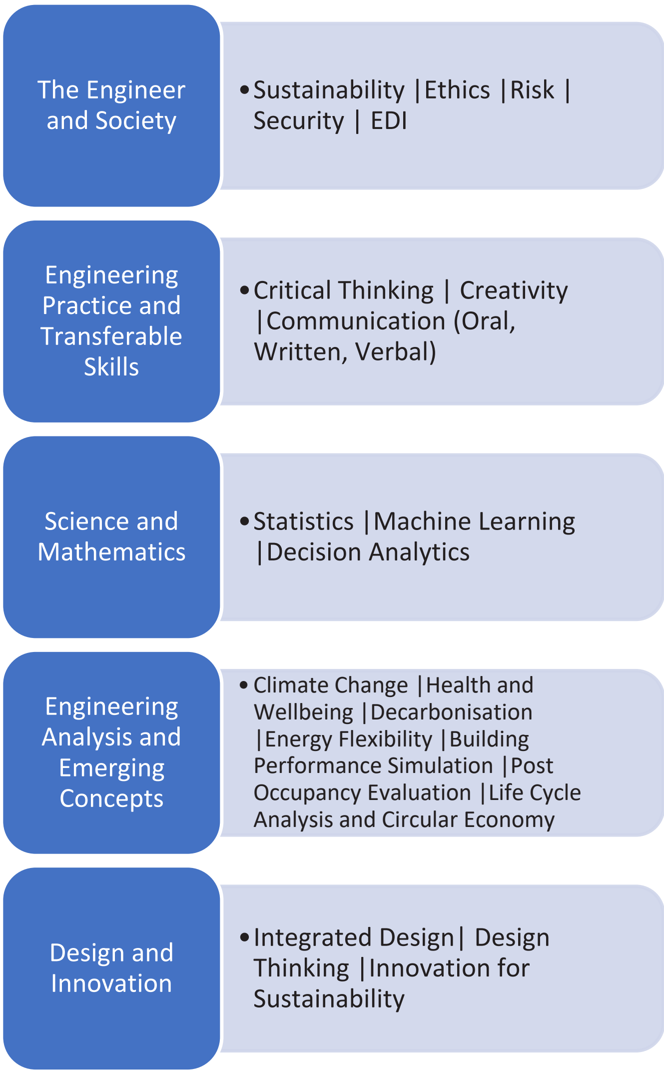


Figure 1. Key inputs into modern building engineering academic courses.

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

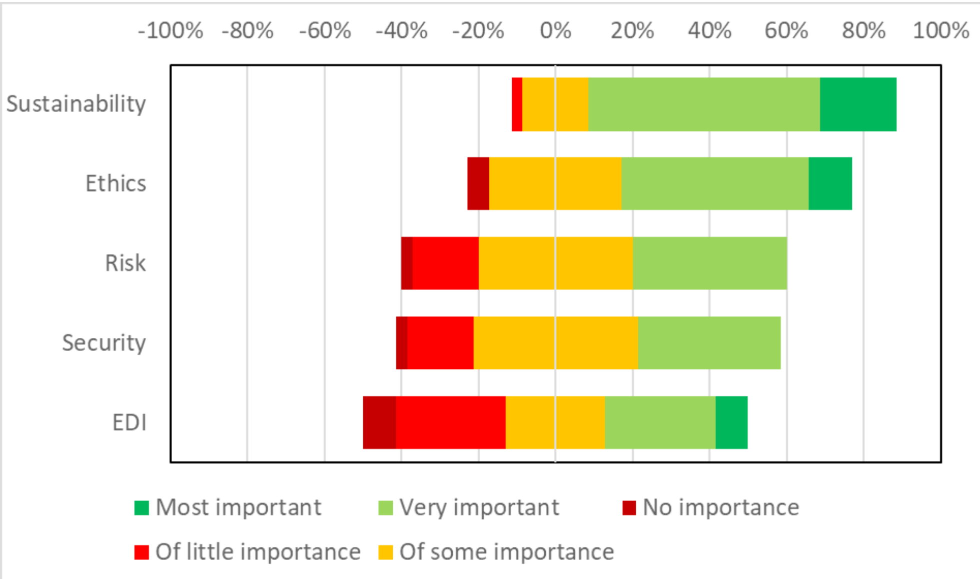
Recruitment on undergraduate courses differed widely and is, in part, a function of national HEI characteristics, as well as the composition of local industry. The image of HVAC/building services engineering as staid and uninspiring was reported to contribute to declining numbers in high-quality applicants 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



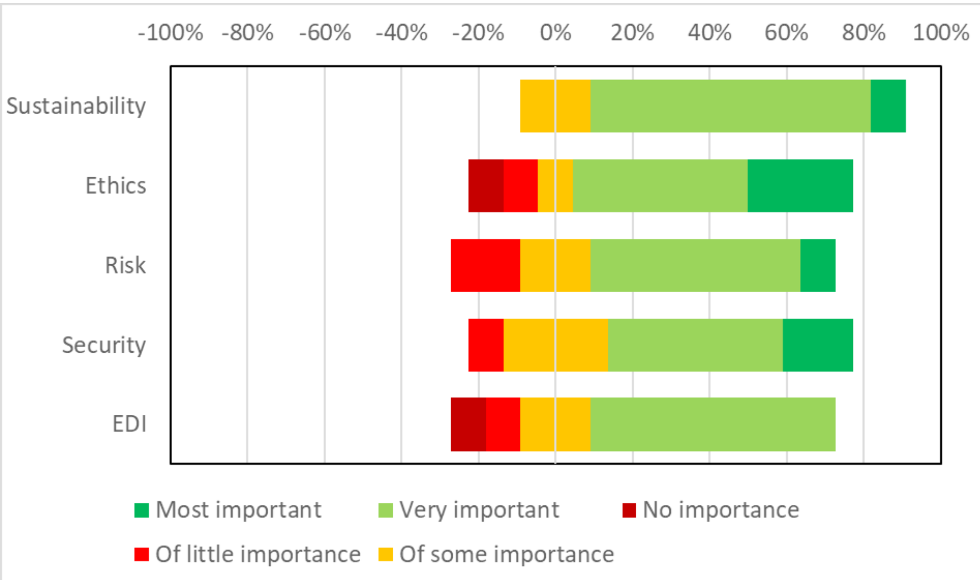


Figure 2. Comparison of societal considerations within academic teaching (above) and importance within industry (below).

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'.

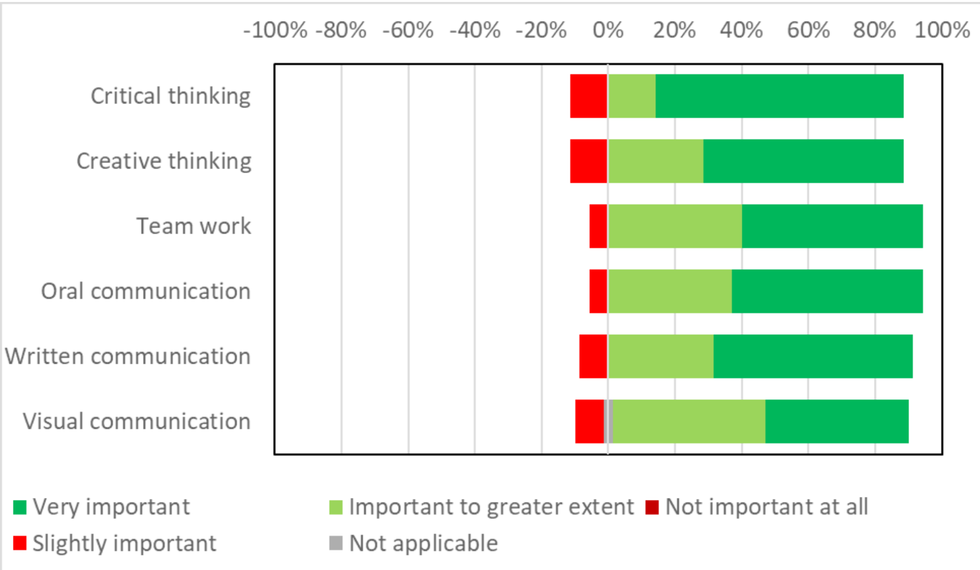
Respondents from academia also provided comments on the innovative methods to incorporate these skills into courses. Primary amongst these techniques were design or project-based approaches which were cited by 10 of the 17 respondents.

"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



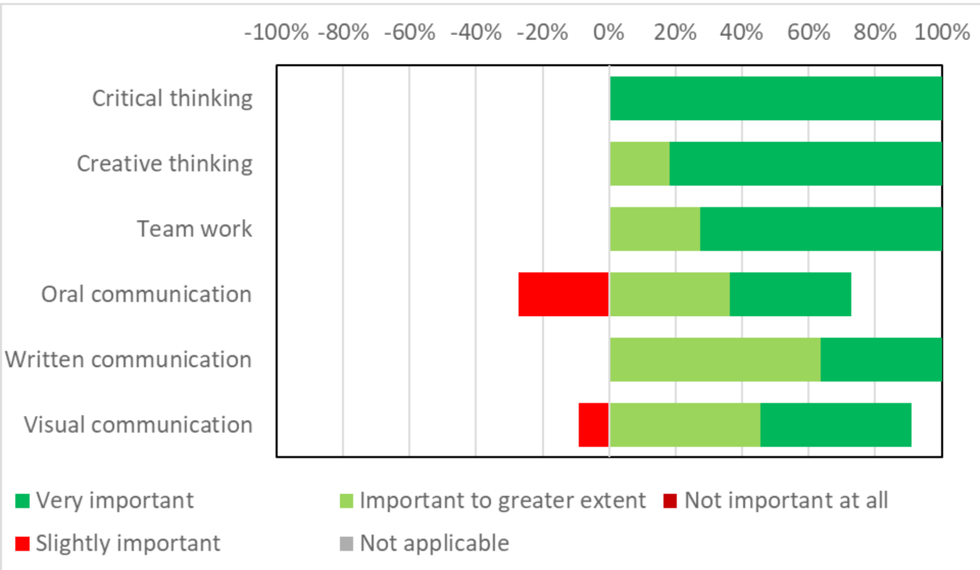


Figure 3. Comparison of importance of skills within academic teaching (above) and for industry professionals (below).

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

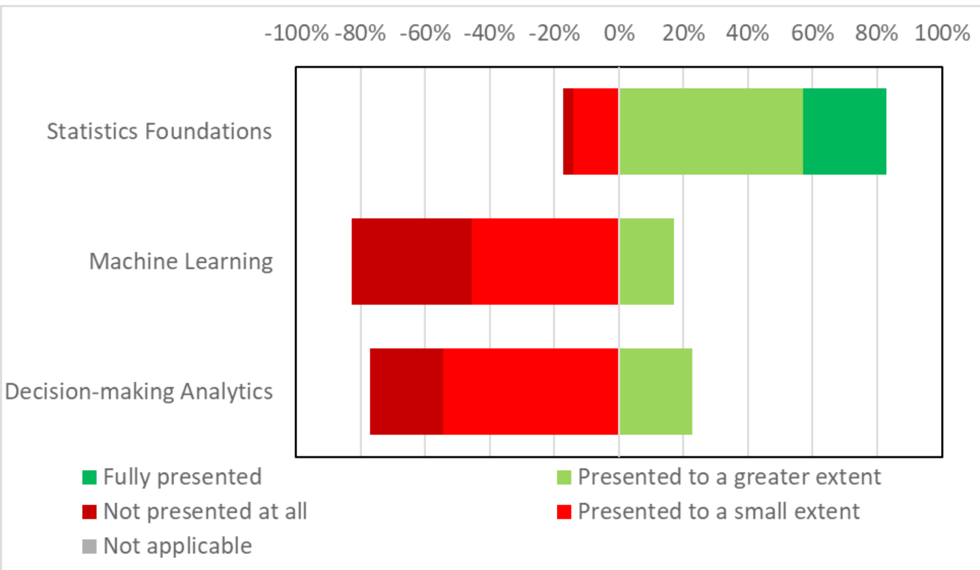


Figure 4. Presentation of skills by applicants to engineering programmes reported by academics.

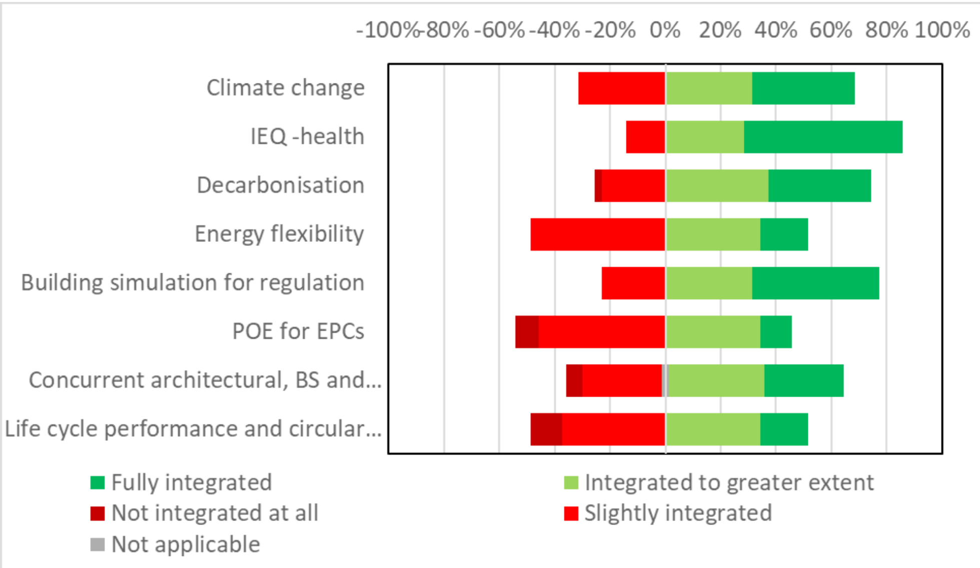
professionals in **Figure 5** below. There is general agreement with IEQ – health being viewed as fully integrated by more than 80% of both types of respondents. Both groups also see room for improvement in the integration of POE and life cycle performance and circularity into engineering analysis.

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



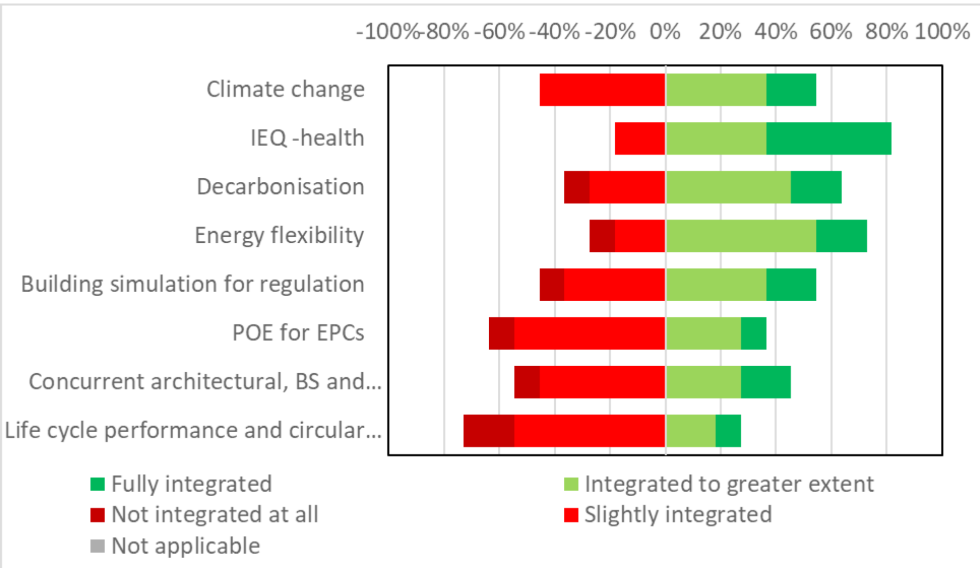


Figure 5. Integration of key concepts into engineering analysis, responses from (35) academics (above) and (11) non-academic (below).

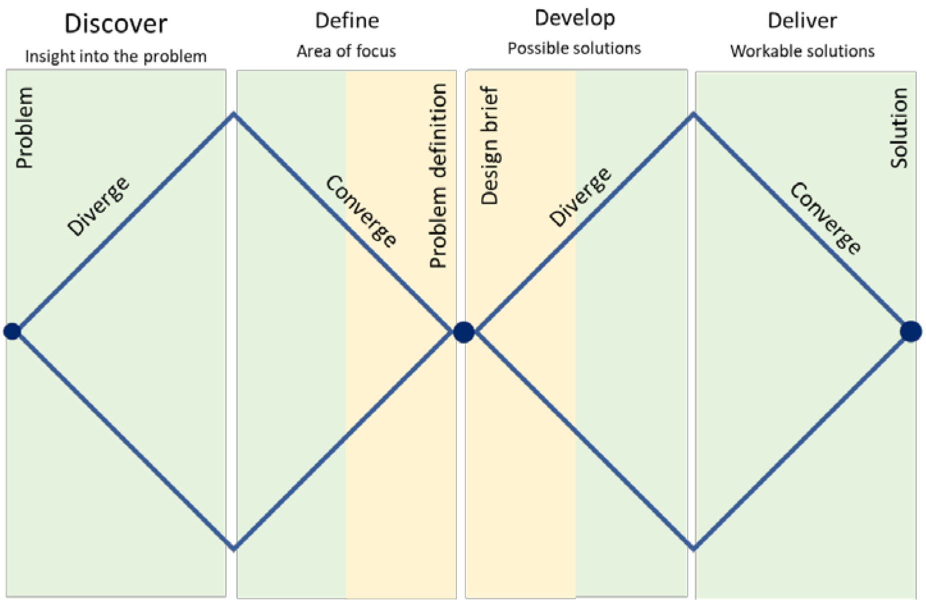
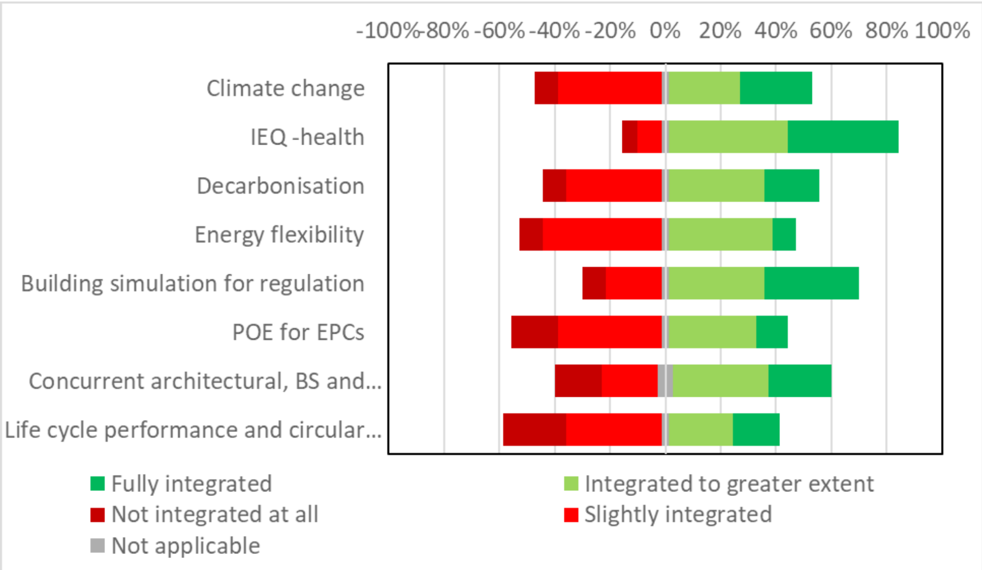


Figure 6. Diagram of the convergence and divergence typical of the design thinking process.



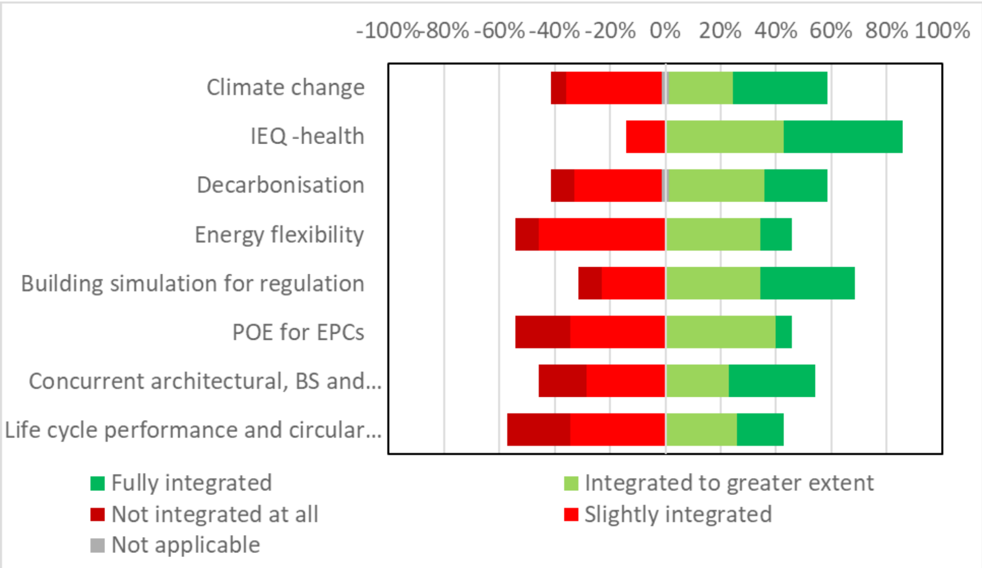


Figure 7. Integration of key concepts into analytic tools, responses from (35) academics (above) and (11) non-academic (below).

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. ■

Please find the complete list of references in the online version of this article at rehva.eu/rehva-journal

Teaching the fundamentals of building performance simulation in the 21st century

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Why BPS matters

Building performance simulation (BPS) tools employs a large number of mathematical models to simulate a building's performance under a given set of weather and operating conditions. Many aspects of performance can be appraised, including energy consumption, ventilation effectiveness, thermal comfort, lighting quality, etc. The objective is to represent the significant physical processes so that the simulation provides an accurate—or at least a useful—representation of reality.

This technology provides tremendous potential for addressing some of the key challenges facing the building industry in the 21st century by improving design and operation: climate change, energy dependency, renewables integration, health/wellbeing, etc. For example, BPS can allow architects and engineers to compare the performance of innovative concepts inexpensively and to contrast design alternatives rapidly throughout the various stages of design development. This is critical as we move towards design solutions that more tightly integrate architecture, thermal and electrical systems, and energy storage.

However, much of BPS' potential remains unfulfilled. There are various reasons for this, but one important factor is a credibility gap that can only be addressed when we adequately prepare users to effectively apply tools with full knowledge of their applicability, modelling limitations, and default methods and data, and provide them the skill set to scrutinize their results.

Using BPS is easy, and difficult

Today we have access to numerous BPS tools that offer modern and intuitive user interfaces. With these, new users can quickly ascend the learning curve to describe complex building and energy systems in order to produce simulation predictions more rapidly than ever before imagined. **Figure 1** provides a demonstration of how easy it is for new users to learn the basics of operating BPS tools. I provided some introductory training on tool operation to students who were brand new to the BPS field. Within two weeks all were able to simulate the performance of a simple building using two different BPS tools. Their predictions of the building's cooling load are plotted in **Figure 1** and contrasted to a reference result (the expected outcome).

