Resource efficiency and circularity in engineering higher education

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Abstract: Changing engineering student's knowledge, skills and attitudes about resource efficiency, regenerative design and circularity in the built environment is a serious challenge. The development of engineering students' capabilities to design within a circular economy paradigm in higher education can foster sustainable behaviour and contribute to the global sustainable development global agenda. This chapter presents the experience of introducing the concept of regenerative design within a project oriented design studio for undergraduates. The regenerative design objective and principles are used a method to develop engineers capabilities to design within a circular economy paradigm. The aim of the study is to evaluate the adoption of circular economy principles and their influence on the decision making and final outcomes. A state of the art provides an over view on the similar approaches to incorporate sustainability into university courses and curricula with a focus out case study to make a step forward. The chapter describes a thorough evaluation of the course and report the outcomes in the form of projects evaluation and students' feedback, interviews and surveys, in order to assess the students' knowledge uptake, learned skills and design capabilities. Students completed a knowledge, skills, and attitudes questionnaire before the curriculum, after the final learning experience, and one year later. This chapter provides insights into the effectiveness of introducing circularity in an engineering course. Based on the lessons learned from our case study we provide a discussion on the main challenges such as complexity, decision making uncertainty and interdisciplinarity, institutional reforms in engineering higher education. Finally, the chapter presents a range of tangible and realistic recommendations to better incorporate resource efficiency and circularity in engineering higher education.

Keywords: sustainable development, regenerative design, project-based approach, students, interdisciplinary, lessons learned

1 Introduction

The radical changes necessary for our planet require a vision that is rooted within an ecological paradigm. The tendency of urban sprawl and resource intensive built environment during the last decennia is contradicting with the need for positive impact development and the principles of sustainability. The urban sprawl is not only consuming large areas of resources and soil but is associated with negative environmental impacts, social and cultural disparities beside the overall decreasing incremental environmental cost.

Today's problems require more complex, dynamic and sustainable solutions. Resource efficiency and circular economy are new paradigms that will influence both the ease of acceptance by and the direction in which circularity and regenerative design will change our society. Leaders and policymakers face requirements to simultaneously meet multiple needs and manage complex problems. In this context, Universities are expected to prepare students to work on the topic of resource efficiency and circularity and get engaged to address this new paradigm from a professional and academic interdisciplinary approach. According to Nandan and London (2013), social change initiatives are best approached from an interdisciplinary approach that is more holistic. In literature, there are several studies that identified the skills and competencies required to address complex problems including critical thinking, collaboration, communication, leadership, motivation, analytical thinking, group work and adaptive competence.

Moreover, interdisciplinary teams are found in the professional work and operate among heterogeneous groups of professionals and not in academia. Interdisciplinary work includes a different set of values, codes of conduct, and ways of learning. On the other side, traditional engineering higher education is based on deep specialization and reductionist approaches within tightly bounded disciplinary silos (ABET 2017). The specialization creates social and cognitive boundaries reducing collaboration and innovation (Nandan and London 2013). Therefore, graduates do not learn and develop skills required for being socialized into interdisciplinary work, which is essential for addressing resource efficiency and circular economy.

To counteract these silos and face these challenges the architectural design studio of the third year architectural engineering students at Liege University in Belgium, is playing a central role for challenging its students to generate building that are resource efficient and circular. Within the Faculty of Engineering (Applied Sciences) the students are challenged to apply the principles of regenerative design for a collective housing project. The key question of the studio is: How can architects construct buildings with positive impact on the environment while addressing habitat, materials, energy, water and biodiversity.