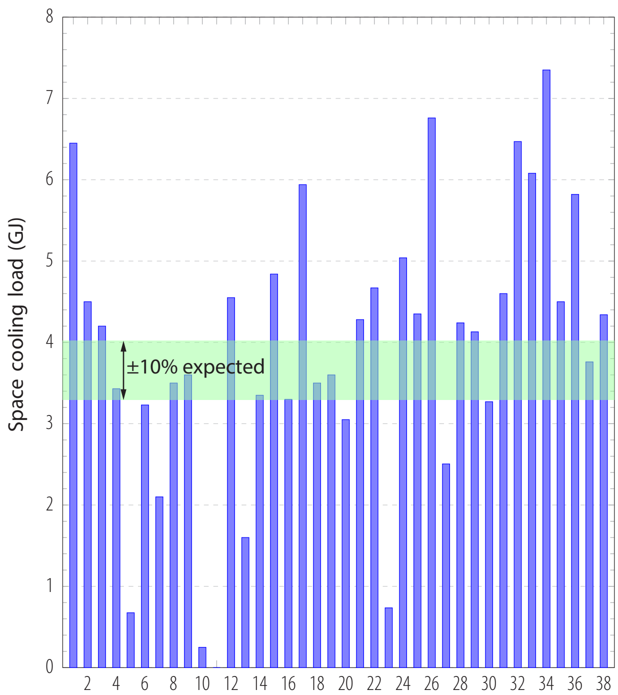

Figure 1. Simulation predictions produced by novice users trained to operate two BPS tools (38 combinations of users and tools).

Although a handful of the simulation predictions were within 10% of the reference, it can be seen that the majority are significantly higher or lower.

This is not a unique finding. The literature is full of such anecdotes, and fidelity does not seem to vary much with the experience level of the user (practicing engineers, researchers, novices) or the choice of BPS tool. It is challenging to produce accurate BPS results. Buildings are complex entities so predicting their performance requires simulating myriad interrelated heat and mass transfer processes which are excited by uncertain boundary conditions. Accurately predicting performance requires the user to select modelling options and input data to characterize all the significant processes. Deciding how to prioritize efforts on the most important and impactful parameters and modelling choices is not always easy. Should efforts be focused on geometry and zoning, characterizing air infiltration, described HVAC systems and their control, or describing convection and radiation heat transfer processes? It depends upon the building and the objectives of the analysis, so universal and simple rules cannot be prescribed.

Teaching vs training

Too often we train users to operate BPS tools – as I did in the demonstration shown in **Figure 1** – but we neglect to teach them to comprehend the underlying methods and their inherent limitations. As a result, users can easily feel overwhelmed and are often ill-equipped to operate tools accurately and with greatest impact. Because of this, many users rely upon default methods and default inputs (e.g. ground albedo, part-load-ratio efficiency curves, convection regimes) without realizing the implications of these choices. And they are not equipped to answer the above questions about prioritizing efforts.

To address the key 21st century challenges facing the building industry it is imperative that we develop advanced tool users who have an understanding of BPS fundamentals. These people will have the ability to prioritize efforts, decide which inputs and modelling choices will have the greatest impact upon simulation predictions, configure fit-for-purpose models, and scrutinize simulation results. This will help us to achieve the full potential of BPS.

An approach for teaching the fundamentals

I have authored a textbook to help address these needs (**Figure 2**). This book—endorsed by the International Building Performance Simulation Association—is aimed at teaching the fundamentals of BPS and can be used to support university-level courses in engineering, building physics, and architectural science. It can also be used to support professional development courses or as a self-study guide by BPS practitioners wishing to deepen their knowledge of the fundamentals. It presumes basic knowledge of heat transfer, thermodynamics, building physics, and the terminology of buildings and HVAC systems, but does not require prerequisite knowledge of BPS or experience applying BPS tools.

Figure 2. Fundamentals of Building Performance Simulation textbook.

Readers who complete all the book's learning elements (described below) will be able to:

- Understand the models that have been implemented into BPS tools for treating the significant heat and mass transfer processes.
- Appreciate the simplifications inherent in these models and the necessity for these simplifications.
- Comprehend the implications of modelling choices and default modelling methods and input data.

- Select appropriate models, simulation methods, and BPS tools for a given analysis.
- Understand which modelling choices and input data have the greatest impact upon simulation predictions.

The book employs an experiential teaching approach structured upon four interrelated modes of learning, which are illustrated in **Figure 3**. The result is a learning spiral wherein the completion of one topic's cycle through the four learning modes leads into the next topic. Most of these topics focus on an individual heat or mass transfer process, such as longwave radiation from external building surfaces, heat transfer to the ground, air infiltration, etc.

Each chapter of the book is dedicated to one of these topics and follows a common structure. Basic theories are first introduced and then the methods commonly used in BPS are described (the *Study theory* mode of **Figure 3**). This is done in a tool-agnostic manner whereby the spectrum of commonly employed techniques is outlined, and the strengths and weaknesses of each are described. Mathematical descriptions are provided where necessary to illustrate concepts, but these chapters are not meant to be a comprehensive compendium of models.

Each chapter guides the reader to experiment with BPS tools in the *Simulation exercise* mode of learning. These exercises provide instructions aimed at isolating specific algorithms, requiring readers to consult BPS tool technical documentation and to explore and experiment with their chosen tool to conduct sensitivity analyses and to extract particular results.

Student results are compared, contrasted, and collectively analyzed during the *Autopsy* mode of learning. These sessions are most effective when they are led by a course instructor and involve group discussions. By examining simulation input files and collectively diagnosing issues students develop skills in scrutinizing simulation results and learn from their own experiences and those of peers.

In the final mode of learning—*Reflect & connect*—students individually reflect upon the findings highlighted during the autopsy and perhaps revise their simulation input files and conduct new simulations to update their results. This is also an important mode for connecting the studied theory to observations derived from the simulation exercises.

This teaching approach is demonstrated by drawing some examples from a graduate-level university course and from a professional development course that I recently taught.

Teaching example—solar energy absorption by external surfaces

We'll focus on the book's chapter dedicated to solar energy absorption by external surfaces. Students commence this topic by studying some theory. This chapter of the book outlines the factors that influence the amount of solar irradiance incident upon the

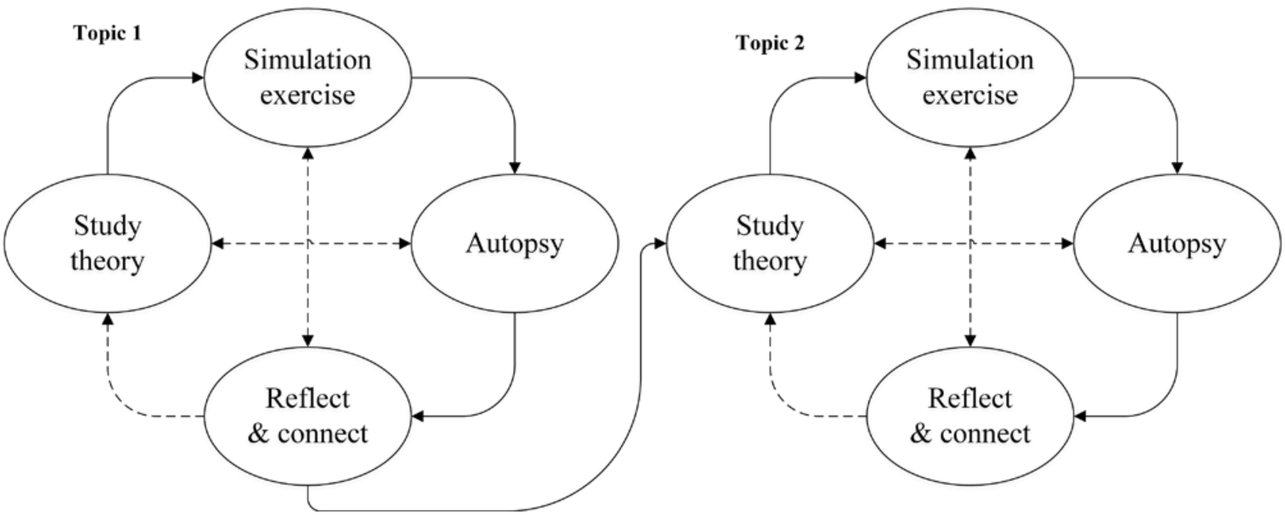

Figure 3. Two cycles through the learning spiral showing the four interrelated modes of learning.

external surfaces of the building. This includes scattering of solar radiation by the earth's atmosphere, the geometrical relationship between the building and the sun, shading by surrounding objects, and the reflection of solar radiation by the ground.

The book then explains that it is common for BPS tools to treat the global incident irradiance as the summation of three components: beam, sky diffuse, and ground reflected radiation. The algorithms that are used to derive the beam component from solar radiation data contained in weather files are explained, which develops an appreciation for solar geometry calculations and concepts such as solar declination, solar elevation, and surface azimuth. Readers then learn about the complexities and uncertainty in predicting sky diffuse irradiance and come to realize the factors that cause scattering of solar irradiance by the earth's atmosphere (**Figure 4**). They are introduced to the breadth of models that have been developed to estimate this scattering and the empirical nature of these models, and they discover that different BPS tools employ different models and provide different options to the user. Finally, they learn about the factors—such as vegetation and snow accumulation and melting—that complicate the estimation of ground-reflected solar irradiance and come to understand some of the modelling approaches available.

This chapter of the book then guides the reader through a series of four structured simulation exercises focused on solar energy absorption by external surfaces. In one exercise they alter the solar absorptivity on a single building surface and examine the impact this has upon the building's heating and cooling loads. By contrasting this result against an exercise from a previous chapter focused on the modelling of solar absorption by internal building surfaces they come to realize the relative significance of these input data. In another exercise they explore the optional methods their chosen BPS tool offers for the modelling of sky diffuse solar irradiance and the impact this kind of modelling decision can have upon simulation results. The other exercises have them discover the options for treating ground-reflected solar irradiance and solar shading.

The student's simulation results are gathered and analyzed collectively during an autopsy. **Figure 5** presents one of the graphs examined during this session, this for the exercise examining ground-reflected solar irradiance. (For illustration purposes the figure includes results from only a handful of students.) Each student independently decided how to model the solar reflectivity of the ground and their predictions are compared to their simulations performed using their tool's default approach. All students observed that their modelling choice had an important impact on the buildings heating loads, but some (students 4, 7, and 9) saw less impact that others. This led to discussions where each student explained their approach and its rationale and the theory previously studied was revisited. The conclusion of the group was that user choices for the modelling of ground-reflected irradiance can have a significant impact, so it would be unwise to casually accept BPS tool default methods for some simulation analyses.

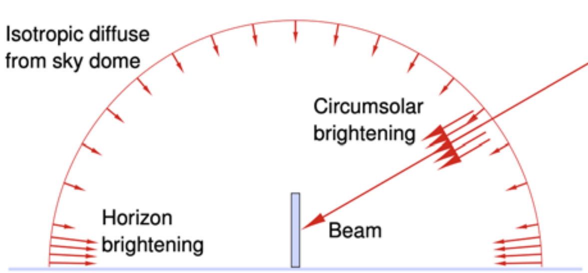

Figure 4. Methods for predicting sky diffuse solar irradiance to building surfaces.

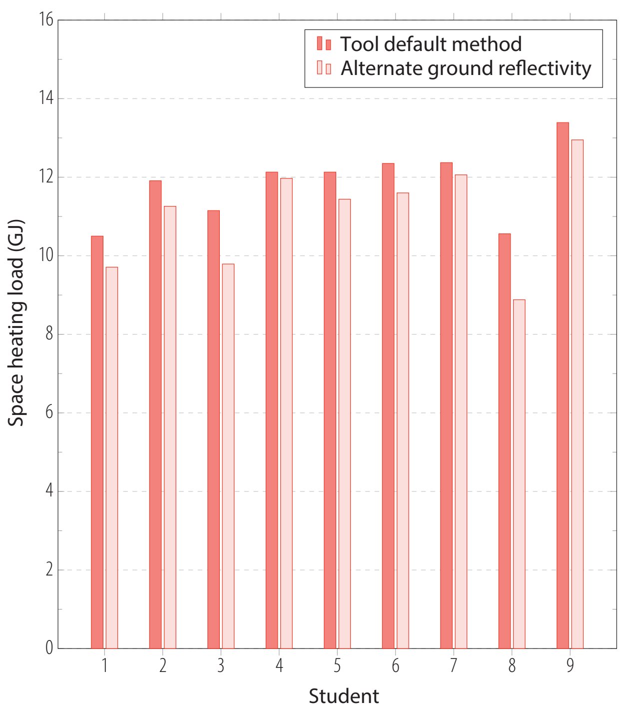

Figure 5. Student results from simulation exercise focused on modelling ground-reflected solar irradiance.

Teaching example—air infiltration

Another chapter of the book is dedicated to air infiltration and natural ventilation. Once again, students commence this topic by studying some theory. The book explains that infiltration results from pressure differences across openings in the building envelope which can be induced by wind or by mechanical ventilation systems that supply or extract air from a zone. It also describes the stack effect and explains how hydrostatic pressure differences between indoor and exterior environments can also cause pressure differences across openings. It helps the reader understand that these pressure conditions are highly variable, depending upon the speed, direction, and turbulence of the wind, and that they also depend upon the building's shape, the local terrain, temperature conditions, and the functioning of combustion equipment and HVAC systems.

The options for treating these complex phenomenon are then outlined. This includes two approaches commonly employed by users, that is ignoring air infiltration or prescribing constant airflow rates. Theories underpinning single-zone models and network airflow modelling approaches are then elucidated. Methods are described for establishing the necessary inputs for these methods, including interpreting empirical data from building depressurization tests.

This chapter also includes a series of structured simulation exercises which cause the reader to explore the facilities available in their chosen BPS tool. **Figure 6** presents some of these simulation exercise results that were examined collectively during an autopsy. (Again, the graph is limited to a handful of students for illustration purposes.) From these exercises the students gained an appreciation for how impactful air infiltration can be on the prediction of heating and cooling loads. All four students whose results are plotted in this figure predicted substantially different space heating loads using the two simplified—and commonly used—methods of prescribing constant airflow rates or ignoring infiltration. This impact was observed to be far more significant that many of the factors examined in the simulation exercises from previous chapters, such as geometrical details, transient conduction calculation methods, longwave radiation view factors, and the distribution of solar gains to internal building surfaces.

Through these exercises students discovered how to configure single-zone models based upon empirical data from building depressurization tests and they also developed an understanding of the modelling resolution that can be realized—and the associated complexity for the user—with network airflow models. By sharing their experiences with their peers through the autopsy, students understood how these models are influenced by user decisions on locating airflow openings, specifying data such as crack sizes and discharge coefficients, and choosing pressure coefficient sets. The significance of these decisions was discovered by comparing results (e.g. compare student 4 to the others).

Scope of learning

The above descriptions serve only to provide some examples of the topics covered by the teaching approach that is supported by the book, whose aim is to guide the reader through all of the significant heat and mass transfer processes.

The first part of the book briefly introduces BPS, defining what it is, how it is used, and discusses the central role the user plays in ensuring valid BPS predictions. Each of the next three parts of the book contains a series of chapters. Each distinct heat or mass transfer process is treated by a dedicated chapter appearing in one of these three sections. Part II treats the heat and mass transfer processes relevant to the building interior, while Part III focuses on heat transfer processes relevant to the exterior environment. Heat and mass transfer occurring through the building envelope

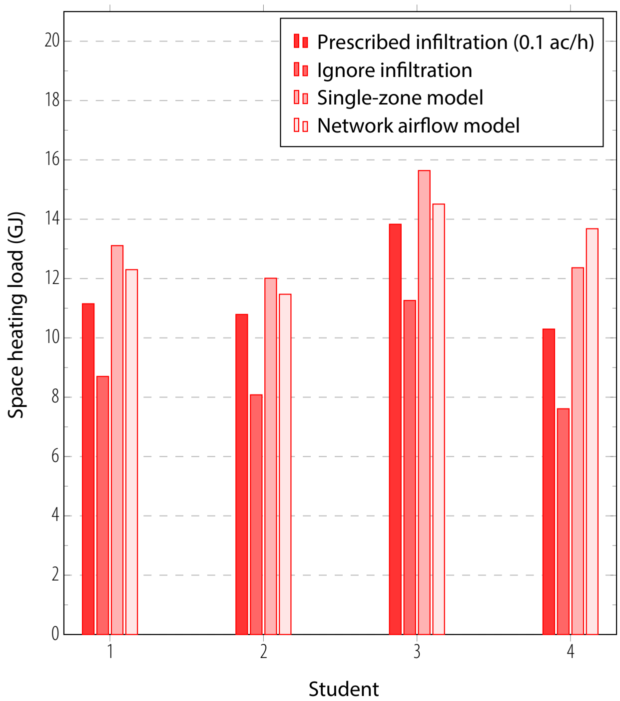

Figure 6. Student results from simulation exercises focused on air infiltration.

are the subjects of Part IV. This is followed by Part V, which focuses on HVAC systems.

The final part of the book includes a *Culminating Trial* in which the reader applies all the knowledge and skills they have developed in the preceding chapters by representing an actual building with their chosen BPS tool and by comparing their simulation predictions to measurements.

This book emphasizes depth at the expense of breadth. Its scope is limited to heat and mass transfer processes relevant to the building's form and fabric and HVAC systems. There is, of course, much more to learn—model abstraction, daylighting, occupant comfort, acoustics, electrical energy conversion and storage systems, managing uncertainty, etc.—but this book can serve as a starting point for learning the fundamentals of BPS.

Closing thoughts

I have delivered many university-level and professional development courses based upon the approach outlined in this article. The multiple iterations through the spiral's four modes of learning have been found to be effective and critical for students to concretize theoretical concepts, to help them develop techniques for interpreting, scrutinizing, and verifying simulation predictions, as well as making them aware of the impact of using tool default methods and data, and the myriad sources of uncertainty in BPS. From my experience, any shortcuts around the systematic experimentation at the heart of the approach would be detrimental. This has been validated through feedback provided by students who universally state that the course's learning objectives were fully achieved. The theory in the book, the simulation exercises and autopsies, and the Culminating Trial were consistently rated by the students as the most helpful for supporting their learning.

Understanding the fundamentals is critical but much more is required to develop the next generation of BPS users that we require to address the major challenges facing the building industry in the 21st century. It is also necessary for BPS users to develop the necessary skills for collaborating and interacting with building designers. Skills such as interpreting design questions and translating them into simulation analyses, interpreting results, and providing timely and appropriate feedback to inform design teams must also be cultivated, but this cannot happen without a solid understanding of the fundamentals.

It is my hope that the teaching methods outlined here can be borrowed, adapted, and improved by others to help move us forward. ■

Mainstreaming Education for Sustainable Development: *Vertically Integrated Projects for Sustainable Development*

– A Case Study from the University of Strathclyde

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Introduction

UNESCO (United Nations Educational, Scientific and Cultural Organisation) define Education for Sustainable Development (ESD) as "the process of equipping students with the knowledge and understanding, competencies, skills and attributes needed to work and live in a way that safeguards environmental, social and economic wellbeing, both in the present and for future generations." Significantly, ESD is widely recognised as being more than simply educating students *about* Sustainable Development; critically it focuses on educating students *for* Sustainable Development – as Sir Jonathan Porritt, Vice Chancellor of Keele University, puts it, actively "preparing our students for the work of the world and not just the world of work" (Porritt, 2012). ESD is about preparing our students to face future shocks and shape a just, sustainable, healthy and peaceful future for us all.

(Kolmos et al. 2016) and (Kreber, 2009) also speak of education about sustainable development as an assimilation strategy where 'Sustainable Development', is treated as a subject that "we look at", and that can be learned "principally through extensive reading, listening and memorising," e.g. by developing a new module on sustainable development informing students of the background to, motivation for, and progress made on the Sustainable Development Goals. By contrast, Education *for* Sustainable Development, asks students to treat Sustainable Development not exclusively as a subject only to be 'looked at' and learned *about*, but as an activity and agenda they can actively participate in, and influence – or more overtly, as a challenge to be met. In doing so, it seeks to connect students to the subject matter and 'challenge', not just cognitively, but emotionally and practically too – the so-called 'head, heart and hands' (Sipos, et al. 2008) competency framework - inspiring students to a deeper level of learning, and applying their learning to deliver positive impacts on target communities. This also speaks to Kreber's description of "what actually happens in situations when teachers succeed in fully connecting their students with their subject".

Like many other HE institutions, Strathclyde has already embarked on this journey to embed ESD with examples of 'add-on' modules that have been purposely designed around sustainable development, and others that have re-oriented towards, or realigned subject content and context, with sustainable development. One of the most innovative programmes that has been introduced at Strathclyde is our award winning Vertically Integrated Projects for Sustainable Development Programme (VIP4SD) - winner of 2019 International Green Gown Award and the 2020 Association for Advancement of Sustainability in Higher Education Award. VIP4SD is also included as a case study in the 2021 QAA and Advance HE Education for Sustainable Development Guidance and on the Sustainable Solutions Development Network (global network of universities focusing on sustainability challenges) website, and as an exemplar of best practice in the Scottish Government report "Scotland and the sustainable development goals: a national review to drive action".

The Vertically Integrated Projects (VIP) model for embedding undergraduate research into curricula, was brought to Strathclyde from Georgia Institute of Technology in 2012, to create undergraduate research projects that were led by academics and researchers, and engaged undergraduate students from all year groups. From the students' perspective, this means they can work collaboratively with academics and their peers, consistently, on the same real-world research area through all years of their programme studies at Strathclyde (i.e. vertical integration). From a research project and academic's perspective, this means projects can be longer lasting, more ambitious in their scope and, over-time, self-sustaining, as more senior student team members assume mentorship roles to more junior members. This also allows academics and students to build stronger, longer lasting, collaborative research and educational partnerships. More broadly, the VIP model focuses on the nexus between education and research.

In 2016, the University of Strathclyde integrated and aligned its existing VIP programme with the 17 UN Sustainable Development Goals, creating the Vertically Integrated Projects for Sustainable Development (VIP4SD) programme. This allowed research projects to focus on SDGs, and make explicit how they planned to advance agendas towards specific SDG targets. This allowed the University to both embed Research-Based Education (RBE) and Education for Sustainable Development (ESD) into undergraduate curricula – now focusing on the nexus between education *for sustainable development* and research, and hence we refer to the VIP4SD programme as a model of Research-Based Education for Sustainable Development (RBESD) (Strachan et al. 2018) (VIP4SD, n.d.).

Operationalising VIP4SD and ESD

The main challenges that institutions are likely to experience in implementing a programme of this nature, centre around institutional buy-in and its promotion, regulatory and quality assurance processes, rigidity of the curriculum (historically due to accreditation requirements), staff and student engagement, timetabling, assessment and supervision resource. The extent of each of these challenges is also likely to differ, and is in most cases based on operational and academic nuances that exist between the faculties, departments or programmes, where a VIP4SD pathway (i.e. 'vertical' route through each study year of a programme's curricula) must be 'carved out'.

Achieving institutional buy-in and finding a VIP4SD pathway through a programme of study, are probably the most significant of these challenges. This section focuses on these and proposes strategies for overcoming these, but also points to recent developments across the UK HE sector that are anticipated, over time, create the enabling environment required to embed programmes like VIP4SD in HE degree programmes, and facilitate the more general mainstreaming of ESD in HE.

Buy-in at executive level at Strathclyde was achieved early on by pointing to the success of Georgia Institute of Technology's VIP programme and then proposing and implementing a plan for a proof-of-concept pilot, initially involving a limited set of engaged academics, and subsequently delivering on this. Furthermore, if it can be demonstrated that this programme complements and resonates with other aspects of your institution's strategic plan (e.g. student experience, employability, sustainability, equality, diversity and inclusion, enterprise and entrepreneurship, internationalisation of the curriculum, etc.) this can also strengthen the case for implementation and mainstreaming.

There are two main approaches to defining a vertically integrated pathway through a programme's curricula. One approach is to take advantage of a curriculum review, and work with Vice Dean Academics and Programme Directors to establish robust and fully-integrated pathways through the programme. This is analogous to considering a degree programme as a moving train, where its necessary to wait until the train (or programme) has stopped at the station before then switching out carriages (or modules) and replacing with new ones. This is undoubtedly the most orderly, most sustainable and hence most desirable approach to embedding VIP in a programme. The other approach is to find a more pragmatic approach to embed (or retrofit) the pathway into an current and established programme curriculum, without waiting for a curriculum review, and with as minimal disruption to the programme and department as possible (e.g. when the opportunity for curriculum review is not available). Achieving this, also requires close collaboration between VIP programme coordinators, department heads and course directors to work around curricular constraints such as elective credits being limited to particular years of study, or navigating a way through, what may considered, from a course accreditation perspective, as a curriculum filled with 'indispensable' modules. One such alternative approach may be to identify a "surrogate" or "container" module, in the shape of an existing module, that equates to the same level of student effort (and credit) as required by a VIP project over an academic year, and which has comparable learning outcomes (perhaps more competency-based, such as those aligned with a professional skills development or research/project-based/case-study/capstone modules). This module could continue to run its existing syllabus with one section of the cohort, while offering others the opportunity to participate in a VIP4SD project, under the auspices of the same module and class code. This is analogous to re-arranging the furniture in specified carriages of the train as it continues travels between stations, without stopping. While a workable solution, this is also more of a 'work-around' solution, which may not be applicable or suitable for all degree programmes, and which may be more challenging to sustain. It is for this reason that more formal, sector-wide guidance from QAA and professional bodies and academies is required. Without this, programmes like VIP4SD, and ESD more widely, would likely remain an adjunct, add-on extra included in some, but by no means all, degree programmes. Therefore, it has been a welcome development to see ESD and other non-technical or subject-specific elements being actively promoted from such quarters; providing the influence and leverage required to motivate and legitimise the kind of structural change needed to mainstream ESD in HE.

Levers for Mainstreaming ESD

There is a perception that programme accreditation bodies may have the potential to act as a barrier to, or powerful enabler of, education innovation. In terms of ESD, and engineering education, as mentioned, there has been some welcome advances in this regard. Many Professional Engineering Institutions (PEIs) and bodies are now acting as agents of change, actively advocating for ESD within HE, responding not only to the moral imperative, brought about by a climate emergency, to mainstream ESD in HE, but also to the market demand of employers and students. There is a growing recognition of their role as a key lever for the kind of curricular and educational reform needed to 'refresh' HE, and equip graduates with the knowledge, skills, attributes and competencies needed to meet the types of global challenges they will encounter in their personal lives and that will undoubtedly shape their careers.

The Engineering Council's most recently published Accreditation of Higher Education Programmes - AHEP 4, asks for programme learning outcomes to have "a sharper focus on inclusive design and innovation, and the coverage of areas such as sustainability and ethics", and emphasises that "HEIs are encouraged to make use of the United Nations Sustainable Development Goals, and Engineering Council Guidance on Sustainability in programme design and delivery." Further to this, is the Engineering Professors' Council (EPC) and Royal Academy of Engineering's (RAE) Engineering Ethics Toolkit, which has been designed as a resource to "help engineering educators integrate ethics content into their teaching…including how engineering students need to see ethics in action." Even more recently, the RAE, the EPC and Siemens have collaborated to create a Sustainability Toolkit Steering Group, which while acknowledging "many excellent resources explain the sustainability knowledge, skills, and mindsets essential for 21st-century engineers", also recognised that "very few resources exist that support engineering educators to integrate these into their teaching in a comprehensive and effective way." Therefore, this group will "develop and curate a toolkit of resources that help academics explicitly embed sustainability in their day-to-day practice of engineering teaching, and help make sustainability integral to, rather than tangential to, engineering learning" (EPC, n.d.). In a broader sense, what has contributed to this drive for the mainstreaming of ESD from PEIs and other quarters, not only in engineering education, but across all degree disciplines and programmes UK HE, is the QAA Subject Benchmark Statements (SBSs). These "have been drafted and published by UK QAA for over two decades, and describe the nature of study and the academic standards expected of graduates in specific subject areas. They show what graduates might reasonably be expected to know, do and understand at the end of their studies." The current review cycle of SBSs, requires "incorporation of consideration of how practice within disciplines addresses wider social goals, comprising equality, diversity and inclusivity; the requirements of disabled students; enterprise and entrepreneurship; and **education for sustainable development.**"

Conclusion

This paper has presented the University of Strathclyde's approach to embedding Research-Based Education for Sustainable Development into its curricula, using the Vertically Integrated Projects model for undergraduate research developed initially at Georgia Institute of Technology. It has provided some historical context around how the programme has evolved from VIP to VIP4SD, as Strathclyde's vision to embed ESD in its curricula started to emerge soon after the UN's Agenda 2030 and the Sustainable Development Goals came into being. It demonstrates how the SDGs offer a powerful and inspirational framework on which the VIP4SD programme has built its portfolio of undergraduate research projects around. In addition, while these projects are wide and varied in their scope, disciplinary focus and nature, they all share a common, unifying sense of purpose amongst all staff and students participating in the VIP4SD programme.

The paper also highlights some of the academic and logistical challenges that may be anticipated when attempting to create and operationalise a programme of this nature, but also points to welcome developments across the HE sector that will mean what may have been perceived as barriers to educational innovation of this kind previously, are now increasingly seen as key enablers of it.

Key Messages

Engineering education, like all others, needs to adapt and refresh to become fit for purpose in the face of the challenges its graduates will be instrumental in meeting collaboratively, through technological innovation and business leadership.

Many HE institutions across the UK and globally, have been focusing on education enhancement around ESD, with many successes such as the VIP4SD programme at the University of Strathclyde to point to. However, mainstreaming ESD across intuitions and the HE sector as a whole, requires legitimising it through more formal, sector-wide guidance from QAA and professional bodies to help achieve institutional buy-in for ESD, while at the same time providing the necessary staff training and support that is combines to create the necessary 'enabling environment' for institutions and staff to engage with ESD through a whole institution approach. ■

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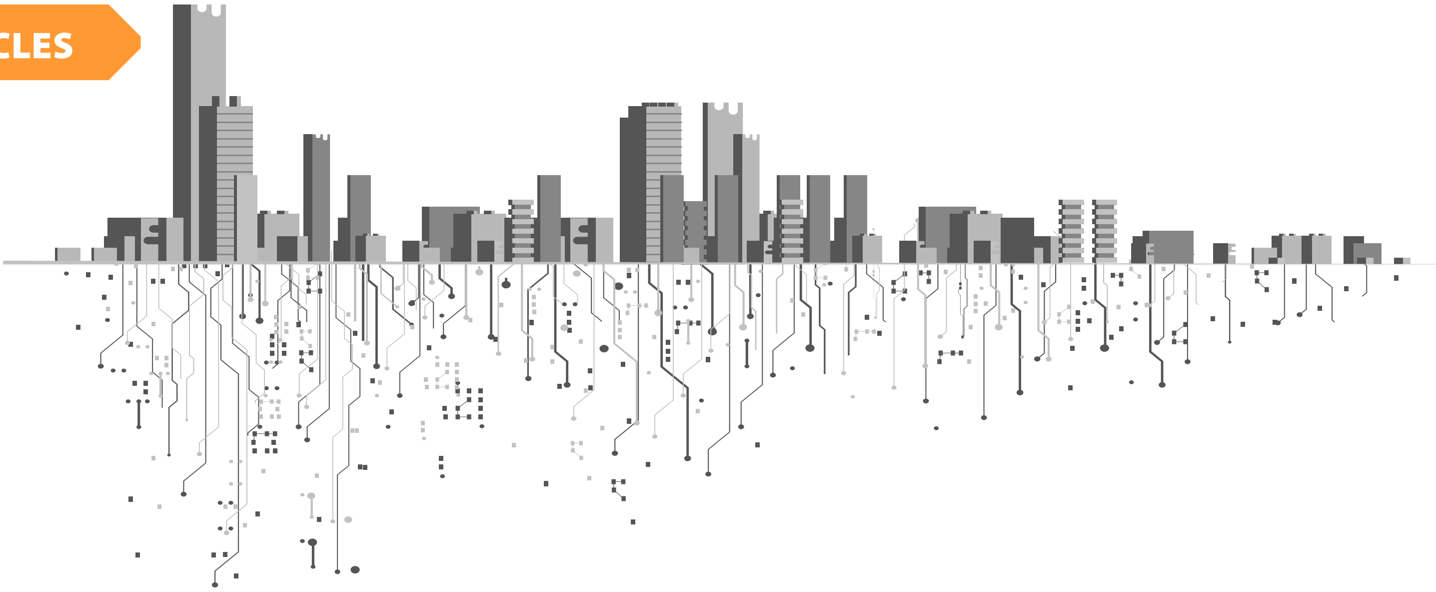
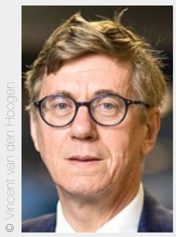
ARTICLES



Integral design – a necessity for sustainable building design



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Due to the rising demand for more sustainable buildings, it is essential to make optimal use of natural resources. However, therefore it is necessary to end the dichotomy between architecture and technology leading to far from optimal functional buildings responsible for high operational and failure costs. To close the gap between technology and architecture, it is time for integral design. The necessity for this was recognized by the Dutch Royal Society of Architects, BNA, as well as the society of Dutch consulting engineers, NL Engineers, and the Dutch Building Services society, TVVL. A design methodology was developed and implemented in the education curriculum of the Technical University of Eindhoven. In this paper, the method and the added value for the professional domain will be presented.

Keywords: Integral Design, Collaborative conceptual design

Introduction

> *"Architecture will become more informed by the wind, by the sun, by the earth, by the water, and so on. This does not mean that we will not use technology. On the contrary, we will use technology even more because technology is the way to optimize and minimize the use of natural resources"*
> *[Richard Rogers]*

Collectively, buildings in the EU are responsible for 40% of our energy consumption and 36% of greenhouse gas emissions, which mainly stem from construction, usage, renovation, and demolition [EU 2020]. Global warming and the depletion of materials and resources are major problems. There is a clear need to change the way how buildings are designed and not try to solve the problems using the same kind of approach/logic that caused them in the first place.

The concept of a building, the basic design, is conceived by the architect first, then there is room for other disciplines. Design of buildings is seen largely as an individual's creative act. However, more and more it is realized that effective collaboration during the concept design phase in architecture provides the greatest potential for the overall success of a building project [Leon et al 2014]. This is not really a new idea as already Le Corbusier one of the most famous architects of the last century showed, see **Figure 1**.

The design of a highly sustainable building, due to the increased complexity of building design [van der Linder et al 2016], inevitably calls for more design collaboration in the conceptual design phase as well. Only the early open collaboration of architects and engineers can facilitate the creation of the necessary new knowledge and solutions beyond the specific scope of each individual discipline [Kovacic and Fitzmoser 2014]. According to the Royal Institute of British Architects (RIBA) president Jane Duncan, architects, engineers, and builders must collaborate [CIBSE 2016]. Designing Sustainable Buildings needs synergy between the architectural and engineering domain to create new solutions. This innovation is needed to reduce the environmental load caused by buildings. A holistic planning process is required in order to reduce the high complexity and achieve a goal-oriented procedure during the planning of buildings and the development of integrated systems [Honold et al 2019]. However, in comparison to conventional buildings, such adaptive sustainable buildings require much higher planning effort and an interdisciplinary planning team with disciplines that have typically not been involved in building planning thus far [Honold et al 2017].

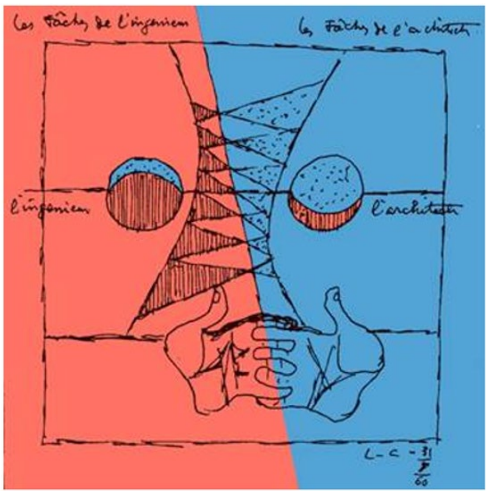


Figure 1. Necessary change in relationship between Architect and Engineer. (Source: Le Corbusier 1960)

Norman Foster and the design board at Foster + Partners are strong supporters of sustainable design and are keen to interpret and integrate engineering principles within design concepts [Smith 2019]. Their philosophy is that the best projects arise from a totally integrated approach to the design process, where the core disciplines work together to conceive and design a project from its earliest inception [Jackson and Heywood 2019]. Clearly, Building Design is a team effort, teamwork is key therefore it is necessary to create a place for the needed innovation. The benefits of the integrated design are better decisions, higher speed of response, and improved ability to iterate and thus reduce the complexity. Early engagement is essential within building design teams.

However, just putting all disciplines together is not enough, there is a clear need for design support to facilitate collaboration between the various design team members from different disciplines. Design deals with complex ill definite wicked problems which are difficult to solve. Therefore, it is important to give designers the right tools as well as a supportive process framework to order the design process. However, in the field of architecture, there is a lack of a body of theory to support the study of architectural design methods [Plowright 2014], which makes it necessary to review concepts from other foiled of study like mechanical engineering. Therefore, we looked for a framework to support the activity of building design. In the early 1960s researchers and practitioners began to investigate new design methods to improve design process outcomes [Cross 2007] right up to the present day [Le Masson et al 2017].

Integral Design where the architect and consulting engineers truly collaborate in the conceptual phase of the building design process is needed is an optimal exchange of interpretations and ideas, see **Figure 2**.

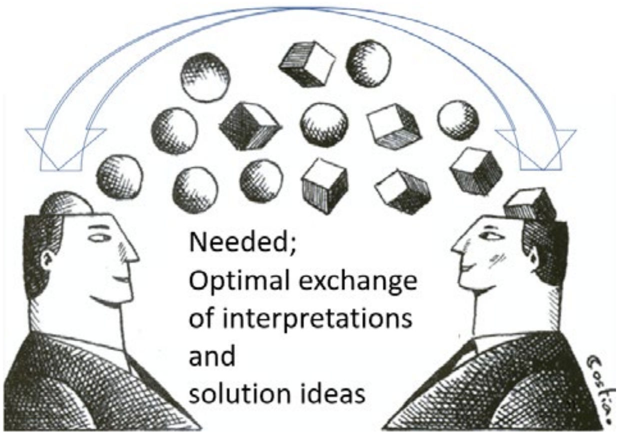


Figure 2. The needs with the conceptual design phase.

In section 2, details of the developed methodology are described. In session 3 the experimental setting was provided to improve the design process and descriptions of the experiments for testing the method and interventions with professionals and with students. In section 4, the results of the different experiments are provided, in section 5 the analysis of the results is followed by a discussion of the results in section 6. Finally, section 7 provides the conclusions about the added value of the design approach as an educational support tool and research tool as well as some remaining needs for further research and developments in relation to the morphological aspects of the developed design tools. This article is an updated overview of an earlier published paper [Zeiler 2016] and represents the result of research on Integral Design that started in 1999 up to now.

Methodology

It is important to provide a theoretical basis to encourage the strategic use of design methodologies as teaching strategies [Curry 2014] fully and strictly applied in industrial applications [Dorst 2016]. It is better to develop a design method as close as possible to practice and with help of industry. Therefore, in 1999 the professional Dutch organization for architects BNA and consulting engineers NL Ingenieurs together with the University of Technology Delft and the Dutch Building Services Society started research in close cooperation with the industry to develop a design method to improve the conceptual building design process. This led to research with workshops organized with professional organizations to test a specific design method, see **Figure 3**. Integral Design based on Methodical Design and the extensive use of Morphological Charts and Morphological Overviews [Savanovic 2009].

The Integral design method is based on in the tensive use of morphological charts [van den Kroonenberg 1988] and its outcome was evaluated in a situation as close as possible to practice amongst professionals. The design method has a distinctive feature, the step pattern of activities (generating, synthesizing, selecting, and shaping, that occurs within the design process, see **Figure 4**.

In the first step of the integral design method, the individual designer has to make a list of what he thinks are the most important functions that have to be fulfilled based on the design brief. This is derived from their own specialist perspective. The morphological charts are formed as each designer translates the main goals of the design task, derived from the program of demands, into functions and aspects and is then put

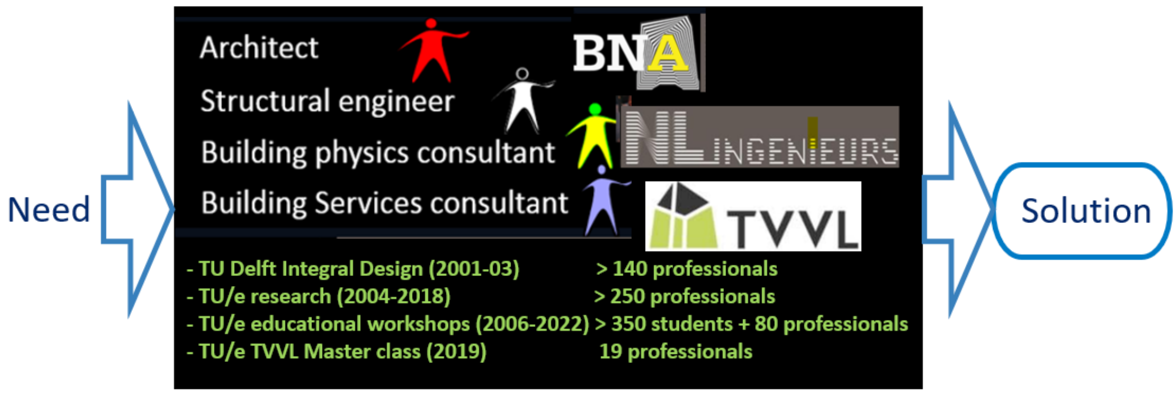


Figure 3. Black-box approach to building design with all professional organizations involved.

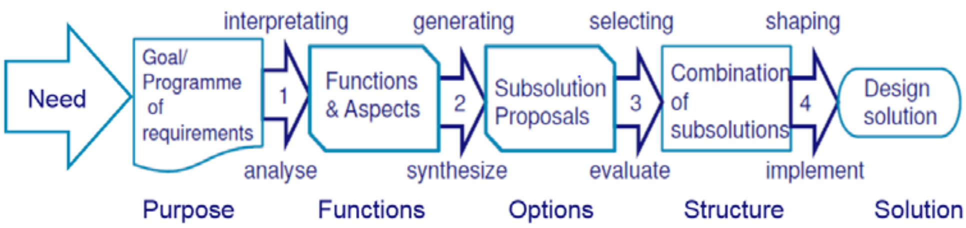


Figure 4. Basic steps within the Integral design process.

into the first column of the morphological chart, see **Figure 5**. A morphological chart is a kind of matrix with columns and rows which contain the aspects and functions to be fulfilled, see **Figure 5** step 1 and the possible solutions connected to them, see **Figure 5** step 2. These functions and aspects are derived from the program of demands. In principle, overall solutions can be created by combining various sub-solutions to form a complete system solution combination [Ölvander et al 2008].

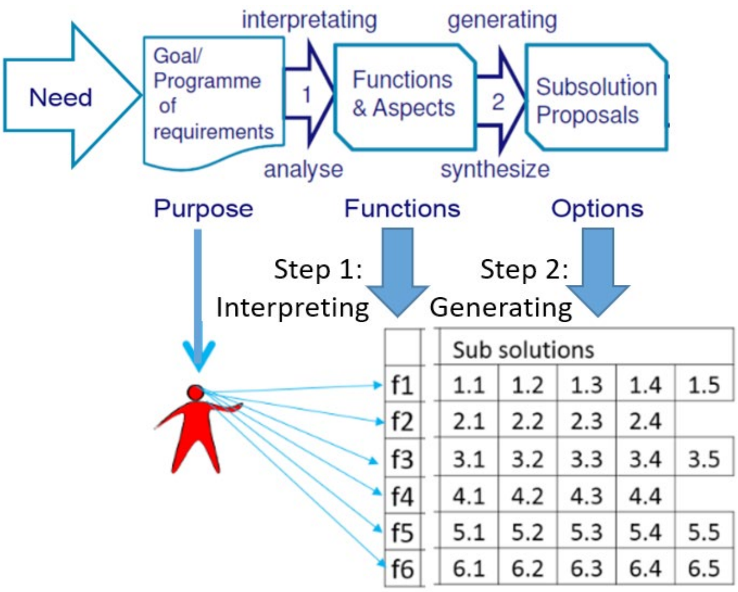


Figure 5. Concept of a morphological chart: Step 1 Functions and aspects to be fulfilled and step 2 related sub-solutions to the functions and aspects.

In the second step of the process, the designers add the possible part solutions to the related rows of the functions/aspects of the first column, see **Figure 6** Step 2i. The morphological charts represent the individual interpretation of reality, leading to active perception, stimulation of memory, activation of knowledge, and definition of the needs of each individual designer. These individual morphological charts can be combined by the design team to form one morphological overview, see **Figure 6**. This is done in two steps, the team members have to agree on what are the most important functions and aspects to be fulfilled see **Figure 6** step 1t. After this, the team can decide on which sub-solutions are relevant to be added to the agreed functions or aspects, see **Figure 6** step 2t. Putting the morphological charts together enables 'the individual perspectives from each discipline to be put on the table', which in turn highlights the implications of design choices for each discipline.