In this context, the chapter intends to assess the students' learning experience using qualitative and quantitative evaluation methods. In order to clarify the discussion on how to introduce resource efficiency and circular economy into engineering curriculum and in order to provide suggestions for implementation, this study aims to:

- Contribute to conceptualizing 'resource efficiency and circular economy' in academic education

- Suggest a range of actions that could contribute to the integration of circularity and sustainability in academic education

The importance of this study is significantly highlighted in the studio's ability to achieve an informed decision making process regarding regenerative design and circularly in the built environment. Secondary, the study provided a reflection on the assessment of learning outcomes, expected knowledge, skills, attitudes, competencies and habits that student acquired during the studio's learning process. With its focus on the design experience and knowledge uptake this article will be of interest to engineers, architects, educators and researchers concerned with engineering education of sustainable development (EESD). The chapter determines the needs for interdisciplinary approaches, pedagogical and educational engagement to ascertain and quantify the effort needed to understand and apply the circular economy principles in future curricula.

This chapter is organized into five sections. The first section identifies the research topic. The second describes similar studios and courses that have been presented in literature aiming to describe the state of the art. The third section identifies the research methods and studio evaluation metrics and setting. The analysis of the results and the self-reported survey and questionnaires findings are presented in Section 4. The final section discusses the research finding and study limitations along with implications for future teaching and education.

2 Resource efficiency and circularity in engineering higher education

Resource efficiency and circularity in engineering higher education is a growing field of research and practice. This section describes the resource efficiency and circularity and sets a frame of definition to make it easier for the reader to understand and recognize those terms. Setting definitions qualifies to develop sub concepts and translate them into a common understanding. Also we will explore and review scientific literature and examine the approaches that introduced sustainability in the engineering curricula.

2.1 Definitions

Resource efficiency and regenerative design forms an essential basis for circularity in the built environment. The increasing population growth and ecological destruction requires increasing the ecological carrying capacity beyond pre-industrial conditions. Regenerative design seeks positive impact development that incorporates maximizing the viability of harnessing renewable resources and become independent from depleting and polluting resources. In order, to achieve positive building footprint we must move from the cradle to grave paradigm that aims to reduce, avoid, minimize or prevent the use of fossil energy to a regenerative paradigm that aims to increase, support, and optimize the use of renewable (Lyle, 1996a). As shown in Figure 1, the previous efficiency strategies have been operating within a carbon negative or neutral approach that will never reach a positive and beneficial building footprint. Even the existing net balance approach assumes a fundamental dependence on fossil fuels. Therefore, we define the positive impact of the built environment from a renewable self-efficiency paradigm.

Figure 1: Paradigm shift towards a beneficial, circular and positive impact footprint of the built environment.

Regenerative design in the built environment seeks the highest efficiency in the management of combined resources and maximum generation of renewable resources. It seeks positive development to increase the carrying capacity to reverse ecological footprint. The building's resource management emphasizes the viability of harnessing renewable resources and allows energy exchange and micro generation within urban boundaries (Attia & De Herde, 2011). Over the past years, regenerative positive development paradigm has been garnering increasing influence on the evolution of architecture. The progress is dramatic: plus energy plus, earth buildings, healthy buildings, positive impact buildings. This new way of thinking entails the integration of natural and human living systems to create and sustain greater health for both accompanied technological progress (Attia 2016a and 2017a).

2.2 Past research

There is an extensive body of literature examining the effects of introducing sustainability in the engineering curricula on the students' knowledge and skills and final learning outcomes. Higher education institutions have always been actors of change and innovation in the society (Huge et al. 2016, Kohtala, C. 2015, Peer et al. 2013). The research on sustainability in academia has found a solid ground in publications, campuses and curricula all over the world (Lidgren et al. 2006). Higher education institution act as models in the society and have a critical role in creating a future that is sustainable.

In this context, we reviewed the key references drawn from a wide range of relevant journal and conferences. The international conference on Engineering Education in Sustainable Development (EESD) proceedings include several examples of integrating sustainable principles, resource efficiency and circularity as a framework for a redesign of engineering education and of engineering education institutions. Also the International Journal of Sustainability in Higher Education, the Journal of Cleaner Production, the Journal of Perspectives: Policy and Practice in Higher Education and the Journal of Architectural Education provide a series of valuable publications related to introducing sustainability into engineering curricula. Also, we looked in the local Belgian context by reviewing the outcomes of the Doctoral Seminar on Sustainability Research in the Built Environment (DS2BE 2017). Three screening criteria were used to reduce the initial pool of 60 conference and journal articles to a focused set of representative studies: (a) review articles; (b) empirical studies (c) studies with an educational assessment or intervention with learner outcomes measured quantitatively or quantitatively; and (c) research that focus on architectural and engineering curricula due to the specific nature of our architectural engineering students.