By structuring design (activities) with morphological overviews as the basis for reflection on the design results, stimulates communication between design

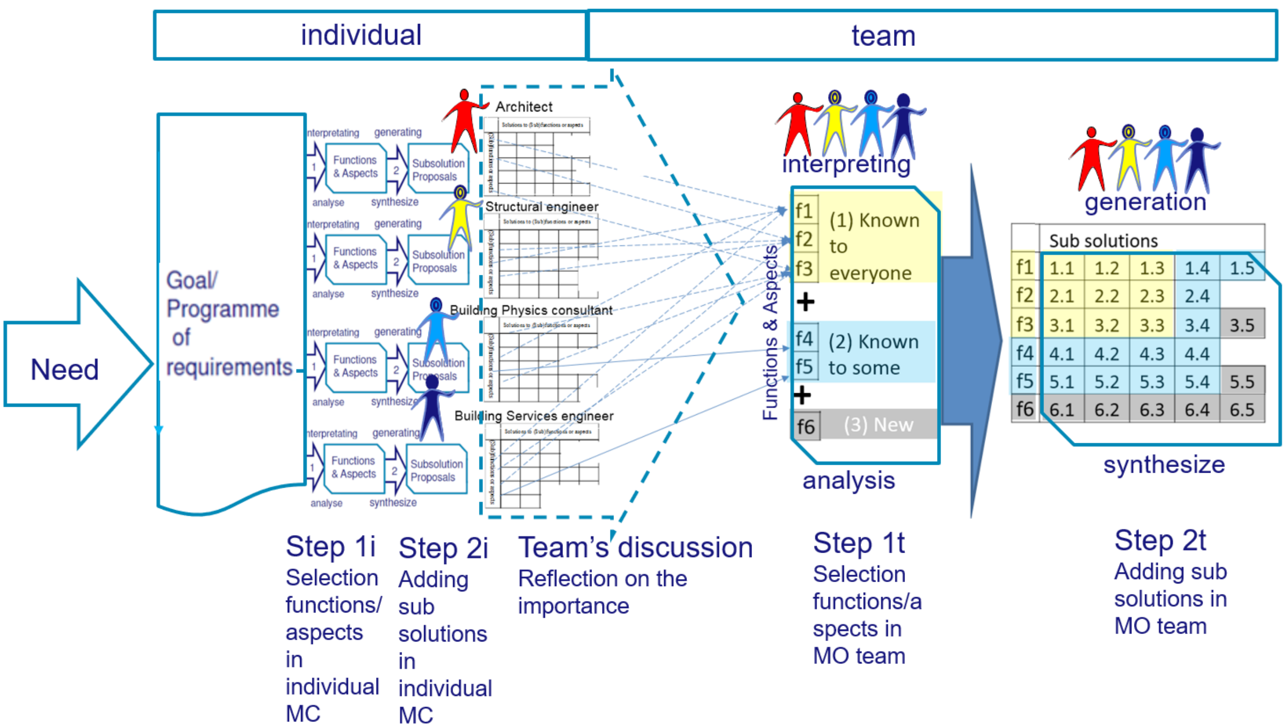


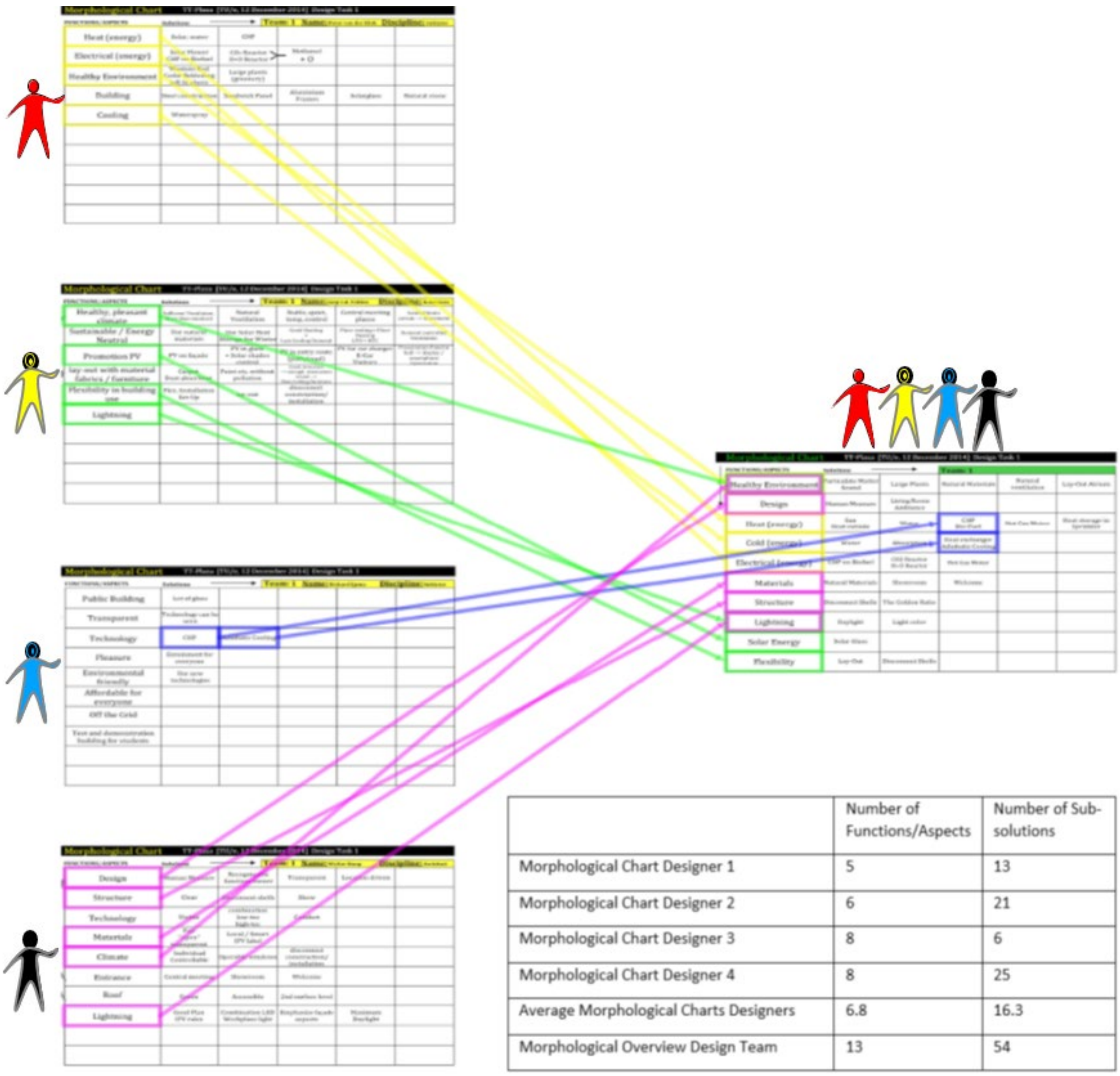
Figure 6. The first two design steps of the design team's process cycle, interpreting the design brief and list the functions in the first column of the individual morphological chart and the related sub-solutions.

team members and helps the understanding within design teams. It eases collaboration as it makes it easier to come forward with new design propositions. Visualizing the contributions, the morphological overview stimulates the understanding of the different perspectives among design team members.

Unfortunately, in the conceptual phase of the design, it is not possible to accurately evaluate the quality of the mentioned functions/aspects or sub–solutions. Only a quantitative analysis is possible by counting the number of mentioned functions/aspects and sub-solutions. The number of functions and sub-solutions mentioned by the designers in their morphological charts and the design team's morphological overview were counted, for example, see **Figure 7**.

Experiments

Since the year 2000, together with the Royal society of architects (BNA), the Association of Consulting Engineers (NLIngenieurs) and the Society of Building Services Engineers (TVVL), different series of workshops were organized in the Netherlands. More than two hundred professionals, with at least 12 years of experience, of the involved professional organizations, voluntarily participated in these workshops. After extensively experimenting with different setups for the workshop, a 2-day workshop setting was selected [Savanovic 2009]. The two days workshop was organized as part of a professional training program for architects and consulting engineers (structural engineers, building services engineers, and building physics engineers)



	Number of Functions/Aspects	Number of Sub-solutions
Morphological Chart Designer 1	5	13
Morphological Chart Designer 2	6	21
Morphological Chart Designer 3	8	6
Morphological Chart Designer 4	8	25
Average Morphological Charts Designers	6.8	16.3
Morphological Overview Design Team	13	54

Figure 7. An example of the transformation of the individual morphological charts into a morphological overview, indicate the functions/aspect in the morphological overview and where they came from [Zeiler 2018].

In connection with the Integral design research project for professionals in the Dutch building industry, we developed an educational project, the master project Integral Design. The concept of the integral design workshop for professionals was implemented within the start-up workshop of our multidisciplinary masters' project. The different design assignment all were related to the design of zero energy buildings. These complex tasks require early collaboration of all design disciplines involved in the conceptual building design and as such let the students experience the added value of the design method. Master students from architecture, building physics, building services, building technology and structural engineering participated in these projects. The basis of this project, which serves as a learning-by-doing start-up workshop for master students, is a method with extensive use of morphological charts combined to a morphological overview of the design team. During the start-up workshop, professionals participated in the student's design teams and this specific intervention within the design process has been investigated. Having a tested framework for introducing the design method allowed us to investigate the effects of different interventions as well as the analysis of several aspects, such as the effectiveness of different designers or the effect of communication in words or sketches. The framework of the approach is presented in **Figure 8**, the program and setup of the workshop.

All the assignments had a similar level of complexity which made the results comparable. To investigate the effect of the morphological tools of the Integral design approach they were used in similar workshop setting for different types of students, professionals, and practitioners, in brackets is the number of participants;

Bachelor students (181) 2015-2022

The students of the course in which the workshop was held were 2nd and 3th year bachelor students, age around 20-22, all Dutch. The students were from the Faculty of the Built Environment and of the Faculty of Psychology and Technology.

Master students (150) 2011-2018

These were 4th-year students (architectural, structural, building physics, and building services) all from the Faculty of the Built Environment, aged around 22-24.

Architectural Master students (11) 2017

One workshop was held for students of architecture all working in a Master thesis project design atelier as part of their MSc graduation project. So they were 5th-year students who nearly had finished their studies, aged around 23-25. This was the only mono-disciplinary group in the comparison.

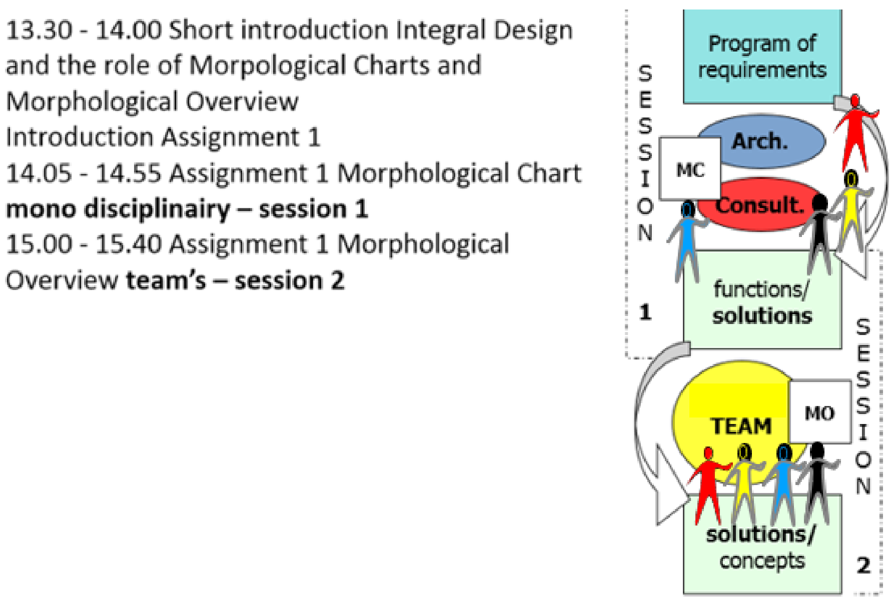


Figure 8. Program and set-up of start-up workshop.

PDEng students (18) 2012-2013

The students from the Post Doctoral Engineering (PDEng) program Smart Energy Buildings and Cities (SEB&C) were from all different International MSc discipline backgrounds, age 24-26.

Professionals (24) 2009

In the research of Savanovic [2009] the concept of working with morphological overviews was tested in different series of workshops for professionals, with at least 12 years of experience. There were 4 series of workshops with in total 96 participants for testing different set-ups. Here only the results of the final 5th workshop are included.

Professionals (8) 2015

In 2015, the researchers participated in the start-up of a real professional project for the design of a nearly Zero Energy Building [de Bont et al. 2016]. The professionals had around 20-year experience.

Practitioners (19) 2019

The Dutch society for Building Services Engineers TVVL, together with the TU Eindhoven organized a master call. There were no restrictions on the participants, unlike the workshops for professionals in the research of Savanovic [2009] where the participants should have a least 12 years of experience.

Results: From Morphological Chart to Morphological Overview

The central element of the Integral Design process is the use of Morphological Charts by individual designers which were combined into one Morphological Overview by the design team. The average numbers of functions and solutions as mentioned by the design teams in their Morphological Charts and Morphological Overview as well as the relative increase are represented in **Figure 9**.

Discussion

The group interaction is of great importance during the conceptual design phase and has a clear positive effect on the number of functions and aspects discussed as well as on the number of generated sub-solutions. This was found by the original research with professionals [Savanovic 2009] as well as in the educational setting with different types of students, as well as in experiments in real projects and professional settings. Given the number of involved design teams in the series of workshops, with 347 students and 123 professionals as participants, there is a sound quantitative basis for the conclusion that it really helps to integrate the different design disciplines and create synergy.

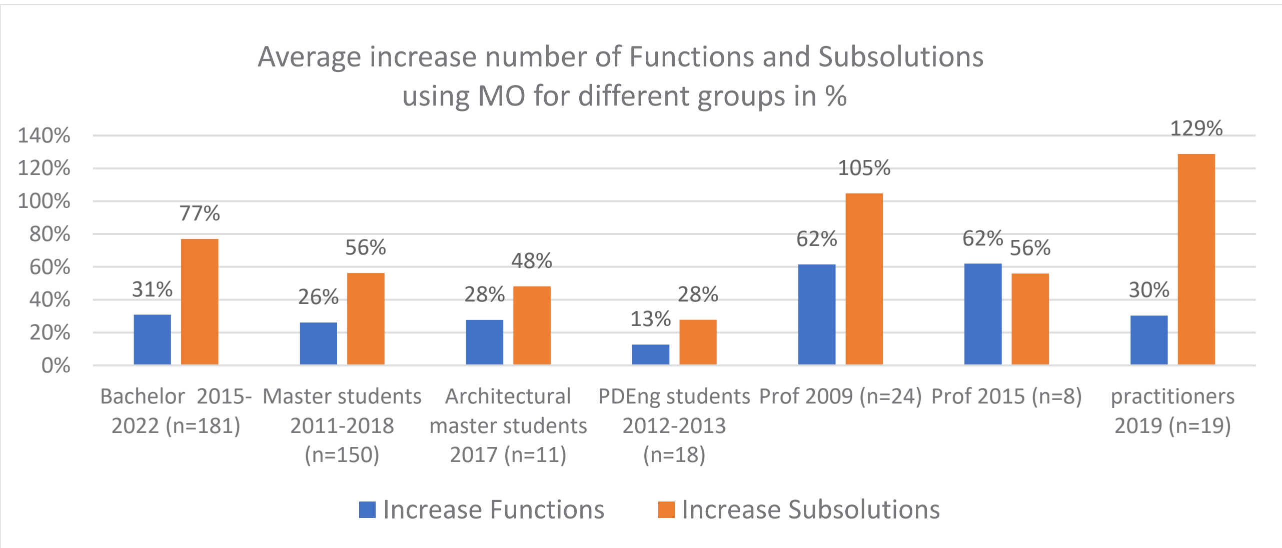


Figure 9. Comparison of the average relative increase in the number of functions and sub-solutions by individual students, professionals and practitioners in their Morphological Overviews compared to the average results from the individual Morphological Charts.

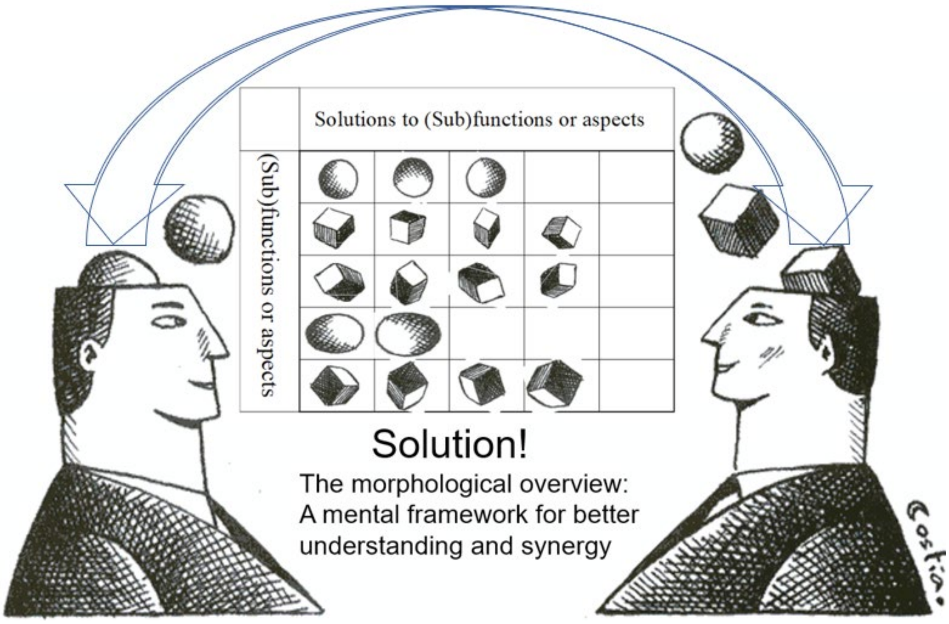


Figure 10. The morphological overview to connect the minds of the design team.

Conclusions

However, a break with the traditional line of thoughts of architects as well as consulting engineers is there for needed. A new design model, Integral Design, was developed to support interaction between all the disciplines involved in the conceptual building design process by structuring the communication and solution generation process in steps. By structuring the information flow about the tasks and solutions of the other disciplines the method forms a design within the design process and enables a structured approach even in the conceptual design phase. The use of the morphological overview based on the individual morphological charts creates a way to share interpretations and ideas for solutions forming a basis for synergy leading to more innovative designs, see **Figure 10**.

The main lessons from this paper are that Integral Design with its use of morphological overviews stimulates collaboration and exchange of ideas and perspectives between architects and engineers. It helps them with their communication. As such it is a good method for supporting the education of a new generation of architects and engineers, whom each have new roles in the highly complex tasks of designing sustainable nearly Zero Energy Buildings energy positive buildings or even Carbon neutral buildings.

The design method had a major positive effect on the number of proposed sub-solutions and also on the number of functions and aspects considered in the conceptual phase of the design process by the design team members. This indicates that the effectiveness and productivity of design teams were largely improved by adding structure to the process. The role of the morphological charts and overview is in structuring the process and enabling analysing the conceptual design process in more detail. As such is it a valuable approach to inventing the necessary new more sustainable solutions for the future. Integral design is a necessity for truly sustainable buildings and as such a prerequisite for the energy transition toward 2050. ■

Acknowledgements

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Advancing transdisciplinary architecture and engineering education: Defining the needs of a new multidisciplinary built environment design professional

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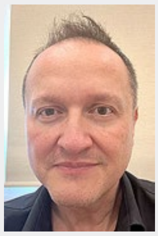

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There is wide recognition in policy, practice and higher education that complex climate change challenges cannot be fully addressed without highly integrated multidisciplinary knowledge and ability. This is especially critical in the built environment. The purpose of this article is to discuss approaches through which educational and practice needs of a new multidisciplinary built environment professional are being considered. The article builds on a prior study by the authors involving a UK case study drawing on the developmental process involved in creating and running a novel highly integrated MEng course and begins to assess the outcomes of the first cohort that completed the programme. The insights help define the approaches that underpin development of a multidisciplinary course, evaluate the outcomes, and articulate the potential competency criteria needed for a new design professional. These criteria will aid future development of engineering professions and ways professional bodies accredit educational provision.

Keywords: Built environment, Design, Engineering, Higher Education, Multidisciplinary

Introduction

There is established recognition in international policy that multidisciplinary knowledge and competencies are critical in addressing growing complexity of climate change and carbon emissions challenges (Friedlingstein et al., 2022). The need for multidisciplinary approaches is particularly significant in the built environment context, a key contributor to carbon emissions globally (Friedlingstein et al., 2022). This recognition has led to an increasing understanding in education and practice that solutions may lie not only in more effective integration of built environment multidisciplinary teams but also in the educational development of a new kind of built environment professional (Butt & Dimitrijević, 2022; Nguyen & Mougenot, 2022).

In the higher education (HE) context, multidisciplinary approaches are seen as a classification of interdisciplinarity with interdisciplinarity seen as the 'integration of knowledge drawn from diverse disciplines to address problems that cannot be solved by one discipline' (Van den Beemt et al., 2020). Though there are emerging courses in the built environment that promote integration of different disciplinary domains such as architecture and structural engineering, architecture and building services engineering and more recently architecture, structural and building services engineering, there have been few accounts of their developmental approaches (Oliveira et al., 2022), and a paucity of published evaluations of the educational or career outcomes. It is widely recognised that identifying pathways to multidisciplinary education remain challenging. A recent review carried out by Van den Beemt et al. (2020) on approaches to interdisciplinary education in engineering suggests that developing both multi and interdisciplinary skills demand a different type of pedagogy and 'teaming experiences' that facilitate new ways of learning. Their review also argues for a greater understanding of resources needed as well as barriers to wider development of interdisciplinary education including awareness of the institutional challenges involved.

Research in architecture and engineering education has mostly approached the issue by analysing ways to achieving multidisciplinary curricula largely through either incorporating sustainability or enabling design-studio and/or project-based learning delivered by multiple disciplines (Oliveira et al., 2022). The purpose of this paper is to discuss the development and early implementation of educational and practice needs of a new multidisciplinary built environment professional drawing on authors' prior case study of a UK MEng Course (Oliveira et al., 2022). The discussion has benefits to both higher education providers and practitioners in helping articulate the potential competencies and needs of a future built environment professional, and the underpinning processes that may shape its delivery.

Methodological approach and case

This work builds on the empirical case study explained and discussed in the authors' recent paper (Oliveira et al., 2022). The methodological approach of this previous work involved narrative synthesis including reflection and dialogue of a prior empirical case study as well as thematic review of the literature (Lisy & Porritt, 2016). A review of the development processes for the UCL MEng Engineering and Architectural Design course, with the primary focus being on understanding how the multidisciplinary content and delivery mechanisms developed during the initial stages of the course development, was conducted. In addition to extensive documentary analysis, the case study also involved holding interviews with educators and industry advisors on the curriculum design process. The course was developed to provide a fully accredited pathway for chartered engineer status through JBM and CIBSE, with expanded attributes in architectural design. These requirements informed the initial criteria through which discussions developed amongst the curriculum design team. The curriculum design team involved expertise from multiple departments representing diverse disciplines including academics from The Bartlett School of Architecture, the UCL Institute for Environmental Design and Engineering and the Department of Civil, Environmental and Geomatic Engineering as well as leading industry experts.

The course development also included discussions of facility provision and the site for course delivery was a critical aspect of joining up disciplinary thinking and developing the multidisciplinary ethos of the course. The following section describes the empirical setting, the rationale for the course as viewed by its creators and the ways future graduates and their experiences were conceived.

The rationale for the course – a paradigm shift

The UCL team's contention in developing the course was rooted in their view that 'grand challenges facing society, and indeed the planet i.e., sustainability, well-being, changing climate, and intercultural interactions, all implicate the built environment'. The course was described to be aimed at creating a novel interdisciplinary workforce, and network, of creative professionals each with complimentary knowledge and skill in both engineering and architectural design, who are better equipped to exploit the opportunities afforded by new technologies and methods. The need for this programme was described by its creators to be also evidenced in the paradigm shift that is taking place in the way our built environment is designed, procured, constructed, and regulated.

The rationale for launching this new programme also related, according to the team developing it, to UCL's location in London and its unique proximity to many of the world's leading consultants operating in the forefront of the field such as, AKT II, Arup, Foster and Partners, Fielden & Clegg, Buro Happold, Price and Myers, and Laing O'Rourke. The programme is based at new facilities at Here East, Hackney Wick which house a sequence of multi-functional and adaptable large-scale spaces. These extend from 1) public/exhibition/foyer/studios, to 2) a large collaboration hub for demonstrations/assemblies/and gatherings of variable scale, through to 3) a large volume fabrication space for large scale manufacture and assembly, and 4) a large research hub for dedicated projects at an advanced level, including environmental chambers. The ensemble is promoted to provide a state of the art, world-class facility with unrivalled transparency and ease of engagement between the constituent parts of learning, research, and enterprise. Occupants are said to be provided with an entirely novel environment that is part gallery and archive, part auditorium and theatre, part studio and office, part laboratory and factory, and part social generator, all in one envelope.

Student experience and teaching delivery was described to be centred on a combination of the design studio model that underpins ARB/RIBA validated programmes with engineering problem-based learning excellence. This was viewed to be a unique mix, placing creativity and design at the centre of engineering education, to challenge conventional models, allowing students the opportunity to understand and develop advanced design methodologies whilst acquiring expertise on how they are augmented and resolved through engineering knowledge. The course development team also initially described how graduates needed to develop the confidence, knowledge, expertise, and creative propositional abilities to undertake the critical first steps of a project including brief development and design in a context of significant uncertainty, and to advocate their designs and engage in robust critical interdisciplinary discussion as they evolve. The course structure is graphically summarised in **Figure 1** and an outline of the core and elective modules is provided in **Table 1**. Rooted in discussions of developing key knowledge and ability were initial thoughts on key competencies needed.

Approaches to initial thinking on key competencies for multidisciplinary built environment design professionals

The course is intended to provide an environment where completing graduates will:

- Be prepared for a professional life in the integrated design of the built environment
- Have the educational competencies for corporate membership of a relevant professional institution such as the ICE, IStructE or CIBSE
- Practically apply fundamentals to real-world scenario to enable rich and divergent analysis and development
- Critically apply appropriate tools and processes to expeditiously deliver advanced and pertinent propositions
- Have the tools and confidence to bridge and unify previously disparate disciplines
- Develop a study, research and work principle that is both conceptually and practically interdisciplinary Be equipped with the necessary skills and expertise to discover and grow their own design and engineering vision within a diverse culture and fast-changing environment
- Have knowledge and skills to authoritatively challenge status-quo and develop new paradigms
- Lead in meeting the national and international demands for productive and environmentally effective built environments
- Have the acumen and knowledge to undertake further research and scholarly activity
- Be inspired, prepared and fully supported individuals with opportunity to fulfil their personal goals, their intellectual and creative potential

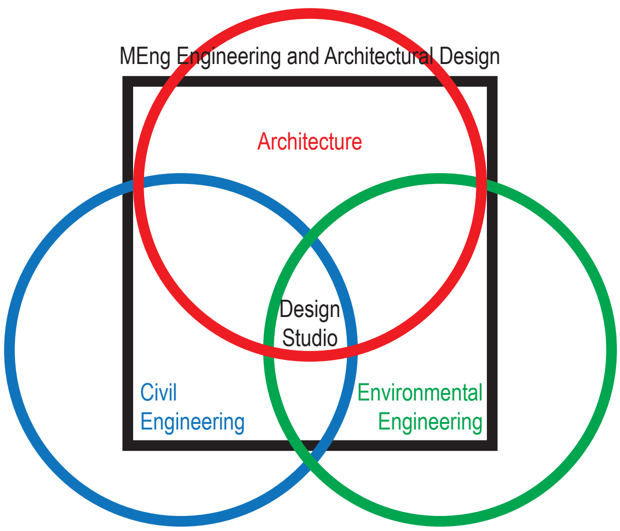

Figure 1. Course structure diagram. (Oliveira et al., 2022)

Integrated master's degrees (often denoted MEng) accredited for the purpose of CEng registration need to demonstrate an emphasis on developing solutions to problems using new or existing technologies, through innovation, creativity, and change. The integrated master's is promoted to go beyond the outcomes of accredited bachelors (honours) degrees to provide a greater range and depth of specialist knowledge, within an authentic environment, as well as a broader and more general academic base. As such the development team drew on the Accreditation of Higher Education Programmes (AHEP4) learning objectives, noting how they provide a sharper focus on inclusive design and innovation, and the coverage of areas such as sustainability and ethics. The coverage of equality, diversity and inclusion is also noted to be further strengthened to reflect the importance of these matters to society as a whole and within the engineering profession.

Courses like this, according to the team developing them, were seen to provide a foundation for leadership and innovative engineering practice. Graduates from an integrated master's degree such as this were intended to achieve interdisciplinary learning outcomes, possessing a broad and coherent body of knowledge including mathematics, natural science and engineering principles, and a proven ability to apply that knowledge to analyse and solve complex problems. Graduates need to be able to select and apply quantitative and computational analysis techniques in the absence of complete data, discussing the limitations of the methods employed. With an appreciation of professional engineering practice and ethics, graduates were also expected to be commercially aware and able to apply their knowledge and skills to design, deliver and evaluate innovative new products or services to meet defined needs using new or existing technologies.

Whilst the above section explained the ambition and initial thinking conveyed by the development team, the following section discusses key findings that emerged from the narrative synthesis of the development process itself, positioning the findings as discussed in Oliveira et al. (2022) within extant literature. Additionally, the section presents the findings from an initial review and analysis of the final classifications and job placement of the first cohort to complete the programme. The student outcomes are presented to begin to evaluate the strengths and weaknesses of the structure described in detail by Oliveira et al. (2022) and to inform the future refinement and development of the course, and of architecture and engineering education more broadly. In this way, evidence will be added to support one of the indicators of engineering education success as described in Graham (2018), that is, the 'value added' to the student. This work also aims to

Table 1. *Summary outline of the course structure.*

Year 1	Year 2	Year 3	Year 4
Core Module 1 History and Theory of Engineering & Architecture	**Core Module 8** Structural and Foundation Analysis and Design	**Core Module 13** Mechanics of Buildings	**Elective Module 1** (Range of options)
Core Module 2 Mathematical Modelling and Analysis I	**Core Module 9** Advanced Mathematical Modelling and Analysis	**Core Module 14** Sense, Sensing and Controls	**Elective Module 2** (Range of options)
Core Module 3 Building Physics and Energy	**Core Module 10** Urban Physics	**Core Module 15** Practice and Project Management	**Core Module 18** MEng Dissertation
Core Module 4 Building Physics and Environment	**Core Module 11** Environmentally Responsible Building Systems	**Core Module 16** Making Buildings	**Core Module 19** Design Practice 3: Vertical Design Units
Core Module 5 Materials Mechanics and Making	**Core Module 12** Design Practice I: Design Studio	**Core Module 17** Design Practice 2: Vertical Design Units	
Core Module 6 Design Make Information			
Core Module 7 Design Make Live			

help fill the gaps defined by Richter and Paretti (2009), notably a lack of measurable outcomes of interdisciplinary engineering education.

Findings

Narrative analysis

A key ingredient to developing multidisciplinary curricula was found to be ensuring that the team has a shared ethos and understanding, flexibility and agility in meeting both professional and personal expectations of the process, and critically obtaining institutional support. These findings are echoed in much of the literature on multidisciplinary education and practice. Power and Handley (2019) discuss three interrelated approaches for better integration of interdisciplinarity in HE including, maintaining clear communication, providing an adequate structure, and facilitating cultural change through shared values.

In the Oliveira et al. (2022) study these shared values were found by the participants to be not only of a professional character but also deeply personal. Some participants observed and discussed the importance of conveying a sense of a 'common desire' to achieve an 'integrated approach' that 'realised the importance of each team'. In addition to shared beliefs, most participants reflected upon a sense of having 'a blank sheet of paper' when developing the course content to ensure that all content created was bespoke and could fit the diverse professional body criteria. This 'ground-up' approach differs from ways many similar interdisciplinary integrated courses develop by fitting around shared modules and content. Professional expectations were also found to reflect many of the participants own professional experiences, working across disciplines with many discussing the importance of that experience to provide the skills to transcend disciplinary boundaries. Whilst many described the future graduate to be a new type of professional, a 'building designer' as well as a 'specialist generalist', many also discussed the potential other possibilities the course could offer to a developing industry need for greater collaboration and integration.

When personal expectations were discussed, these tended to convey the practicalities of developing shared values such as maintaining a positive focus and ensuring starting points and goals were well communicated. Some describe the inherent challenges of communicating across differing disciplinary expectations and the need for maintaining a shared vision and positive outcomes as critical to managing those differences. For many, their life experiences beyond the course shaped their understanding of their particular roles in the course development – seen by some as fulfilling the role of negotiators, others as visionaries. Whilst much of the detail was uncertain at the start of the discussions, there was a wider acceptance that the process was largely unknown and flexibility and agility to adapt to the process was observed by all as key. The need for flexibility and agility supports and extends work by Clevenger et al. (2017) on the importance of a shared programmatic and course level vision as well as providing opportunities for iteration and risk taking in facilitating multidisciplinary curricula.

Whilst being mindful of both professional and personal expectations was found by all to matter, the critical, and possibly most significant challenge, was obtaining institutional support. The institutional support and resource to ensure all content created and developed was bespoke to the needs of the course was found to be a critical component of the discussions' successful outcome. Insights also suggest that willingness to take risks by both the institution and the course developers is critical to the success of the course development process. Participants discussed the process of developing the course as being challenging as well as open and a venture into the unknown. Many participants stressed the importance of the course being a new type of discipline- neither engineering nor architecture. Institutional support as well as having the possibility of the course being delivered in a purpose-built facility driven by a design studio style teaching delivery were important factors in maintaining vision as well as overcoming cross departmental challenges. Many participants discussed the importance of 'maintaining ambitious vision' as an important aspect of the course development conversations. The need for institutional support is also reflected in other studies as a key condition to enabling multidisciplinary curricula to evolve (Richter & Paretti, 2009).

Review of the outcomes of the first cohort

According to UCL's Bartlett School of Architecture (BSA), there are 300 permanent members of staff at BSA and 1,600 undergraduate and postgraduate students, or an academic staff to student ratio of approximately 1:5. In comparison the academic staff to student ratio for UCL as an institution is approximately 1:10. The MEng Engineering and Architectural Design has about 30 primary teaching staff and 44 tutors for a maximum 'steady-state' student enrolment of 240 (60 per year for 4 years), or a staff to student ratio of just over 1:3, making this a staff-resource intensive programme.

Thirty students made up the first cohort, and as of May 2021 twenty-three had completed their dissertation. The average final dissertation mark was 71, the highest mark was 88 and the lowest mark was a 44; where marks above 70 are equivalent to an 'A', 60-69 a 'B', 50-59 a 'C', and marks below a 50 are fails. Results from eighteen students of this first cohort were reviewed, sixteen with a Master of Engineering and two with a Bachelor of Engineering. Of those who completed the MEng eight earned first class honours with final marks above 70; seven received second class honours (upper division) with marks above 60; and one earned a second class honours (lower division) with a mark above 50. In modules that are shared across programmes, the students enrolled in the MEng EAD programme were some of the highest performers. Reasons for this could, in part, be due to the type of students that were attracted to the nascent programme. Information gathered from initial interviews with staff suggest that the first cohort were largely self-motivated high achievers. It is unknown if the distribution of final classifications will remain skewed to as many distinctions as the programme matures.

Early reports from graduates and employers indicate high rates of employment with some students receiving offers of employment as early as the first term of their final year. Comments from employers suggest that the broad set of skills learned by graduates is very desirable. However, both students and employers expressed concerns about how, or where, they fit into a traditional practice. Approximately one quarter of the first two graduating quarter are working towards RIBA Part 1, another 25% report employment as 'graduate structural engineer', an additional quarter list their job as 'architectural engineer' or as part of a sustainability team, the remaining graduates report a wide variety of job types including, digital media, robotics, or further education (e.g., RIBA Part 2).

Further evaluation of the programme through extensive interviews with graduates, current employers, and staff is on-going.

Conclusion

It is well established that developing multi-, inter-, and transdisciplinary curricula is a complex endeavour and that it requires coordinated efforts by academics and industry from different university departments and different disciplines. However, it is less well known that coordination and communication of such efforts can also be shaped by professional and personal expectations as well as institutional contexts as discussed above. In addition, many of the academics involved in the course development discussed above had prior experiences of working or learning in multidisciplinary environments and this prior experience and knowledge enabled an open mindset and positive focus on shared outcomes.

Whilst the implications of this study are primarily in advancing engineering and architecture curricula, there are helpful insights that might benefit other curricula in other engineering disciplines. For instance, the importance placed on personal experiences and expectations. Most participants engaged in developing this course had some prior experience of multidisciplinary curricula, either as students or educators in past institutions. There may be further helpful benefit in developing STEM professional courses or seminars that could offer insight and experience of learning in a multidisciplinary environment, leading to a positively led curricular approach that merges and draws on different disciplines. Whilst the participants did not reflect on the role of the environment both on terms of equipment or space needs, it may have been helpful to further explore how the physical design of a very novel and bespoke space facilitated or enabled certain curricular understandings or discussions. Future studies could further explore how this novel environment may inform or enable particular types of activities and learning environment that otherwise may not have been possible. It is also recognised that this study is based on one course. Future studies could compare course development processes with regards to multidisciplinary content of two or more courses, perhaps across different sectors or between different countries. Future studies are also needed to analyse further the role different people and their activities, vision and expectations play in developing multidisciplinary content.

Transcending multiple disciplinary boundaries is becoming increasingly important for devising solutions to the world's most pressing issues, such as climate change and decarbonisation. Multidisciplinary education offers opportunities to help develop new competencies and attributes of future built environment professionals. There is emerging evidence, from the review of the interdisciplinary MEng programme in Engineering and Architectural Design at UCL, that both students and industry find the educational approach to be of great value. The insights from this paper offer helpful pathways to how curricula that ensure development of new competencies could be considered. ■

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ARTICLES

Air cleaner as an alternative to increased ventilation rates in buildings: A simulation study for an office

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Abstract: This study analyses the feasibility of utilizing advanced air cleaner technology for air purification in a system-based filter (recirculating ventilation system), a room-based filter (local recirculation in each room), and a beam-based filter (recirculation in an active chilled beam). The results show that choosing the appropriate air cleaner can significantly impact energy performance and improvement of indoor air quality.

Background

Air pollution poses significant risks to human health, as it comprises a combination of gaseous and particulate contaminants. Both indoor and outdoor air quality are affected by air pollution, which can either originate from indoor sources or be brought into buildings from the outdoor environment. Given that people spend most of their time indoors, exposure to air pollution primarily occurs inside buildings. This exposure has been linked to adverse effects on the immune [1], respiratory, and cardiovascular systems [2-4], as well as an increased risk of lung cancer [5] and premature mortality [3]. Short-term symptoms of exposure to poor indoor air quality include headaches, eye, nose, and throat irritation, fatigue [6], and asthma [7], which can lead to decreased productivity and increased workplace absenteeism [8].

Indoor air quality is affected by both indoor and outdoor sources [9]. Outdoor air pollutants come from different sources, such as burning fossil fuels for heating, transportation, and production of electricity, as well as waste incineration. Typical indoor sources of pollution include cleaning products, office equipment, cooking, and biological activities by humans, pets, and mould [10, 11].

To mitigate the negative impacts of outdoor-to-indoor pollution transfer, the use of supply air filters in the ventilation system improves indoor air quality. To reduce the impact of indoor pollutants, the most effective approaches are to reduce or eliminate those sources and to ventilate the space with cleaned outdoor air. An alternative technical solution to increase ventilation rates with outdoor air is to utilize filters. This can be carried out by three different methods: filtering air centrally using the HVAC system, placing air cleaners in each room [12], and utilizing a combined active chilled beam with a filter.

Studies suggest that filtration can enhance the effectiveness of source control and ventilation in enhancing indoor air quality. Installing a portable air cleaner or using the air filter in a cooker hood or using recirculation in combination with a filter in the HVAC system can be an effective strategy to reduce indoor air pollution.

Air filtration technologies need to address a range of pollutants, each requiring a different mechanism for removal or degradation. Different types of air filters have their own strengths and limitations in removing specific pollutants. This complexity can result in cumbersome and complicated multi-stage air filtration systems. The challenge of simultaneously removing both particle and gaseous pollutants necessitates a better understanding of the mechanisms involved. One potential solution is the combination of multi-stage devices into a single-stage air filter, an area that remains underexplored. Achieving a balance between healthy air quality, energy efficiency, and the effectiveness of the heating, ventilation, and air conditioning (HVAC) system requires careful consideration of HVAC components.

When designing filters for air cleaning, it is important to consider several criteria. One of these criteria is total building efficiency, which can be enhanced by creating filters with a lower pressure drop, reducing energy consumption while maintaining the filter's pollutant removal capacity. Another challenge is to develop filters that do not add complexity to the ventilation system. Moreover, solutions that are easy to produce, operate, and maintain while also being cost-effective should be prioritized to ensure their widespread adoption in buildings.

An HVAC system works diligently to ensure that occupants of a building are provided with the ideal thermal climate and satisfactory air quality required for their activities, compensating for any shortcomings in the building's tightness.

Two primary mechanical ventilation systems are commonly used: extract ventilation systems which rely on outdoor air supplied through wall vents and windows and balanced ventilation systems using heat recovery and filtration. Natural and hybrid ventilation systems are also used; however, traditional natural ventilation systems do not include air filtration in their design.

Approximately 35% of the energy used by commercial and residential buildings is attributed to HVAC systems [14], underscoring the significant role these systems play in the overall energy use of the building sector. Therefore, it is crucial for HVAC systems to operate at their optimal efficiency in today's context [15]. The energy use of HVAC components varies significantly based on various factors such as building type, glazing percentage, and properties, the efficiency of heat recovery, occupancy patterns, internal gains, building location, and climate. Moreover, the ventilation system design (natural or mechanical) and operation time, which can differ depending on the building type (residential or commercial) and occupancy, significantly affect the system's energy use.

Fans are responsible for air distribution and typically consume around 34% of the total energy used by ventilation systems [16]. The power required to run an HVAC fan is influenced by several system design parameters such as air flow, flow resistance, and fan efficiency. The air flow rate and fan system efficiency are determined by the system's needs, equipment selection, and building requirements, whereas flow resistance depends on component selection and ventilation system design. Air filters introduce air resistance into the system, and their contribution to the total system pressure drop can range from 20% to 50%, depending on the loading conditions, filter efficiency, and system configuration [17].

Providing a comfortable indoor climate requires technical installations that consume a considerable amount of energy. To reduce energy demand and maintain an optimal indoor environment, new solutions based on the needs and activities of occupants must be developed. The objective of this study is to investigate the feasibility of utilizing advanced air purification technology in combination with different ventilation strategies to improve indoor air quality and optimize energy use. The study aims to evaluate the benefits and drawbacks of these alternative system solutions.

Building model

The building model was chosen to be representative of a typical office room located on the middle floor of a high-rise building. The room has a heated area of 16 m² and a volume of 48 m³. All the surfaces are considered adiabatic (thermally isolated), except for the south-oriented façade (wall), where ambient boundary conditions are applied. This facade also includes a window of 6 m². The facade has two parts, an opaque element, and a glass element, with U-values of 0.3 W/m²K and 1.5 W/m²K, respectively. Shading devices are installed outside the window, which can block 50% of incoming radiation when direct solar radiation on the south facade is higher than 150 W/m². Shadings from nearby obstacles are not considered.

Hourly resolution profiles for occupancy, appliances, and lighting were used to represent user behaviour and internal heat gains. The profiles were generated based on different user behaviours for weekdays and weekends. The peak heat gain was assumed during working hours on weekdays and was set 20 W/m². The natural infiltration rate was assumed to be constant and the air change per hour was set to 0.2 ACH.

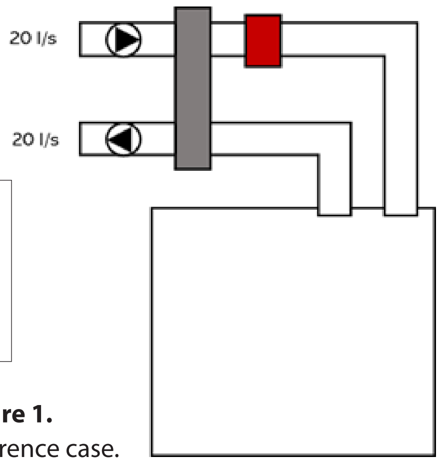
The filter was modelled to reduce the concentration of pollutants by 80%, with CO_2 being used as the primary pollutant. During working hours, an indoor production of 9.1E-6 kg/s of CO_2 was assumed, while an outdoor concentration of 400 ppm was used as a reference concentration.

An ideal space heating and cooling system was modelled in order to keep the indoor air temperature within the range of 20-24°C equal for all systems simulated.

System models

Four different HVAC system configurations were implemented, namely: 1) Reference case, 2) System-based filter, 3) Room-based filter, and 4) Beam-based filter.

The reference case (**Figure 1**) represents a typical office ventilation system consisting of a heat recovery unit, a heating coil, and supply and return fans. The heat recovery unit was modelled as a rotary heat exchanger where the speed of rotations (effectiveness) was regulated according to the actual needs in terms of heat transfer between supply and return air streams. The maximum effectiveness was set to 0.8. An outdoor air flow rate of 20 ℓ/s is delivered to the office room by the supply fan. The office room receives an outdoor air flow rate of 20 ℓ/s from the supply fan, which has an efficiency of 0.6. The ducts were set to have pressure drops of 150 Pa, whereas the heat recovery unit was set to have a pressure drop of 200 Pa. The heating coil, which maintains the supply air temperature at 20°C, was assumed to have a pressure drop of 50 Pa.



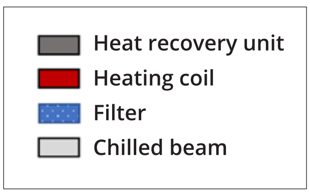


Figure 1. Reference case.

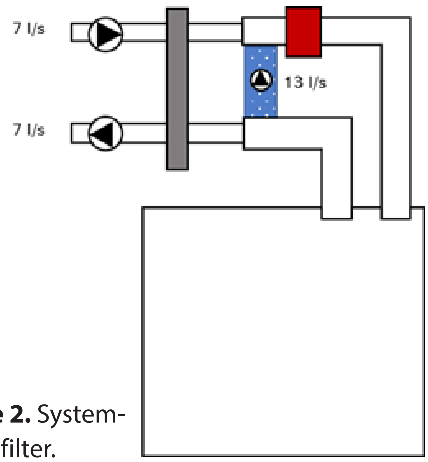
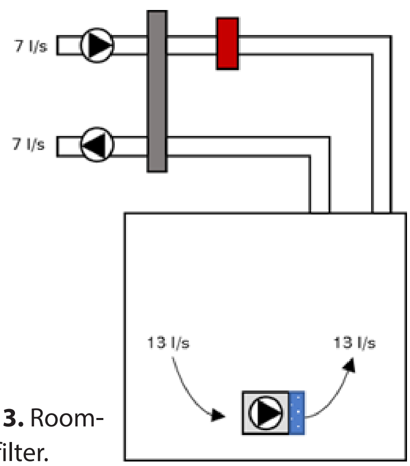


Figure 2. System-based filter.



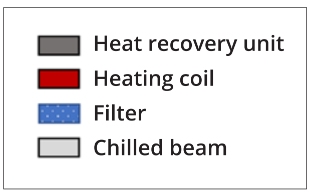


Figure 3. Room-based filter.

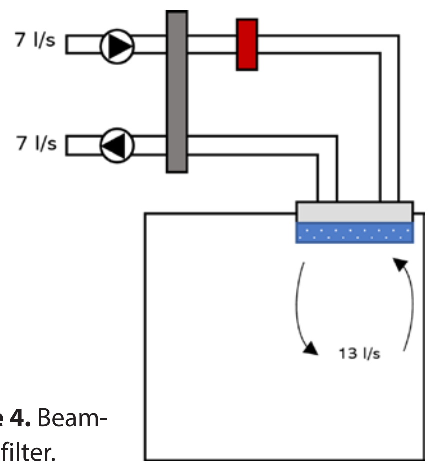


Figure 4. Beam-based filter.