Under the review articles we grouped the manuscripts under two groups. The first group is focused on integrating sustainability into engineering curriculum and second group is focused on integrating sustainability into architectural engineering curriculum. The first group of manuscripts include the study of Davidson et al. (2014) that discussed some efforts taken place in the United States, namely the activities of the Centre for Sustainable Engineering operated by a consortium of universities. The paper describes an initiative to develop a community oriented platform to serve as a repository for educational materials. Similarly McPherson et al. (2015) compared engineering programs in Canada and review and analysed the sustainability integration in curricula but with a focus on sustainable energy. The undergraduate programs reviewed by the authors were classified as conventional engineering programs with a sustainability add-on courses and did not embed sustainability fully in the curricula. Likewise, the study of Vargas, L. et al (2015) reported embedding sustainability in the curriculum of engineering school but only for the University of Chile.

The second group of manuscripts has an architectural focus including the work of Álvarez et al. (2016) who compared the presence of sustainability in architectural education is Asia with a focus on professional degree curricula. The study provided an overview of 20 selected influential schools in 11 countries according to contents, intensity and teaching modalities. Sustainability design studios received a special attention by the study and were examined against the three sustainability areas of ecology, society and economy. The study provided qualitative and compared the curricula without describing their sustainability thematic content in detail. Similar to this study is the study of Olweny (2013) who investigated the presence of environmental sustainable design and energy efficiency in architecture education in East Africa and the work of Trebilcock (2011) in Chile. His study highlighted the basic integration of sustainability with at least one course in the studies curricula and the need for more integration efforts. Moreover, Wright (2003) provided a brief review on introducing sustainability into the architecture curriculum in the United States. The paper is out-dated and focused on the integration of sustainability in architectural programs. However, the publication of Iulo et al. (2013) provided an interesting overview of six architecture programs in the United States considered to be leaders in sustainability education. The study findings highlighted consistent approaches to promote sustainability core values to undergraduate architectural education by supporting courses fulfil needs for sustainable education and encourage students' choice and specialization to sustainable design.

The most important manuscripts in this group are the COTE and EDUCATE reports. The Committee on the Environment (COTE), which serves as the community and voice on behalf of AIA architects regarding sustainable design works, together with the Association for the Advancement of Sustainability in Higher Education (AASHE) provides a more recent assessment of the state of ecological literacy and the teaching of sustainable design in architecture education as part of a proposal for a large-scale, long-term effort, led by the AIA COTE, to inject ecological literacy and sustainability principles into architecture education in the United States. The COTE mapped the strengths and gaps in teaching methodologies and identified top ten measures of a definition of sustainable design that are developed as a framework for different types of courses and studios. COTE reported that at many architecture schools, the mentor model is still firmly in place; students are "filled up" by the knowledge of a professor. The report (AIA 2007) indicate the use of other teaching modalities involving multidisciplinary, participatory, iterative, designing for place, designing across time and involving students to become more involved in framing the questions, shaping courses, and interacting with practitioners and in the community. Also a similar project took place in Europe in 2009, where Altamonte (2009) investigated environmental design in University Curricula and Architectural training in Europe. The European review identified mainly the status quo of integrating unsustainability across most European member states and encouraged the holistic approach to architecture education.

3 Methods

After reviewing the scientific literature regarding circularity and sustainability in engineering curricula and the built environment, the research was conducted through five phases as shown below:

1. Curriculum design
2. Assessment of students' knowledge, skills, and attitudes
3. Assessment of students' self-reported behaviours
4. Jury Evaluation
5. Curriculum Evaluation

The study methodology is partially inspired by the work of Madigosky et al. 2006, who investigated the changing knowledge, skills and attitudes of medical students regarding patient safety and medical fallibility. The sections below describe the different methods used to create and assess a case study with 50 students.