The case "system-based filter", as shown in **Figure 2**, introduces a filter at the system level. This allows for lower outdoor air flow rates by filtering return air from the room. For this case, an outdoor air flow of 7 ℓ/s was assumed, with a 50 Pa pressure drop set for the filter. It's worth noting that this approach allows for smaller ducts to be installed in correspondence to the heat recovery unit. The filter was modelled accordingly.

The case "room-based filter" introduces a filter at room level, as illustrated in **Figure 3**. In this case, the air is filtered within the room using a small fan. It's worth noting that, such fans are generally less efficient, with a typical value of 0.25 assumed in this study. A pressure drop of 50 Pa was set for the filter.

The case "beam-based filter" introduces a filter incorporated into a chilled beam unit, as shown in **Figure 4**. In this case, the induced room air is filtered by a device integrated into the beam unit. To induce air through the beam unit, the pressure drop in the duct system was increased to 210 Pa.

Results and discussion

A previous study [18] explored the combination of active chilled beams (ACBs) and air cleaning technologies to improve indoor air quality in offices. The researchers conducted laboratory experiments to test the effectiveness of a low-pressure mechanical filter in removing particles from the air in combination with ACBs. The results showed that the combined system was effective in removing both large and small particles from the air, resulting in improved indoor air quality. The study suggests that the combination of ACBs and air-cleaning technologies can be an effective strategy for improving indoor climate in offices. Furthermore, the measurement results of the combined system showed that adding the filter accelerated the removal rate of the particles by 2 h^{-1}. However, the efficiency of the chilled beam in exchanging heat was reduced by 38% when the pressure loss was less than 5 Pa.

It should be noted that the reduction in efficiency depends on a lower induction rate in the chilled beam. In the above-mentioned study [19], the induction rate is reduced from approximately 3 to 2. In the present study, the induction rate is less than 2. It means that the size of the chilled beam must be larger when installing a filter to keep the same cooling power.

Energy demand

Figure 5 shows the annual cumulative energy use for space heating in the four system configurations. The profiles are remarkably similar for the cases room-based filter and beam-based filter. The highest energy demand 23.8 kWh/m² were observed in the reference case. This is attributed to the lack of air recirculation in the reference case, resulting in lower indoor air temperatures compared to the other cases.

Figure 6 shows the annual cumulative energy use for space cooling. The highest energy use was observed in the cases room-based filter and beam-based filter, with their profiles being almost identical. Conversely, the lowest energy demand was observed in the reference case. This can be attributed to the higher amount of outdoor air being supplied to the room in the reference case, thereby increasing the potential for free cooling during the summer months.

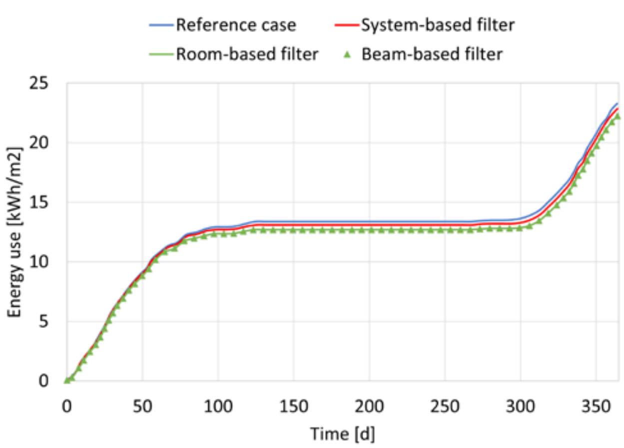


Figure 5. annual cumulative energy use for space heating.

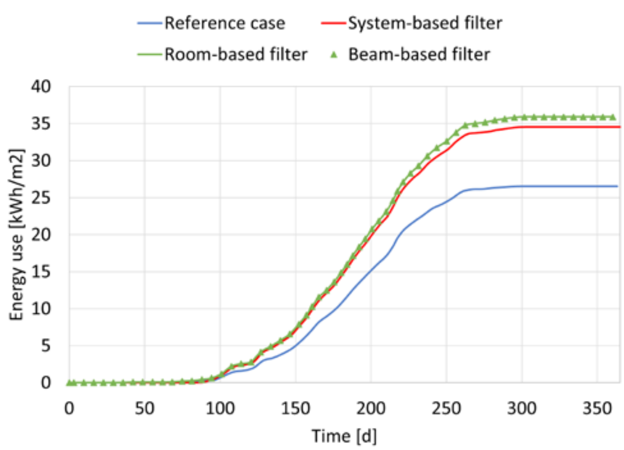


Figure 6. annual cumulative energy use for space cooling.

Figure 7 shows the annual cumulative energy demand for the heating coil. The highest energy demand was observed for the reference case (24.3 kWh/m²), whereas the lowest energy demand was observed for the system-based filter (5.8 kWh/m²). This can be attributed to the higher amount of outdoor air being supplied to the room in the reference case.

Figure 8 shows the annual cumulative electricity energy demand for fans. The highest energy demand values were observed for the reference case (13.7 kWh/m²), while the lowest values were observed for the beam-based filter (5.2 kWh/m²). This is attributed to the recirculation of air that occurred through induction in the beam-based filter case, which is more efficient than using a fan in the room (as in the room-based filter case).

Figure 9 shows the total primary energy use for the four cases. A factor of 0.8 was used to convert space heating and heating coil energy use to primary energy use (assuming district heating or boiler as heat source). For electricity, a factor of 2.5 was used. It was assumed that space cooling was provided by a chiller with a seasonal coefficient of performance (COP) of 2.5. It can be noticed that the integration of a filter in the beam unit resulted in primary energy savings of approximately 26% in comparison to the reference case, as observed in the figure.

Indoor CO_2 concentration

In the present study, the concentration of indoor CO_2 is used as a measure of overall indoor air quality.

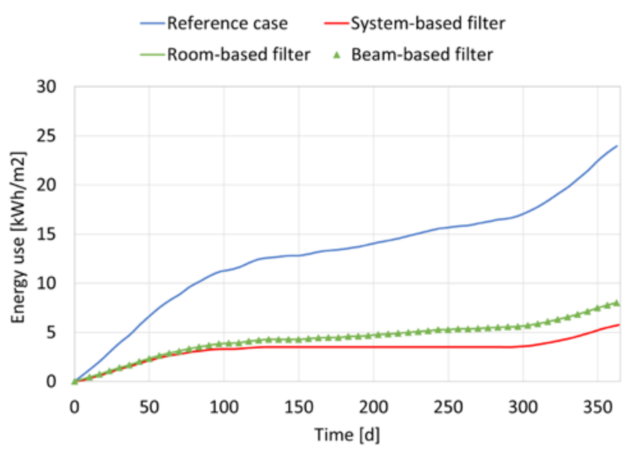


Figure 7. annual cumulative energy use for the heating coil.

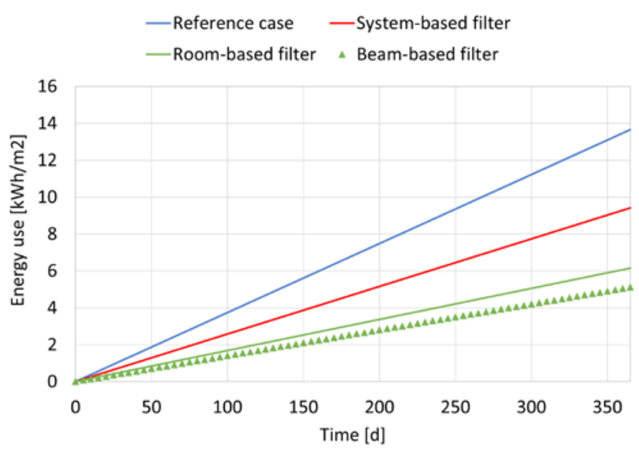


Figure 8. annual cumulative electric energy use for fans.

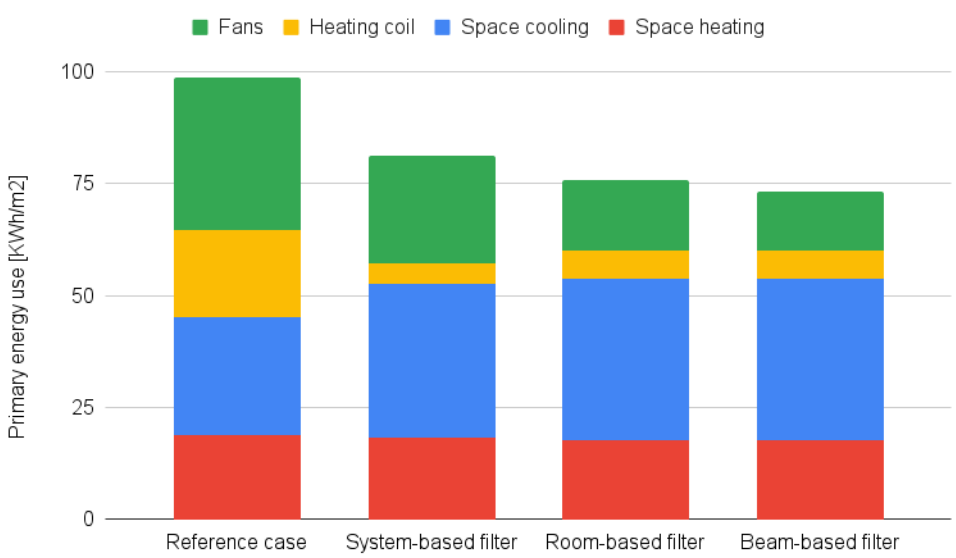


Figure 9. Annual primary energy use for the four cases.

Figure 10 shows the CO_2 concentration during a typical day for the reference case (no filter) and for all three cases with integrated filter (with filter). The graph shows that the integration of a filter reduces the CO_2 concentration in the room to approximately 160 ppm during unoccupied hours and to approximately 450 ppm during occupied hours. This is a significant reduction in comparison to the reference case, indicating that the use of filters can have a positive impact on indoor air quality.

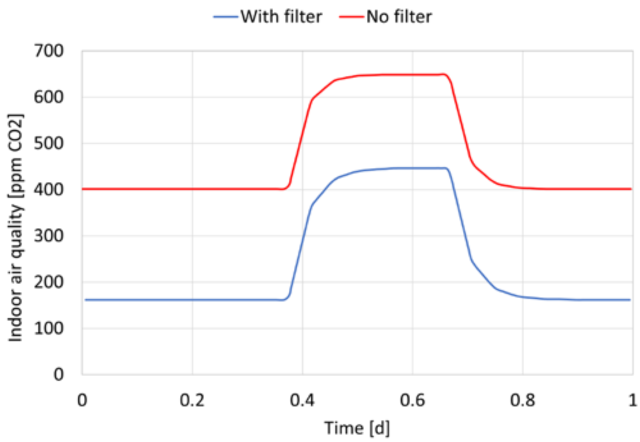


Figure 10. The CO_2 concentration during a typical day for the reference case (no filter) and for the cases that integrate a filter (with filter).

Conclusions

Indoor air pollution can be effectively mitigated through air cleaning. Portable air cleaners or combined chilled beams with air cleaners are viable solutions for removing pollutants and enhancing the air quality in a specific room. One important question is how the placement of an air cleaner affects its ability to improve indoor air quality.

Overall conclusion:

- The study highlights the importance of considering energy performance when selecting air cleaners and ventilation systems for indoor climates.
- These findings suggest that choosing the appropriate air cleaner and ventilation system can significantly impact the overall energy performance and improvement of indoor air quality.

The results suggest that:

- The room-based and beam-based filter systems have similar energy demands for space heating, while the reference case has a slightly higher energy demand due to the lack of air recirculation.
- For space cooling, the room-based and beam-based filter systems have the highest energy demand, while the reference case has the lowest energy demand due to a higher supply of outdoor air.
- The system using filters has the lowest energy demand for the heating coil, whereas the reference case has the highest demand.
- For fans, the beam-based filter has the lowest energy demand due to efficient recirculation of air through induction, while the reference case has the highest due to higher air flow through the air handling unit.
- Integrating a filter in the active chilled beam unit results in primary energy savings of approximately 26% compared to the reference case. ■

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A New Learning Programme to Facilitate nZEB Implementation

Abstract: The goal of nearly zero-energy can be achieved nowadays with existing technologies and practices, but the concept is still unfamiliar and elusive in most of the European countries, considering the whole process chain, despite all previous initiatives in this direction. At this moment there are still barriers in the value chain, making the nZEB concept difficult to arrive at the final users. The nZEB market analysis at European level reveals a significant gap between the countries with a high level of implementation and those which are not so well performing, and which remain more and more behind. To overcome this, a new learning programme to facilitate the nZEB implementation, has been launched in 2021 with the main objective to create support mechanisms and stimulating the development of skills frameworks by new market driven mutual recognition training and certification scheme for nZEB deployment that will facilitate the necessary legislative changes.

Keywords: nZEB, nZEB learning programme, nZEB implementation

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Introduction

Buildings account for 40% of total energy consumption in the EU and generate 36% of the greenhouse gases in Europe (1). These are resulted from construction, usage, renovation and demolition of these buildings.

According to the European Energy Efficiency Plan 2011 (2), the greatest energy saving potential in order to lower the energy consumption lies in buildings. This is because 75% of the EU's building stock is still energy inefficient and the rate of building renovation remains very low at around 0.4% to 1.2% per year. To meet EU climate and energy objectives, the current rates of renovations should at least double. Also, the annual new buildings growth rate is assessed at around 1% in the European residential sector (3). The decrease in the rate of new constructions in the last decade is mainly due to the financial crisis of the construction sector.

The Energy Performance of Buildings Directive (4) (EPBD)'s specific concept, "nearly Zero Energy Buildings" (nZEBs), has now become a critical requirement for the building sector, along with the challenge for the architects and designers who are divided between keeping up with indoor environment quality standards and solutions for decreasing energy consumption (e.g. airtight buildings). New harmonizing solutions are thus required. Optimising indoor environmental quality with energy reduction is essential for the new buildings and in solving the problem for the existing buildings that are not meeting the expected performance. These buildings can drive occupants to take actions that may compromise the energy economy of the building. In the new context, occupant's comfort and health is one of the key drivers to stimulate the renovation and quality new construction market.

The goal of nearly zero-energy can be achieved nowadays with existing technologies and practices, but the concept is still unfamiliar and elusive considering the whole process chain, despite all previous initiatives massively financed by European Union. There are still barriers in the value chain, making the nZEB concept difficult to arrive at the final users. This discrepancy is even higher when compared within different countries.

A significant problem in the nZEB process is the performance gap between the designed and actual energy performance in buildings. Main reasons behind that are: inadequate design, bad quality of the construction work, lack of soft landings, lack of continuous commissioning after the installation has been handed over, lack of proper use of systems and implemented technology, lack of understanding of how the technologies work, too general information in O&M manual, difficulties in changing users' previous behaviour etc. Even if, due to EPBD implementation, the public buildings should already be nZEB, the designers still do not know how to apply the nZEB requirements as indicated in the legislation because these are still not clearly linked to the current construction laws.

Results show that feasibility studies will not be focused on nZEB criteria but rather on the classical building functionality. Moreover, based on the feasibility study, tender specifications are further created for design and execution contracts, but usually the design is considered only based on classical construction requirements. Thus, the result is a technical design which is not for nZEB, even if it should be, and being at high risk during execution phase to be blocked by the beneficiary consultant or inspector. This is a classical story of the construction market in Romania. Bulgaria encounters same problems. It could have another version in Poland or Portugal. In Poland for example, the nZEB legislation is not really challenging. The nZEB uptake is driven by bottom-up initiatives, which however are not very frequent due to the lack of tender specifications with higher energy performance. On the other hand, some more advanced countries demonstrate a higher degree of nZEB level, despite of the existing specific barriers. These stories show how a two-speed Europe is represented in the nZEB and energy efficient construction field, leading to gaps and an unharmonized market.

Moreover, these barriers are considerably more important in the residential field, where the concerned end users do not have the information on materials, construction technologies (or renovation packages) and available funding opportunities. Thus, the market is missing important pieces from the nZEB puzzle, like skilled building professionals, across the whole building design, operation and maintenance value chain, ready to implement nZEB concept.

Although legal obligations are provided in the National legal framework by transposing the provisions of the 2010/31/EU Directive, the Nearly Zero Energy Building (nZEB) concept does not seem to be easily applicable yet in many countries from EU. Previous research showed that defining the cost- feasible optimal integration of the technologies suitable for nZEB and the skills gaps experienced by the building sector are among the most important barriers. While the current qualification courses and training schemes are still generally, there are still at a level of not satisfactory and underdeveloped to face the challenge of effective nZEB implementation, the requalification to skilled professionals for renovations and the new constructions of buildings. Despite strong political push towards nZEB and deep energy renovation, the traditionally conservative real estate market is still slow in the uptake of the new building standards and practices, especially in the residential sector. Considering our built environment, the policy efforts are hardly being transposed to more sustainable and environment- friendly lifestyles, and the benefits of nearly zero- energy buildings in terms of comfort, health and well-being are still widely unknown for the broader audiences, being left out of the media attention.

It can be observed that there are several causes that contribute to the difficult application of nZEB criteria in buildings in EU member states. The need to address these issues has become a necessity to increase the level of application of nZEB. For this, a new programme to facilitate the nZEB implementation, has been launched and financed from 2021, in the frame of a H2020 project (5). The main goal of the project is to support the increase of the market readiness for an effective nZEB implementation and to stimulate the demand for energy related skills and is oriented toward three different pillars: awareness, training, and support, responding to the critical points of market barriers, as identified in most European countries.

The aim of nZEB Ready project is to leverage the market drive by responding to 3 key questions: "Why nZEB?"; "Who can provide nZEB?"; and "How to reach nZEB". Thus, the nZEB Ready project will prepare ready to use frameworks to answer the needs related to lack of awareness, lack of skilled professionals and lack of support instruments, implementing the nZEB ready labelled procedures in 5 pilot countries in order to obtain a broader range of results, representative at European level. The frameworks obtained will be validated by specific stakeholders which are already part of the advisory board of the consortium and will be the starting point for the nZEB readiness roadmap for further replication in a wider use at the European level.

Objectives of the learning programme

Usually, improvements in energy efficiency planning and investments can decrease the energy consumption in the construction sector and unlock the nZEB market, but the reality shows us that it is not enough. The nZEB market analysis at European level reveals a significant gap between the countries with a high level of implementation and those which are not so well performing and which remain more and more behind (6). For these countries, energy efficiency is still an area with great potential to reduce greenhouse gas emissions.

Concerning this aspect, the countries like Bulgaria and Romania are consistently underperforming.

Related to the nZEB market it can be seen the problems related to jobs and qualifications needed. Through the market sustainable initiatives, countries like Croatia and Poland would preserve jobs in the construction sector, create new jobs and stimulate both public and private investments, thus contributing to the green recovery which will further contribute to other sectors like innovation and the development of new technologies, the production of new sustainable materials, new systems based on renewable energy sources. Moreover, some countries such as Bulgaria, Poland and not long-ago Romania, have low levels of ambition for tackling the energy transition, being still highly dependent on fossil fuel.

As previously stated, an nZEB building is a very high energy performance building with nearly zero or very low amount of energy use that should be covered to a very significant extent by on-site or nearby energy production from renewable sources. On one hand, reaching the nZEB target is very complex in new buildings and the level of difficulty rises in case of energy renovation of existing buildings, where the implementation of the renovation measures is limited. The renovation process to high energy performance, or even new construction process, is reduced by social (lack of reliable information or doubts on the potential benefits), technical (lack of skilled workers and proper support tools) economic (energy savings are not clear and the investment results reduced), and financial (scarce capital or limited financing scheme available or knowledge) barriers.

We are proposing in this paper a new learning programme to facilitate the nZEB implementation, which its main objective is to create support mechanisms and to stimulate the development of skills frameworks by new market driven mutual recognition training and certification scheme for nZEB deployment that will facilitate the necessary legislative changes. It can be observed that the lack of skilled professionals is one necessary step to break the vicious cycle of a blocked nZEB market (**Figure 1**).

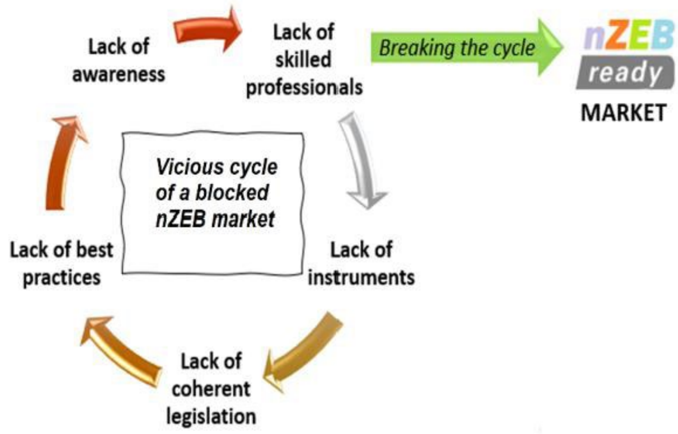

Figure 1. Breaking the vicious cycle of a blocked nZEB market. (5)

Thus, the objective of the learning programme, namely the increasing the number of the skilled nZEB professionals is responding to the market barriers and needs, generated by the lack of skilled professionals which are essential in the nZEB construction chain, by expanding the pool of nZEB specialists for the design, execution, evaluation and validation of nZEB projects through dedicated training modules and replication activities. This will facilitate the increase of the available pool of skilled persons to be requested in nZEB tendering documentation.

The objective to increase the number of skilled nZEB professionals is referring at both "blue collar" and "white collar" professions across the building design, operation and maintenance value chain (designers, architects, engineers and other building professionals). In the frame of this objective, an important goal is to achieve and to implement mutual recognition procedures. The lack of skilled professionals is a problem extended to European level, but more critical on several markets. Among these critical markets, the 5 pilot countries that are partners in the nZEB Ready project encounter different concerns related to market labour for the nZEB specialists (5).

Approach of the learning programme

The nZEB Ready programme will provide a complex set of learning/training frameworks for nZEB concept, design, evaluation, execution, and exploitation by gathering together the already existing courses from previous European initiatives with new courses addressing domains not covered yet, to fully complete an nZEB approach.

Iven the discrepancies in the nZEB application between European countries, the approach will be specific for each state depending on the needs identified for each of them but the whole courses/training framework will facilitate the mutual recognition of energy skills and qualifications in the building sector. Based on the common learning results obtained from the training programs it will be possible to develop nZEB ready energy skills passports/registers for building professionals at regional/national level and support for their take up at European level.

One of the sensitive points regarding the actual nZEB market and the real demand for nZEB skills is that even if regulations requesting nZEB construction already exist, they are not applicable because of the lack of methodologies or lack of nZEB professionals even at the public authority level. This learning programme will support the public authorities for the requirements for skilled professionals in public procurement by providing guidelines for tender documents oriented towards nZEB skilled professionals. There will be also provisioned training programmes dedicated to public authorities, especially in Romania and Bulgaria, to help the administration to better understand the need to properly enforce the nZEB regulation.

To increase the number of skilled building professionals and/or blue-collar workers the learning programme will contribute to substantially increase the number of nZEB professionals. Modules dedicated to white collars (e. g. architects, auditors, or engineers) and modules dedicated to blue collars related to nZEB buildings are considered. This a critical issue of the nZEB application in European countries because it will produce nZEB skilled professionals available on the market. The implementation of a mutual recognition procedure of the skilled nZEB professionals will be possible relying on the competences validated by the specific training programs.

Implementation of the learning programme

The learning programme to facilitate nZEB implementation will be implemented and tested on different layers in the 5 pilot countries (Romania, Bulgaria, Croatia, Poland, and Portugal) considering the needs addressed locally. This will guarantee the replicability success of the solutions.

According to the study (7), most of the countries from the European Union already introduced concepts regarding the implementation of nZEB buildings in their regulations and national plans. From the **Figure 2**, we can observe that in practice no country implemented the principles 100%.

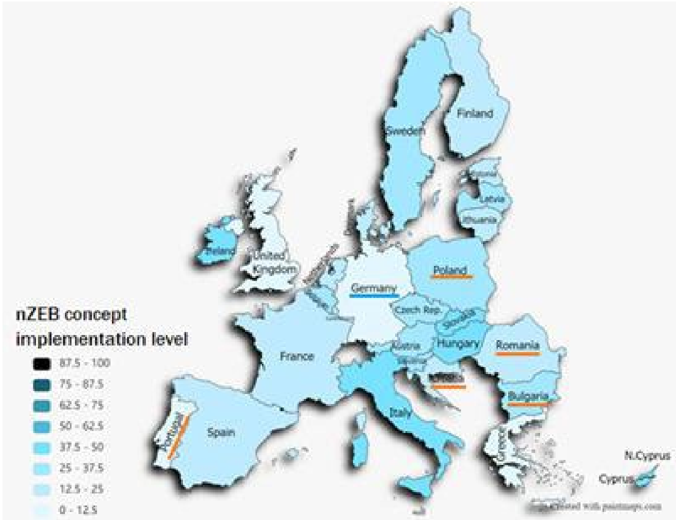

Figure 2. nZEB concept implementation across EU. (5)

The project outcomes will be easily scalable to all member countries and easy to implement in any other country, regardless of the nZEB implementation level and knowledge. This is why the nZEB ready project has a key role in developing the nZEB market needs and skills all around Europe.

The 5 pilot countries were chosen based on a nZEB implementation questionnaire which revealed different needs and different problems on the local market, each indicating a certain level below the nZEB readiness level. Romania has a fair legislation, but it is not enforced accordingly. Moreover, there is an obvious need for new skills for the building designers and the nZEB concepts awareness must be increased to be properly implemented on a wider scale. Croatia has a good level of nZEB awareness and acceptance but needs to improve continuous learning programs regarding the nZEB design and construction skills. Portugal has nZEB regulation with specific requirements although still unclear, while the awareness level is moderate. Poland has fair regulations regarding the nZEB principles, but technical nZEB requirements are not ambitious and can be easily achieved.

There will be learning and training programmes dedicated to white collars especially for designers, architects or engineers but also to execution engineers, programmes that will cover specific skills characteristic to nZEB buildings like blower-door testers or thermal bridge evaluators and programmes for public authorities represented mainly by local administration. These ones will be trained and will get access to specific procedures and know-how relevant for nZEB market helping them to decide correctly regarding building permits authorisation. The circle of learning programmes will be closed by the modules dedicated to blue collars regarding nZEB Ready competences. It is particularly important to outline that the level of knowledge is not the same in each country part of the consortium. The existing successful learning modules from some countries will serve to adapt new modules in the countries where they are partially or completely missing. There will be new learning modules provided where they are totally missing or where the existing learning programmes are not valuable or applicable anymore. Each of the five countries participating in the program will make an analysis of critical categories to be trained and their training needs. Each country will organise pilot learning modules for the selected target categories and regarding the selected training programs to prove the feasibility of the whole nZEB Ready curriculum. The learning results from the whole learning modules will cover the competences needed to be nZEB Ready recognised and to have the "nZEB Ready passport". Finally, the nZEB Ready curriculum will be integrated in the nZEB Ready platform web- development to ensure the content dedicated to continuous learning training and certification program for mutual recognition.

Two main learning programs categories will be defined here based on the needs identified. The first program is dedicated to the nZEB auditors and to the nZEB designers, architects or engineers. The training program is addressed to architects and engineers which are already energy auditors, and the learning outcomes will allow the graduates to assess an existing building and, in addition to the energy audit of the building, will provide technical solutions to increase the energy efficiency of the house toward nZEB. The program is dedicated also to the design of nZEB addressing the three professionals' categories involved in achieving the nZEB target: architects, civil engineers and MEP engineers. The purpose of this learning program is to cover the gap of knowledge between nZEB concept principles and normal building principles, which is designed on a daily basis in each country. The designers will need to focus on a new integrated design concept and to unify their knowledge to design nZEB buildings. There will be six course modules: Thermal bridges calculation, Mechanical ventilation system with heat recovery, Building air tightness evaluation, Solar Shading systems, Bioclimatic Design Renewable energy sources. Romania and Bulgaria will implement most of the training programs because the competences are missing there. Croatia and Poland are better covered in current practice. Portugal will also develop learning programs for the missing competences identified. The second learning program is dedicated to execution civil engineers and MEP engineers, and it will be divided in two learning modules, one for each category. This program will provide learning outcomes for the stakeholders involved directly in the on-site execution: workers, site managers, site coordinators, site professionals, contractors etc.

Two dedicated specific modules for key specialists in the market needed for nZEB certifying will be developed: blower-door testers and thermal bridges evaluator - infrared evaluator. These very specific skills are needed to sustain the nZEB assessor to complete the building certificate. Not only engineers or architects but also skilled workers could be integrated within these modules. The learning outcomes will be strictly related to practical methods used to measure technical parameters. This kind of learning programs will be developed mainly in Bulgaria where they are rather missing and in Croatia where some adult learning programs or university learning programs exist but are not enough. In Romania and Portugal there are already developed continuous learning programs dedicated to the above professional skills, which needs however to be significantly improved. Even so, each partner from the consortium will develop pilot modules in its own country for blower-door testers and thermal bridge evaluators as it is outlined in the table below.

Specialized training programs for blue collars professionals to integrate the learning outcomes regarding the nZEB buildings corresponding to the appropriate level of knowledge. The learning program related to this task will be split in two modules: 1) Construction skills related to nZEB; 2) Mechanical, electrical and plumbing (MEP) skills related to nZEB. They will attend either the Construction skills module, or the MEP skills module depending on their specialization.

Not the least, Public Authorities Staff and other decision makers will gain a deep understanding of the impact of policy instruments for supporting nZEB initiatives and support their specific design. The decision makers involved will get access to specific procedures and know-how relevant for nZEB market. This participation can provide transparency and confidence in the long- term perspective of this sector. In particular, this learning program is dedicated to people working mainly in local or central administration services who are generally responsible for the building permit authorisation.

The last part of the learning programme consists in creating and developing content dedicated to continuous learning training and certification programs for mutual recognition. The learning programs curriculum will be integrated to an online platform locally by each participant.

Conclusions

A new learning programme to facilitate the nZEB implementation, has been launched in 2021 with the objective of increasing the number of the skilled nZEB professionals is responding to the market barriers and needs, generated by the lack of skilled professionals which are essential in the nZEB construction chain, by expanding the pool of nZEB specialists for the design, execution, evaluation and validation of nZEB projects through dedicated training modules and replication activities.

Modules dedicated to white collars and modules dedicated to blue collars related to nZEB buildings are considered as well as the modules dedicated to Public Authorities Staff in order to gain a deep understanding of the impact of policy instruments for supporting nZEB initiatives and support their specific design. ■

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A structured approach to online education of future HVAC and energy professionals



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Abstract: The HVAC sector is essential to realize the energy transition and is facing numerous challenges like educating enough HVAC engineers to carry out the task and being able to integrate knowledge from the construction, energy, IT and health sectors and to cope with rapid technological changes. The availability of structured and easy-to-follow courses on HVAC and energy systems for buildings at higher education level could help to motivate (future) engineers to contribute to the HVAC sector, and to understand how challenging and high-tech it is. Such a course program would ideally also bring a basic understanding of the field to architects and building engineers, in such a way that a better common ground is created for collaboration and integrated design. It would also be useful to Machine Learning and Artificial Intelligence experts joining the HVAC sector. Last but not least, it could help bridging the gap between engineering and policy making, by here too, offering common views on primary energy, resource depletion and CO_2 emissions relating to HVAC systems. The paper describes the structure and content of such an on-line course program. It was developed based on years of teaching experience with international master students of Mechanical Engineering, Civil Engineering, Architecture, Technical Management and Policy, Electrical Engineering and with professionals from housing associations, ministries and municipalities. The choices for the program structure, based on systems engineering, are underpinned and explained, as well as the choices for specific contents. Additionally, experience with the development of self-assessment tools for students, and self-paced courses is shared, as well as the feed-back from students. A first version of the course program was tested on the edX platform with more than 5000 students participating in each module and is publicly available.

Keywords: On-line education; HVAC; Building services; Professional program; MOOC

Introduction

The Heating, Ventilation and Air Conditioning (HVAC) sector is essential to realize the energy transition and is facing numerous challenges like educating enough HVAC engineers to carry out the task and being able to integrate knowledge from the construction, energy, IT and health sectors and to cope with rapid technological changes. However, the building services sector is facing huge challenges. These challenges have been identified in studies in the Netherlands [1], or in the European BuildUpSkills project [2]. Dealing with these challenges have become even more important because they are decisive in realizing the targets of the energy transition. In detail the challenges relevant to this study include the following:

1. Need for a fast-growing professional work force: There are too few people working in the sector to realize the transition. According to TechniekNL [1], there is a shortage of 3000 workers per year in the Dutch sector. This has two implications related to education considering a) the continuous professional development of the current workforce as also b) the education of new employees, mainly having no background in building or energy engineering services.

2. Rapid change of technologies as also related competences: The sector is facing rapid changes in energy techniques (e.g. all electric instead of gas-driven; low temperature heating networks, integration of heating and electrical networks, NZEB buildings); engineering methods(e.g. digitization, circularity, design for maintenance); types of contracts (e.g. performance contracts including maintenance; lease); and processes (e.g. industrialization, prefab, turnkey).These changes are driven by societal needs while only a few innovators and early adaptors develop and start mastering these issues, leaving the question open how to accelerate fostering the maturity of the early majority.

3. Uptake of basic and integrated knowledge: the main questions here are how to increase and improve the uptake of knowledge inside the company (from senior to junior and vice-versa; cross-specialism (e.g. from electrical to mechanical. From design departments to maintenance department) balancing between innovation, risk management, lack of time and workforce.

The availability of structured and easy-to-follow courses on HVAC and energy systems for buildings at higher education level could help to motivate (future) engineers to contribute to the HVAC sector, and to understand how challenging and high-tech it is. Such a course program would ideally also bring a basic understanding of the field to architects and building engineers, in such a way that a better common ground is created for collaboration and integrated design. It would also be useful to Machine Learning and AI experts joining the HVAC sector. Last but not least, it could help bridging the gap between engineering and policy making, by here too, offering common views on primary energy, resource depletion and CO_2 emissions relating to HVAC systems.

This paper describes the contents of an online program of four courses, and the choices that were made in terms of structure and premise (section 2) and learning objectives and contents of each of the four courses (section 3-6), In section 7 we finally reflect briefly on the experience with the first run.

Structure of the course

Target Groups

Three target groups were defined, based on the challenges described in Section 1:

1. Starting professionals with a technical background like mechanical engineering, architecture industrial design or electrical engineering who want or need to get acquainted with indoor climate systems, including sustainable energy systems.

2. Traditional HVAC engineers used to piping and sizing calculations of conventional systems who want to broaden their view towards sustainable and renewable systems.

3. Technology-minded policy makers who want to be introduced to the basics of energy usage in buildings.

To match the target groups, it was decided that the level of Maths and Physics should be kept limited to high school level in natural/economics sciences.

Overall structure of the course program

An analysis of the knowledge needed to understand and make basic designs of sustainable, renewable-based and low carbon-emission indoor climates and energy systems was conducted, based on multiple discussions and collaborations between the university and companies working in the field of indoor climate, energy and

HVAC design. To the authors' opinion, the premise can be categorized as follows:

1. Because of the importance of energy use in new regulations, conventional maximum load calculation is not sufficient anymore and should be complemented by energy usage estimation on yearly basis. So, a part of the course program should address this.

2. If in the past it was sufficient to know how to size a boiler, multiple options for sustainable energy conversion are present nowadays, and often need to be combined. So a part of the course should address these possibilities and make sure learners do not focus on the one specific solution they know, but are aware of all others and can make an informed choice, accounting for primary energy use and CO_2-emissions.

3. In comparison to industrial applications of energy, applications in buildings strongly relate to indoor health and comfort, which is a point acknowledged very well by professionals, but completely overlooked by engineers/students from other disciplines, although the COVID-19 pandemic may have changed this a bit. So, health and comfort should certainly have a place in the curriculum.

4. Modern HVAC design should include and integrate the three perspectives above. With regards to the target group, the focus should not be on detailed engineering but rather on the principles leading to efficient design of HVAC systems.

The proposed course structure is therefore as described in **Figure 1**. The courses Energy demand, Energy Supply Systems and Health & Comfort can be followed independently and in a random order. However, the dotted lines in the graphic indicate that some basic principles like conservation of energy and the related energy balances are explained in Energy Demand, but not in Energy Supply Systems. The course Health & Comfort makes use of a few concepts explained in

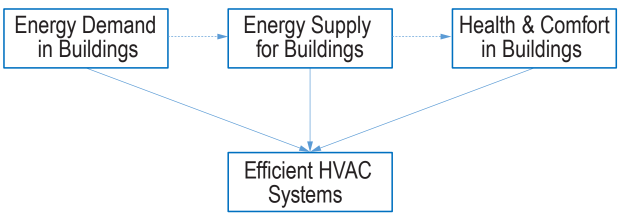

Figure 1. Structure of the course program Buildings as Sustainable Energy Systems.

the precedent courses (like insulation or emissions by burning fuels) and introduces some HVAC systems already. So, depending on the level of the learner, it can be better to follow them in the order.

The fourth course integrates the 3 domains and build up on them, introducing specific HVAC-related knowledge.

In sections 3 to 6 each of these courses is explained in terms of leaning objectives, learning contents and activities.

Cognitive Levels & Constructive Alignment

The effectiveness of teaching is known (e.g. [3]) to depend strongly on the appropriate correspondence between learning activities and the desired cognitive level, which is called constructive alignment. As for the cognitive levels, we used the ones from the widely applied Bloom's taxonomy [4], as represented in **Figure 2**.

The course is an organized mix of the 5 highest level. Lectures and simple quizzes provide understanding and direct application of the knowledge. More elaborated quizzes vary in level from 'applying' to 'evaluating'. Finally, a 'creating' level was introduced in the course 'Energy Demand' in which the students have to create an own design, reviewed by their peers.

Specific for online courses Salmon introduced an additional 5 stage scale [6] stating that knowledge construction by a learner is only one of the phases of learning. In addition to this 4th stage, much attention must be put to: motivating students through efficient access, welcoming and encouraging (stage 1); Online socialization (stage 2); Information exchange like facilitating tasks and supporting the use of learning materials (stage 3); and finally facilitating further development (e.g. links to external sites, stage 5).

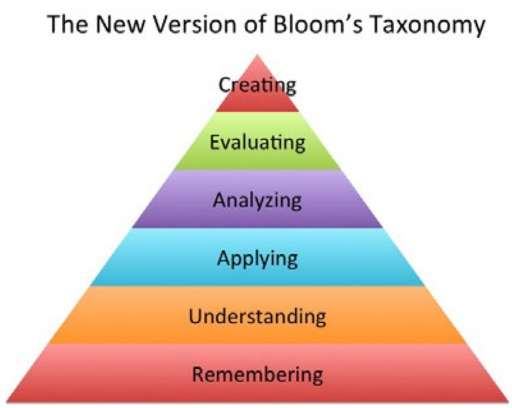

Figure 2. Cognitive levels in Bloom's taxonomy. [5]

In the development of the program stages 1 and 2 are offered by discussion groups moderated from Edx and TU Delft and by putting much attention to the introductions of each week, explanations and activation of the learners by asking about their expectations or sharing their experience in their own countries. In this paper we address only stages 2 and 3, which relate to the contents. In the first version of the course stage 5 was somehow neglected due to time constraints.

Each course consists of 4 to 5 weeks of lessons, organized thematically. Each week consists of 6 to 8 lectures of 10-15 minutes, coupled to many exercises in the form of quizzes to help the learners to understand and apply their knowledge. Much attention was put to make the course suitable for all types of climates over the world and to build understanding of the specific challenges in warm, cold, moderate, dry or humid climates. The course can be used for both new buildings and renovation projects. Learners are expected to study 6-7 hours a week.

Energy Demand in Buildings

The main objective of this course is to discover how building design and occupancy determine the energy demand in buildings and to learn how to (re)design buildings with a low energy demand. This course relates therefore to building design. It is based on the extension of the approach proposed in [7].

Learning Objectives and Subjects

As building design strongly influences the quantity of heating, cooling and electricity needed during building operation, a correct thermal design is essential to achieve low energy and low carbon buildings, with good indoor air quality.

The first objective of the course is to enable learners to understand the basic principles of the energy chain: demand, supply and distribution; and how they relate to design principles for sustainable and energy-efficient buildings. This is handled in week 1, in which the following subjects are addressed:

1. The importance of energy use in Buildings (e.g. climate, resources, comfort), relation with EPBD and with other sectors
2. The energy chain: from demand to supply
3. Design strategies (e.g 3-steps strategy; Reduce; Renewable; Efficiency)
4. Energy Efficient Building concepts (e.g. passive, (N)ZEB)
5. The basics of indoor comfort

The second objective is to discover what type of heat losses and gains take place in buildings and to learn how to estimate these heat flows using simple meteorological data and building materials properties. This way, steady-state heat transfer by transmission, ventilation, solar radiation or caused by internal sources are estimated.

This is combined with the third learning objective which is to learn to make estimates of space heating and cooling loads on an hourly basis by using simple static energy balances. Week 2 therefore includes the following:

1. Principle and components of the energy balance in buildings
2. Heat transfer by transmission
3. Heat transfer by ventilation and infiltration
4. Solar gains
5. Internal Heat gains
6. Guided example heating & cooling loads

The fourth objective is to discover and apply diverse methods how to extend load estimates to yearly energy demand, which is essential to make sure that a building is energy efficient and to estimate energy savings and energy costs. The following subjects are handled in week 3:

1. The difference between energy use and loads (kWh and kW)
2. Nominal loads and size of heating and cooling equipment
3. Annual energy demand for space heating and cooling (full load hours, degree days and hourly simulations over a year)
4. Annual energy demand and loads for hot tap water
5. Annual energy demand for electricity (appliances and lighting)
6. Introduction to hourly based steady-state annual energy simulation with Excel

The fifth and final objective is to learn how to optimize building's thermal design and to determine (for instance) the optimal window size or the optimum insulation thickness, and more generally to understand and be able to make simple calculations on thermal interactions between building components and to make informed decisions on how to increase the energy efficiency of new and existing buildings. The setup of this week is different as the students have to actively use the excel simulation sheet to come to insights and answers. They had to do this using both a climate year in a moderate climate (de Bilt in the Netherlands) and in a hot climate (Mumbai, India). Sample answers were given after each exercise for both climates. The case study was a large office building, the geometry and thermal characteristics of which were given.

1. Determine cooling, heating & electricity demands and loads
2. Effect of varying occupancy and various ventilation systems (including passive cooling)
3. Effect of diverse levels of facade/roof/floor insulation
4. Effect of type, size, orientation of windows and solar blinds
5. Combine all knowledge to design a low energy building in NL and Mumbai.

Finally, a final video recaps what students have learned and put much attention to the *limitations* of the approach (e.g. steady state modelling, neglecting thermal bridges) and what they still could learn in other courses.

Example of Self-Assessment after a Lecture

As the course is self-paced, and therefore teachers are not available to correct exercises, self-assessment is essential. If self-assessment using quizzes may seem too simple or boring, they also can be made exciting if they are correctly designed, accounting on beforehand for most types of misunderstandings learners can come through. They should include guidance about these faults.

In the following example, a picture of a mineral wool package (**Figure 3**) is shown to the students and they have to choose the right answer from 5 possibilities. They cannot find the right answer without making the complete calculation, so they are forced to exercise. Alternatively, they can try all answers and learn from the feedback and hints included after choosing any of the answers.

Figure 3. Picture of a mineral wool packaging for a quiz.

Question: 'You see on the picture a label of mineral wool (λ=0.035 W/mK; thickness = 120 mm, α_i = 7.5 W/m²K, α_o=25 W/m²K), What is the R_c value [m²K/W] of this mineral wool? **Possible answers**: a) 0.29; b) 3.43; c) 3.60; d) 0.28; e) 3429

If learners choose for b (which is the right answer), they are congratulated and also see the right calculation procedure. If they choose a wrong answer, they get a hint, e.g. if they have answered a) or d): 'you are probably confused between U and R_c ($U = 1/R_c$)'; Or, if they have answered c): 'You have added to the resistance the α_i and α_o heat transfer coefficients, but that is not the definition of R_c'.; Or, if they answered e): 'you have forgotten to convert the mm into meters'.

Energy Supply Systems

The main objective of this second course is to discover how to convert natural resources into heat, cold and electricity, what the capabilities of renewable systems are, how to simply match energy supply with buildings' energy demand (the preceding course), and what that means for energy efficiency and carbon emissions. The working principles of the diverse systems are explained without going too much into the details of all components, with as less as possible formulas, except when it comes to efficiencies and CO_2-emissions. Here too, the course is (partly based on the approach proposed in [7].

Learning Objectives and Subjects

The first step is to consider how to convert natural resources into the energy needed by buildings: what are the options to create heat, cold and electricity? Students will also learn about efficiency and use this concept to estimate building's primary energy use and carbon emissions. These methods are widely used in many national and international policies and building regulations, and are essential to counteract climate change.

The second objective of the course is to understand the performances of *single heating systems* like electrical heating, gas, or renewables like biomass, solar boilers and geothermal heat, followed by *single cooling systems* like evaporative cooling and environmental cold. For each of these systems, working principles, efficiencies, primary energy and resources used are studied as well as CO_2-emissions. An additional lecture on heat exchangers was added, as many students appeared not to be familiar with it. Although gas is a fossil fuel, it has been included in the course as a reference, and because many countries consider gas as a transition fuel.

A third objective is to understand systems that *concurrently produce heat and cold* (heat pumps & chillers; Aquifer Thermal Storage systems). These three objectives are divided over the two first weeks of the course. Electrical and fuel burning boilers are handled in the first week, as easy-to-understand illustration of efficiency and carbon emissions.

Week 1:
1. Recap on energy demand (energy vs power, principle of energy balance)
2. Overview of supply systems for heating (resistance, fuel burning, heat pumps, waste heat, geothermal, solar), cooling (chillers, evaporative, geothermal cold) and electricity
3. Efficiency of systems and Primary Energy
4. CO_2 and CO_2-eq emissions, calculation principles
5. Electrical Resistance Heating and grid efficiency
6. Fuel burning in boilers
7. Guided boiler example with annual primary energy, resources used, CO_2-emissions, investments costs and energy costs

Week 2
1. Heat Exchangers
2. Heat pumps and chillers: working principle
3. (Seasonal) Efficiency of heat pumps((S)COP)
4. Geothermal Systems
5. Chillers and their efficiency ((S)EER)
6. Evaporative cooling and Environmental cold
7. Guided example on a reversible heat pump (same setup as in week 1)

The objective of the third week is to understand *electricity generation* methods using turbines (fuel-burning and nuclear based, wind, hydro), photovoltaics and hydrogen fuel cells. It is often left out from courses on buildings' energy use. It is however essential to fully understand primary energy use and CO_2-emissions of buildings, and their relation to the electrical grid. This week is also meant to learn how *cogeneration of heat and power* works and relates to smart heating and cooling grids, and why this is important for the rational use of energy resources.