3.1 Curriculum design

The first three year Bachelor curriculum of architectural engineers of the Faculty of Applied Sciences of Liege University are built around project-based learning cases but also include basic science lectures and an introduction to engineering courses. The Bachelor Program curriculum focuses on developing students' architectural design skills, increasing their understanding of architecture and construction and introducing technical issues. The program is divided into 6 blocks over three years and covers architectural design methodology I-III, sustainable building construction technology I-III, History of Architecture, Graphical Composition, Architectural Studio I-III, Chemistry I-II, Calculus, Algebra, Physics I-II, English, History of Urban Planning, Computer programing, Fluid Mechanics, Building Materials, Solid Mechanics, Geology, Heat transfer, Structural Design, Project management, Structural Engineering, Metallic Structures, Statistics and probability, Thermodynamics and heat engines, Geotechnics and infrastructure (Architectural Engineering 2016).

We identified opportunity for introducing regenerative design and principles of circular economy in the Architectural Studio III. The Architectural Studio III was chosen because of the maturation of the students and the need to develop and crystalize the fundamental knowledge and skills through an integrated project. The existing curriculum was based on introducing a design project of middle sized housing in the third year and we found that it could be linked with a new content. The studio's curricular goals and learning objectives focus on analysing issues specific for the transformation of a European post-industrial city from a perspective of circularity. The studio focused on developing third year students' knowledge, skills, and attitudes relevant to regenerative design and circularity of the built environment. Several references guided our development of the studio curriculum. A body of literature informed students about the (Lyle, J. 1996, Rifkin, J. 2008, McDonough, et al. 2010, McDonough, W. et al. 2013, Mulhall et al. 2010 and Attia et al. 2013a). We implemented and taught the curriculum, which was approximately 4 ECTS equivalent to 120 hours in the fall of 2014, 2015 and 2016. The curriculum was taught by the author and teaching assistant, with the assistance of volunteer jury members and guests for the site visits, debate, jury and small discussion groups.

The studio content addressed seven main themes listed and described in Table 1 (Attia 2015 and 2016b). The activities in this design studio were a synergy between sustainability and regenerative design theory and their integration in an architectural design project. This approach allowed us to address issues of conceptual coherence, spatial and expressive design while exploring simultaneously the possibilities for sustainability as an essential element for the design; which will become an important and essential task in the field of architecture (Guy et al. 2001). The studio focused in particular on studying the interaction between questions of density, mixed functions, quality of life in buildings, while in the meantime integrating the principles of bioclimatic architecture. This included the development of construction details in accordance with a basic understanding of sustainable buildings concerning energy, water and materials. The project design case was based on a study of solutions adapted on the development of a collective housing of mixed density. They are successively developed in a throughout the different scales from the urban form, the clustering of buildings, the building itself and its envelope and materials.

Table 1: Regenerative Design and Circularity in the built environment curricular content and educational modality by theme, Liege University, Faculty of Applied Sciences, 2014-2016.

Theme	Content	Educational Modality
Theory and Principles	Sustainable architecture and regenerative design	Lectures
	Bioclimatic design and Passive House Standard	Lectures
	Human well-being and quality of life	Lectures
	Construction systems and materials	Lectures
	Energy conservation and production	Lectures
	Water Management + Biodiversity and air quality	Lectures
Philosophy	Cradle to cradle: Remaking the way we make things	Reading
Case Studies	Wijk van Morgen (Heerlen), Park 2020 (Amsterdam)	Site Visit
Reasoning	1. How far to go with technology? Low-Tech vs. High-Tech	Debate
	2. Prefabrication or self-construction?	+
	3. To certify or not to certify sustainable buildings?	Role Playing
Application	Concept development follow up (weekly)	Table Critiques
Assessment	Evaluating the design and project dynamics	Pre-Jury
	Provide individual Feedback	Panel Discussion
	Support and motivation for creation and design development	
Evaluation	Evaluating the design and project dynamics	Jury

Provide individual Feedback	Panel Discussion

Four key concepts and principles should be addressed in any design according to the studio guidelines (Attia 2016b and 2017b) and should be implemented on the system level, element level and product level for each building (see Figure 2).

1. Design for Circularity
2. Design for Disassembly and Recovery
3. Design for Quality and Health
4. Design for Value Chain Collaboration

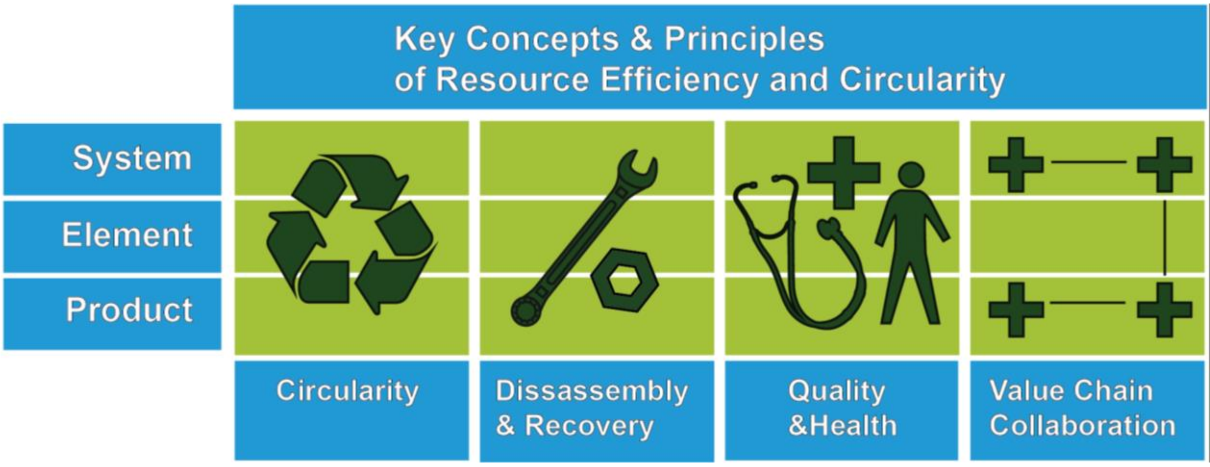

Figure 2, Circularity and regenerative design key concepts and principles for the built environment

In the same time, students had to address the requirements mentioned below. Students had to come up with architectural objects and spatial solutions that embed the project design principles of circularity and regenerative design. Integrating the architectural and building elements in the project layout and mass requires architectural intelligence and technical rigor. Every student has to select the most important elements that can create a beneficial impact for their project and size them. The challenge lies in the engineering sizing of every elements and spatial architectural integration. The design principles listed below are based on the literature review conducted earlier in relation to resource efficiency, circularity and regenerative buildings (Attia 2011, 2016a and 2017):

Energy Saving (Resource Efficiency): Energy efficiency and bioclimatic design plays an important role in this project. The compliance with the Belgian Passive House Standard requirement is essential to guarantee the minimum energy consumption and maximum thermal comfort (Feist et al. 2007). A building that complies with the Passive House Standard should not exceed 15kWh/m^2 annually for heating needs and should have an airtight envelope that does not exceed 0.6 air change per hour under an air pressure of 50 Pascal. Overheating should not exceed 25 °C for 5 % of the building operation hours. To guarantee the high efficiency of the proposed designs each student had to verify that walls have a conductivity between U ≤ 0.1-0.15 W/(m²K) and conductivity of U ≤ 0.1 W/(m²K) roofs and external horizontal surfaces. Based on the insulation material the sizing of the envelope thickness should be done and reflected in the project drawings. Special attention to facades and windows design is important. Passive solar gains should be maximized for south facades. A rule of thumb of Passive House Standard recommends the orientation of large window area to the south while not exceeding 30% of all wall areas. Shading solutions should be provided to avoid overheating. For the North, East and West façade it is recommended to not exceed 20 % window to wall ratio or provide a double skin while addressing solar protection. The value of windows conductivity should fall ≤ 0.85 W/(m²K) and solar factor or solar heat gain coefficient should be g > 0.5. For this project, a double flow mechanical ventilation system is required. Supply and return air ducts must be integrated in the building shaft. Technical service room(s) should be integrated in plans and sections including the heat recovery unit, heat exchanger, heating equipment's and fuel storage. It is encouraged to use free cooling earth cooling tubes. Building thermal nodes should be designed to comply with the Passive House Standard requirements (Feist et al. 2007).