1. Combustion based electricity generation (generator with (combined) gas turbine, steam turbine (including nuclear))
2. Waste heat, cogeneration and rational use of energy
3. Electricity from geothermal heat, hydropower and wind
4. Hydrogen Technology and smart grids

Finally, the last two objectives of the course, handled in week 4, are to understand *solar systems*, and to apply the knowledge gained during the course to *design efficient building concepts* in order to match buildings' energy demand while keeping costs acceptable, using a minimum of natural resources and producing a minimum of carbon emissions. Week 4 is shorter than others to allow time for the final assessment for certified learners.

1. Solar heat
2. Solar electric (photovoltaic)
3. Guided example NZEB and energy positive buildings.

Health & Comfort in Buildings

The main objectives of this course are to raise awareness about the determinants and importance of a healthy indoor environment and to enable the learners to apply the basics of thermal comfort and indoor health theories when designing buildings and their energy systems. People spend more than 80% of their time in buildings. Therefore, a good thermal comfort and quality of the indoor environment are essential for their wellbeing, health and productivity. Part of the course is based on [8, 9,10].

Prior to the first week, learners were invited-if they wanted to, to fill in an anonymous survey about their health and comfort at home. This survey is described in [11] and is repeatedly used to collect new data. Next to activate the students, it is also useful for research purposes.

The objective of week 1 is to understand what is Indoor Environmental Quality (IEQ), what are its parameters and how it impacts health. After IEQ has been defined, two aspects of it, lighting and acoustical qualities are handled briefly. In Bloom's taxonomy we are working here at the level of remembering and understanding. As the focus of the course program is on thermal energy systems, we have chosen to address these 2 aspects only lightly in order to put the focus on indoor air quality and thermal comfort, who are both affected greatly by thermal systems (including ventilation).

1. Why is environmental quality important (links with diseases and disorders)?
2. What is environmental quality (lighting, acoustical, thermal and air qualities)?
3. Lighting Quality: relation with health
4. Lighting quality: parameters of light indoors
5. Acoustical quality: relation with health
6. Acoustical quality: parameters of sound indoors

The second week of the course is devoted to thermal comfort with the objectives to familiarize the learners with the two main theories currently in use and to apply them to assess simple building designs.

1. Thermal quality and homeostasis (link with energy balance of human body and the 6 thermal comfort parameters, consequently handled in the following lectures)
2. Metabolism and Clothing
3. Air Temperature and Velocity; comfort diagrams
4. Relative Air Humidity, simple definition and comfort diagrams
5. Mean Radiant Temperature, definition, relation with insulation and comfort diagrams
6. Fanger's Comfort Model (PMV and PPD)
7. Local Discomfort
8. Adaptive Comfort Model

The third week is entirely devoted to indoor air quality (IAQ), with the objective of the learners becoming aware of all parameters of IAQ and being aware of efficient control strategies in the design of ventilation systems. A special lecture was devoted to the COVID pandemic and aerosols.

1. Reception of air and Health Effects
2. Parameters of Indoor Air (particles; gaseous pollutant and humidity)
3. Pollutants and Sources: Particles (sizes; biological and chemical; health effects)
4. Pollutants and Sources: Gaseous pollutants (inorganic; VOCs; health effects)
5. SARS Cov-2 (particle; droplets and aerosols)
6. Control strategies (low emitting materials; filtering of air and cleaning of ventilation systems; appropriate ventilation strategies)

To close this third week, the general results of the home survey like held in week 1 are discussed.

The objective of the last week of the course is that the students learn to apply their knowledge on the design of healthy buildings and to assess and analyse practices in building design and HVAC systems. All concepts learned before are translated to engineering aspects. In this sense week 4 is also an introduction to HVAC systems. The subjects handled are the following:

1. What is a healthy building? (Summary of preceding weeks, with much attention to control possibilities, which are worked out in next lectures)
2. Introduction to healthy HVAC systems (basic description of air handling units, needs for filtering, clean components and piping and avoid recirculation)
3. Clean components for ventilation systems (characteristics of filters, humidifiers, heat exchangers and location air supply)
4. Healthy air supply (clean ducts, noise prevention, draught in supply grilles)
5. Façade & Ventilation: design of ventilation openings, acoustical and thermal insulation of openings, façade heat recovery, outdoor air quality, double skin facades.
6. Window design: thermal and lighting qualities and control in cold and warm climates, outside view
7. Energy efficient artificial lighting control (needed light levels, electricity use of diverse types of lighting, configurations and zoning)
8. Room heaters and coolers: energy efficiency and comfort (air-based & water-based heaters and coolers, their temperatures and relation to mean radiant temperature, noise and draught and to energy use)

Efficient HVAC systems

All three previous courses are integrated into this last one, with as main learning objective to apply the knowledge in HVAC design practices at the level of basic and preliminary designs. In the design of the course, we aimed at linking with more conventional HVAC design courses –generally focused on air handling units (AHU) and to complete the understanding of learners with essential subjects that were not covered before, like dealing with humidification and de-humidification. The course is based for a part on [10], [12], [13].

The first week of the course is therefore a recap of all three previous courses, presenting the essentials of energy demand, energy supply and health & comfort, to which an additional lecture on the basics of heat exchangers was added.

The second week handles humid air, humidification and dehumidification processes and processes in air handling units. The students should be able to describe related processes and to make simple calculations of energy use and humidity contents. They learn to do so using either Mollier diagrams, psychrometrics charts or equations, to fit with habits in their own country. Learners can test their knowledge about equations if they want, but the attention is put to the use of diagrams and charts, as it fits better with the lower mathematical background of many students. Week 2 is organized as follows:

1. Introduction to properties of humid air
2. Psychrometric charts and humidity
3. Dew point: condensation, cooling & de-humidification processes
4. Enthalpy of humid air; Heating and cooling processes
5. Wet bulb temperature and humidification processes
6. Handling of humid air: summary of the possible processes.

The third week has been designed to familiarize the students with the diverse types of air, heat and cold distribution systems in buildings. We know from previous courses that knowledge is very local and it may be difficult for students to realize that there are diverse options. For instance, learners from hot climates are not aware of water-based heat distribution systems, while learners from cold climates may not realize the problems water-based cold distribution systems would cause. In each presentation calculation examples are given and systems are visualized. The contents of week 3 are:

1. Overview of possibilities to transport hygienic air, heat and cold and their possible interactions; Advantages and disadvantages; Duct sizes)
2. Air handling units: the theoretical processes described in week 1 are applied n AHUs
3. Transport of air in ducts (location of supply, velocity & noise, sizing and efficient routing of ducts)
4. Pressure drop in ducts and fan energy
5. Transport of heat by water systems: hydronic heating (location of generation system; design of hydronic networks; sizing of convective/radiant emitters)
6. High and low temperature heating (advantages and disadvantages in relation to comfort, energy use and use of renewable sources)
7. Hydronic cooling (location of generation system; design of hydronic networks; options and sizing of emitters, low and high temperature cooling; dew point control)

In week 4, the students are familiarized with the basic principles of sizing and controlling simple systems. In view of the target audience, we've deliberately avoided to go into the details of control engineering (which is still handled in the last lecture), but rather focus on designs enabling control.

1. Enabling control (sizing, zoning, readjusting, combining, buffering)
2. Design for control: zoned HVAC systems (zoning of distribution ducts for flexibility in use and maximum efficiency; Introduction to Process and instrumentation diagrams (P&IDs)
3. Readjustments systems at room level (mixed air/water systems; central and decentral control; graphical review of possible configurations, for instance like in shown in **Figure 4**)
4. Load duration curves and generator combinations; relation to investment costs and energy use
5. Buffers for peak shaving, renewable energy and match between supply and demand; Design of buffers
6. HVAC operation control: basics of control (sensors, actuators, controllers) and application to temperature, pressure, flowrate and humidity control, using P&IDs.

The last week of the course handles design and control of integrated systems for Net Zero Energy Buildings. It starts with a lecture about the design process itself, before digging into the aspects of technical design. This includes 2 subjects on specific designs for moderate and cold climates, 2 subjects specific to hot climates, and stresses finally the importance of aquifer thermal storage systems (ATES).

1. Design process for efficient HVAC systems (aims, collaboration with other experts, process from program of requirement to maintenance, commissioning)
2. Efficient control of conditioned air from AHUS (CAV & VAV; energy efficient setpoint temperature control; flow patterns in rooms)
3. Efficient buildings and HVAC systems for moderate and cold climates (reduced heating demand; high quality ventilation, emitters, generators; solar electricity; NZEB)

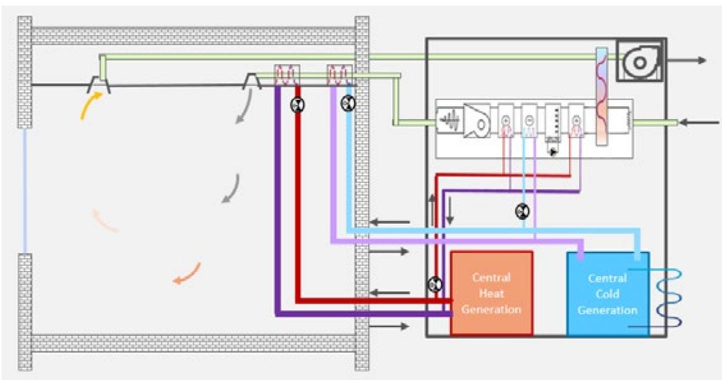

Figure 4. A configuration for central & decentral control.

4. Heat sources for heat pumps (ground, solar, (ventilation) air, working modes and control, collective systems)
5. Efficient buildings and HVAC systems for hot climates (reduced cooling demand, ventilation strategies, generators; solar electricity; NZEB)
6. Heat sinks for chillers and environmental cold (air, water, ground, collective systems; absorption systems)
7. ATES systems for heating and cooling (working modes explained in words and P&IDs)

Reflections

The first run of the complete program took place between September 2020 and November 2021. The four courses were offered in the same order as described in the paper. More than 5000 learners subscribed to each of them and 8-10% of them were following it on an active way, which is quite standard on the edX platform. Course 4 (Efficient HVAC systems) ended in the shortlist of 100 most popular online courses 2021 (out of 2900) [14], indicating a wide and worldwide interest for sustainable HVAC systems.

Although the detailed analysis of the students reviews still has to be done, it can be noted that the courses were highly rated with grades between 8 and 9, except for course 2, what was rated a little bit lower. About half of the students were junior HVAC professionals, many of them from India and US. It is not completely clear yet in how far policy makers have followed and/or appreciated the course.

In general, the technical/theoretical level of course 1 (Energy demand) was found to be right, while the level of course 2 (Energy supply) was too high (mainly because of mismatch with background on heat transfer and heat exchangers). Course 2 was also less well-balanced between the levels of explanations on diverse technologies (e.g. too less solar in comparison to heat pumps). The last of week of course 1 (the only one at 'create' level, see **Figure 1**) was appreciated a lot. Leaners found it 'fun'.

The first lecture in course 4 (design process and stakeholders) was highly appreciated and students asked for similar lectures in the other courses, as this helps to place the activities of the course in their context. Finally, it was noted that there is very little literature or handbooks addressing the subject of design for control (e.g. zoning, readjustment, multiple generators) on a structured way. This is also true for reading and understanding P&IDs. ■

Acknowledgements

We thank Delft Extension School, and in particular Bertien Broekhans, Eloïse Ruby and Rins Lindeman for their support and help with financing, organizing and moderating the program. The development of this professional course program was partly founded by Climate-Kic City Retrofit Ecosystem Build Benelux and Delft University of technology.

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REHVA Annual Meeting 2023

Thursday 11 May, the REHVA standing committees met in Brussels to discuss the activities of the organisation during the year 2022 and to prepare the strategy for the upcoming year. Our industry is constantly changing and evolving toward a greener future and REHVA aspires to be a leader in this movement.

The Publishing and Marketing Committee (PMC) addressed topics around the guidebook sales and the future publication planned by the Technical and Research Committee (TRC). The goal is to assess that we disseminate knowledge is the best way possible so that it can reach all our members and beyond. The point of translation was also put forward, as a European organisation, we must ensure that the content is accessible to the greater number, and that means also non-English speakers. Francesca d'Ambrosio (Italy) was re-elected as chair and Lada Hensen Centnerová (Netherlands) was re-elected as co-chair.

REHVA's TRC elected two new co-chairs, Tomasz Cholewa from Poland and Alireza Afshari from Denmark, who joined the re-elected chair, Jarek Kurnitski and co-chair Ilinca Nastase. The Activity Plan for 2023 was approved with promising outcomes in the active and newly approved Task Forces. The TRC aims to tackle topics related to EPBD revision and RePowerEU, by preparing technical guidance for EPBD implementation and decarbonisation of building stock by phasing out fossil fuels. In the pursue of improving health, comfort, safety and energy efficiency in the built environment, work will continue in TC 156 WG25 revising EN 16798-1:2019 standard, aiming to include infection risk-based ventilation design. Also, in relation to and through occupant targeted ventilation TF and developing effective air distribution related guidance. These topics are supported by air quality control/IEQ requirements included in EPBD revision.

During the Education and Training Committee (ETC), Livio Mazzarella (Italy) was elected as chair, Tiberiu Catalina (Romania) was re-elected as co-chair and Uwe Schulz (Switzerland) was elected as co-chair. The members discussed the need to create challenges to increase skills and knowledge. They also approached the idea to achieve this goal by developing further the already existing REHVA Knowledge Hub and working on new REHVA courses.

The Supporters Committee was skilfully moderated by Kemal Bayraktar (Turkey). The primary objective of the meeting was to elect co-chair Laura Bothar and share important announcements from the supporters. Four notable supporter events were presented, including the ISK-Sodex exhibition in Istanbul, the KGH 54th International Congress at the Belgrade Fair from December 6th to 8th, the Swedvac-RoomVent conference scheduled for April 2024 in Stockholm, and the CLIMA 2025, co-organised with AiCARR conference set to take place from June 4th to 6th, 2025.

Overall, the Committees decided that there is a need for greater communication within REHVA and decided that each Committee should have at least one co-chair from another Committee. As a result, Kemal Bayraktar (Chair of the Supporters Committee) was elected as co-chair of the PMC, alongside Jarek Kurnitski (Chair of the TRC).

The day ended with a special dinner organised at the Royal Library of Belgium. This was the opportunity for the REHVA Family to come together to celebrate the organisation's 60th birthday and recognize the achievement of some of our members.

Milos Lain (STP, Czech Republic) received the Professional Awards for design.

Francesca d'Ambrosio (AiCARR, Italy) received the Professional Award for science.

Iñaki Morcillo Irastorza (ATECYR, Spain) received the Professional Award for Technology.

REHVA proudly recognized the support of two esteemed supporters by presenting them with an award to express our deep appreciation for their continuous dedication. Marc Thuillard from BELIMO and Nerissa Deoraj from SYSTEMAIR travelled to Brussels to receive the REHVA Supporters Award. We extend our sincere gratitude to them and to all the REHVA Supporters who have played an integral role in our mission.

Marc Thuillard from BELIMO.

Nerissa Deoraj from SYSTEMAIR.

The night ended with REHVA President Catalin Lungu cutting REHVA birthday cake!

On Friday 12 May, the members gathered for the Plenary Meeting and the General Assembly.

The 67th REHVA General Assembly took place in Brussels, Belgium on the 12 May 2023. This year more than 60 participants from 22 countries attended the meeting. The agenda of the General Assembly was focused on the general overview of REHVA activities in 2022 and on the key points of REHVA's 2023 activities.

The most relevant outcome of the General Assembly has been the election of a new board member, who will start his mandate in 2023 till 2026: Risto Kosonen (FINVAC, Finland), while the second candidate who sent in his application will be the reserve board member, Jarek Kurnitski (EKVY, Estonia).

The members talked also about the issue of the suspension of SITHOK's membership because of the non-payment of their due since some years. They unanimously decided to suspend SITHOK (Slovenia) and to reconsider during a future General Assembly when they are financially able to pay their membership fees.

Four important announcements were made during the meeting:

- The REHVA Brussels Summit will take place in Brussels, Belgium 13-14 November 2023
- The REHVA Annual Meeting 2024 will take place in Istanbul, Turkey hosted by TTMD. The dates are still to be determined.
- RoomVent 2024, will take place in Stockholm, Sweden from the 23th to the 26th of April 2024
- The REHVA Annual Meeting and the 15th REHVA World Congress CLIMA 2025 will take place in Milan, Italy from the 4th of June till the 6th of June 2025 and will be preceded by the 2025 REHVA Annual Meeting.

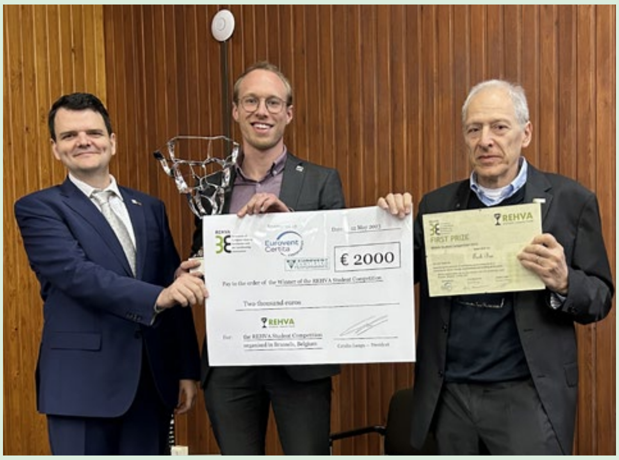
Cătălin Lungu, the 18th REHVA President closed the 67th REHVA General Assembly.

Thank you to all the members of the REHVA Family who came to work and celebrate with us! REHVA could not be a successful organisation without each and every one of you. A big thank you as well to all the members and supporters who could not come during those 2 days, see you next time! ■

REHVA Student Competition 2023

The REHVA Student Competition, held annually, took place in Brussels during REHVA's Annual Meeting on Thursday, May 11. This event brought together 11 students from various parts of Europe who gathered in Brussels to showcase their research projects before a distinguished panel of jury members.

One outstanding participant, Bas Turk from the Netherlands, presented his work titled "Quantifying the potential of overheating countermeasures on a humanitarian shelter through measurements and building performance simulation."



The winner of the REHVA Student Competition, Bas Turk will represent Europe at the HVAC World Student competition.

Lewis Turner secured second place for his paper on "Efficacy of Air Purification to Control Infection in NHS Hospitals," while Miguel Rodríguez Fernández came third with his study on an "Indirect Evaporative Heat Exchanger Prototype Manufactured with 3D Printing." Aurore Toulou won the "best poster" category.

As the winner of the REHVA Student Competition, Bas Turk will now proudly represent Europe at the HVAC World Student competition, an achievement that reflects his dedication and expertise. We extend our heartfelt congratulations to Bas Turk for his remarkable accomplishment, as well as to all the other students who enthusiastically participated in the competition.

During the REHVA Gala dinner (12 May), all the participating students were provided with a unique opportunity to engage with esteemed members and supporters of REHVA, fostering valuable networking connections within the industry. This gathering allowed them to interact and exchange ideas with professionals who are at the forefront of the HVAC field.

Furthermore, the students were privileged to visit the renowned Atomium, an iconic architectural landmark in Brussels. This excursion offered them a chance to appreciate the rich history and innovative design that the Atomium represents. ■

REHVA Community of Young Professionals visiting the Atomium.

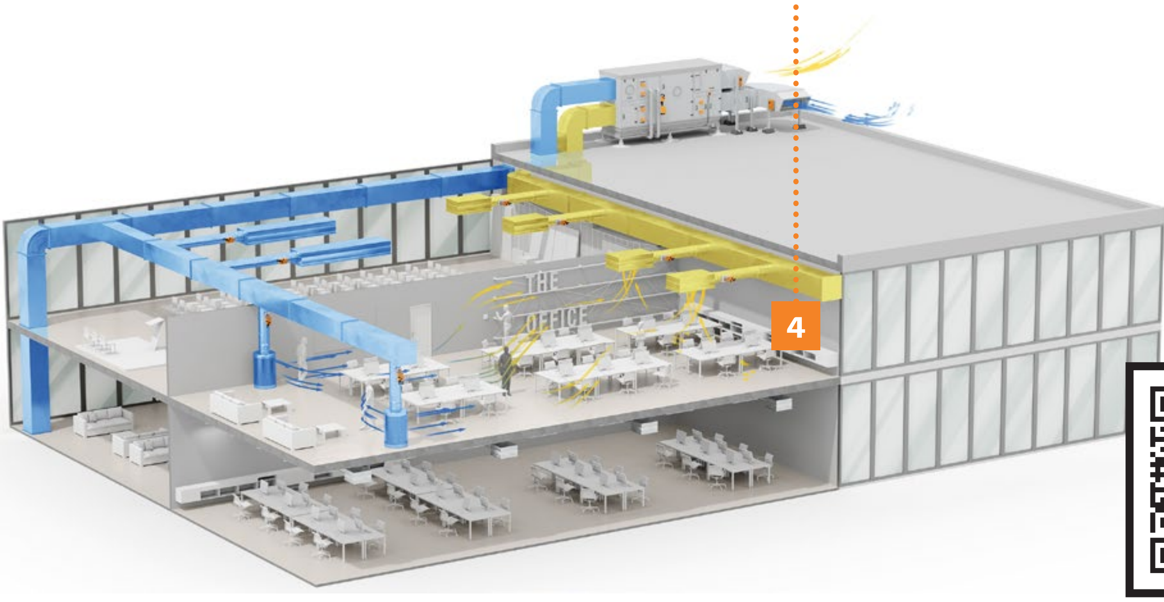
Acknowledgements to Eurovent Certita Certification

We would also like to express our sincere gratitude to our esteemed sponsor, Eurovent Certita Certification, whose generous support made this event possible, once again. Their commitment to fostering talent and promoting excellence in the industry is invaluable.

The Seven Essentials of Healthy Indoor Air

4. Active pressurization of envelope and spaces

Air hygiene in a room is negatively affected by unwanted air currents entering a zone from outside (e.g. a busy road) or from other rooms (e.g. a cafeteria). This typically occurs when air pressure ratios are not properly balanced. There has been much discussion about "cross-contamination" between different rooms in connection with the spread of COVID-19 aerosols inside buildings. The use of VAV controllers in the supply air and extraction of air from a room, as well as the use of differential pressure sensors and controllers between zones, can prevent such undesired airflow.



Learn more about Belimo's 7 essentials of healthy indoor air:
https://www.belimo.com/ch/en_GB/indoor-air-quality/7-essentials-iaq

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20-22 June 2023	European Sustainable Energy Week (EUSEW) 2023 (sustainable-energy-week.ec.europa.eu)	Brussels, Belgium
24–28 June 2023	2023 ASHRAE Annual Conference (ashrae.org)	Tampa, FL, USA
July 2023		
25-27 July 2023	HVACR Vietnam (hvacrvietnam.com)	Hanoi, Vietnam
August 2023		
14–16 August 2023	SuDBE 2023 (sudbeconference.com)	Espoo, Finland
September 2023		
28–30 September 2023	EFS 2023 (efs2023.uc.pt)	Prague, Czech Republic
October 2023		
4–5 October 2023	43rd AIVC – 11th TightVent & 9th venticool Conference: Ventilation, IEQ and health in sustainable buildings (aivc2023conference.org)	Aalborg University, Copenhagen, Denmark
25–27 October 2023	Decarbonization Conference for the Built Environment (ashrae.org)	Washington D.C., USA
March 2024		
12–15 March 2024	MCE 2024 (mcexpocomfort.it)	Milan, Italy

Due to the COVID-19 circumstances, the dates of events might change. Please follow the event's official website.

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