Energy Production: A regenerative building has to produce more energy that it consumes. Every student should estimate the energy consumption of the collective apartments. At least, more than 30% of the total annual consumed energy has to be generated onsite. The choice of the renewable technologies (photovoltaics, solar thermal collectors, geothermal pipes or other systems), their sizing and spatial integration in the project has to be achieved by every student. The area of photovoltaic panels, their orientation and positioning has to be taken into account and represented in the project drawings, schemes and models. The integration of the panels architecturally in the building roofs and facades or technically with the HVAC system should be considered based on rules of thumbs and basic calculation. The installation of solar water collectors for domestic hot water can be based on local approved rules of thumbs. For example, a 4 person household will require a 4 square meter of solar thermal panels. Thus every student should achieve a positive energy balance and validate his choices and estimations for his/her project.

Water Usage: A regenerative building should allow the separation of different water streams and benefit locally from rain water. An optimal beneficial positive impact building would be off-grid and treat its sewage on site using helofytenfilters (a type of reed field or water filtering bioswale). A helofytenfilter would clean sewage water and grey water, will resist heat stress and provide a green landscape that can increase biodiversity. It is not obligatory to include a helofytenfilter system in this project, but every student has to explore the beneficial water elements. Also every student has to integrate a rainwater cistern that can store water at least two months water independence. The sizing and spatial integration of the in the project has to be achieved by every student. The separation of different water loops for potable water, rainwater, greywater and black water has to be reflected architecturally in the building roofs or underground schemes and technically in the building raisers and greenery systems using rules of thumbs and basic calculations.

Air Cleaning and Heat Island Effect Reduction: Air cleaning can mainly be achieved through green areas. Using green walls, green roofs or rooftop garden can provide a lung that can produce clean air for humans and the city. Clean air increase biodiversity and productivity of buildings users. Natural ventilation and air circulation should be coupled to air cleaning. Integrating such elements in the project design is essential and requires careful detailing and technical validation for issues such as roots invasion, artificial irrigation, weight and impact on carrying structure, water storage and overflow issues, erosion, solar access and orientation, plant selection and diversity and insulation.

Healthy Humans: Humans are in the centre of regenerative design. Providing high quality indoor and outdoor spaces for individual and collective usage can bring live hood and satisfaction to users. The design of naturally lit and ventilated atriums, common spaces, gardens, staircases stimulates people's encounter and activity. Introducing vegetation indoors provides a pleasant living environment and provides a good indoor environmental quality (humidity, oxygen, and acoustic). Each project should adapt these elements and integrate them to provide a high quality architectural experience.

Sustainable and Regenerative Materials Selection: The use of regenerative materials whether from the technical or biological sphere should be achieved without losing their quality. In this project Cradle to Cradle (C2C) certified materials or other eco certified products. Special consideration should be taken for fire safety, acoustic insulation, embodied energy beside the thermal, structural and mechanical performance of materials. Biosphere materials such as clay, wood, straw, hemp are encouraged as well as technosphere materials such as concrete, aluminium and steel. As long as those material products are C2C certified that avoid the use of toxic substances or include an environmental product declaration it will be easy to know the environmental effect of each material. Technosphere materials should come in a second priority for essential building elements such as foundations, windows, mechanical installations or for structural safety including lateral resistance or fire safety.

Biodiversity and Sustainable Urbanisation: Enhancing sustainable urbanisation through biodiversity and nature-based solutions can improve the environment; make cities more healthy, and enhancing human well-being. Introducing green areas within and around a project site and consciously enforced the ecosystem resilience and enable plants and species to deliver vital ecosystem services can enable robust ecosystem in the built environment. Biodiversity plays a key role in climate change adaptation and outdoor air quality improvement beside other risk reduction solutions in the area of storm water management. The growing awareness of the value of nature and the importance of introducing it in the city through green areas, trees, green roofs and water drainage solutions make it important for designers to connect their projects to the urban green network and provide spaces for celebrating biodiversity. We learn from literature that biophilia, which is the innately emotional affiliation of human beings to other living organisms, can improve the health of humans and therefore, we look to integrate nature based solutions in the built environment (Keller et al. 1995). Nature based solutions include water sensitive urban design, green streets, urban food, urban forest, integrated water cycle management, living green walls, and green roofs and should be manifested through landscape design .

3.2 Assessment of students' knowledge, skills, and attitudes

We developed a 30-item questionnaire to evaluate the impact of sustainability of the curriculum on architectural students' knowledge, skills, and attitudes. Item development was informed by our literature review. The questionnaire included items modified from existing questionnaires assessing i) the knowledge concerning regenerative design, ii) the decision-making attitude and behaviour (reactions to design uncertainties), the jury evaluation, as well as items based on our curricular learning objectives. We selected items for the questionnaire based on the like hood that they would demonstrate change after students participated in our studio. Five multiple-choice items assessed students' knowledge, five items measured their comfort with skills (using a five-point ordinal scale where 1 = very uncomfortable and 5 = very comfortable), and 30 items measures attitudes (using a five-point ordinal scale of agreement with statement where 1 = strongly disagree and 5 = strongly agree).

Based on our experience from a previous research (Attia 2013b) we pilot tested the questionnaire for comprehensibility with second-year architectural engineering students and for applicability with one Master student with prior involvement with regenerative design. We deleted two attitude items from the analysis because the item wording in French was inconsistent across questionnaire administrations. For each student, we calculated a composite knowledge score as the number of correct knowledge items out of correct knowledge items out of five. For the composite knowledge score and the remaining 28 items, we calculated a 95% confidence interval for paired differences to assess changes between students' pre-test and post-test as well as their pre-test and one-year post-test. We also analysed the paired differences between the post-test; however, because these data did not change our conclusions, the results are no included here.

3.3 Assessment of students' self-reported behaviours

On the one-year post-test, we also asked students to report their behaviours since completing the curriculum. Students responded 'yes' or 'no' to items about whether they used what they learned in the curriculum, design errors, and disclosure and reporting experiences. We calculated the percentage of students responding 'yes' to each item.

3.4 Jury Evaluation

Three project juries, in 2014, 2015 and 2016, were held by experts and invited speakers to the studio and were attended by the entire class. The evaluation was based on assessing each student's project global vision and detailed project solutions. The goal of the jury was not to propose a project that meets actual practice and market conditions but to generate a series of concepts as an exercise to exchange creative and innovative ideas and learn about different energy efficiency and circularity solutions for buildings. For each jury a panel of international and national experts was assembled representing the Cradle to Cradle experts at TU-Delft or Brussels University in additions to the technical director of the Passive House Platform in Belgium (Wallonia) and local resources and materials experts.

3.5 Curriculum Evaluation

We developed studio evaluations to measure students' reactions to the curriculum. Student used five-point ordinal scale to rate how well the curriculum met learning objectives, its usefulness in their medical education, its future benefit to their architectural career, and if it should be continued. We also invited students to describe the most important thing they gained from the curriculum and to offer suggestions for improvement.

4 Case Study Results

In order to assess students' knowledge, skills, and attitudes, 50 students answered the questionnaires before and after the studio. Our analysis of paired comparisons of pre-test to post-test was based on these responses. No students indicated that they had had prior experiences with regenerative design or circularity in the built environment. These results can be divided into three categories: students' responses with improvement, those without change, and those with change in an undesired direction.

4.1 Responses with improvement

Table 2 presents the pre-test means, mean paired differences, and confidence intervals for items with improvement both immediately after students participated in the curriculum (pre-test to post-test). Students' responses to one attitude item addressing the inevitability of regenerative paradigm, another about the effectiveness of this approach to create a positive impact versus the efficiency paradigm, and a third reflecting perceptions about competence and design errors improved immediately after attending the studio. These improvements were sustained after the studio. Four skills items also improved immediately after students took the curriculum: supporting a peer involved in a design error, analysing root causes of a error, accurately estimating the energy loads and production, and disclosing an disclosing an error to a faculty or teaching assistant. Although not improving immediately, students' responses to one attitude item about architects routinely sharing information about errors and their causes improved at one year. Students' responses to an additional attitude item on the effectiveness of design errors, as well as the composite knowledge score, improved immediately following the curriculum, but these changes were not sustained at one year.

Table 2: Questionnaire items with Improvement from a Study of the Effects of a Regenerative Design Architectural Studio Curriculum on Third-Year Architectural Engineering Students' Knowledge, Skills, Attitudes, Liege University, Faculty of Applied Sciences, 2014-2016.

Item	Mean Change (95% CI)		
	Pre-Test mean response	Post-Test mean response	Post-Test after Two-Years
Attitude Questions*			
Making errors in design is inevitable	68.75	31.25	21.5
After an error occurs, an effective design strategy is to work harder to be more careful	62.5	65	61
Competent architects do not design errors that lead to quality decrease	6.25	25.5	22.1
Architects routinely share information about design errors and what caused them	12.5	56.2	53
Design assessment types (weekly meeting with professor, debate, jury) do little to reduce future errors	16.25	3.0	4
Skills Questions**			
Supporting and advising peer who must decide how to respond to a design error	18.5	72	66
Analyzing a design to find the cause of a error	50	48	45
Defend the design successfully in a design assessment	31	56	33
Disclosing a design error to a professor	81.25	12.50	8.5
Knowledge Items			
Knowledge uptake score	37.5	74.5	61

* Scale: 1 strongly disagree, 2 = disagree 3 = neutral, 4 = agree, 5 = strongly agree

** Scale: 1 very uncomfortable, 2 = uncomfortable, 3 = neutral, 4 = comfortable, 5 very comfortable

4.2 Responses without change

Table 3 presents the pre-test means, mean paired differences, and confidence intervals for students' responses that did not change in either of the two comparison intervals. These items – six attitudinal and one skill – reflect that architectural students already believed that a gap exists between regenerative design and actual design practice, that architects and engineers can affect the sources of design errors, and that it takes more than just architects to determine the causes of an engineering error. However, students do not believe architects routinely discuss design errors, and they do not feel strongly that regenerative design and circularity of the built environment is a high priority at our Faculty. The mean student responses were neutral with regard to whether or not architects should tolerate uncertainty of design decision making process regarding regenerative design and in their comfort with errors disclosure to faculty.

Table 3: Questionnaire items without Change, from a Study of the Effects of a Regenerative Design Architectural Studio Curriculum on Third-Year Architectural Engineering Students' Knowledge, Skills, Attitudes, Liege University, Faculty of Applied Sciences, 2014-2016.

Item	Mean Change (95% CI)		
	Pre-Test mean response	Pre-Test to Post-Test	Pre-Test to Two-Year Post-Test
Attitude Questions*			
There is a gap between what we know about regenerative design and we design regularly in other studios	3.92	-0.15	-0.27
Most design errors are due to things that architects can't do anything about	2.57	-0.11	-0.16
Only architects can determine the causes of a design error	1.34	-0.09	-0.11
Architects routinely share information about design errors	2.86	-0.21	-0.23
In my design and learning experience so far, professors communicate to me that regenerative design is a high priority	1.95	-0.13	-0.09
Architects should not tolerate uncertainty in regenerative design	2.31	-0.08	-0.16
Skills Questions**			
Disclosing a design mistake to a professor	2.75	0.38	0.31

* Scale: 1 strongly disagree, 2 = disagree 3 = neutral, 4 = agree, 5 = strongly agree

** Scale: 1 very uncomfortable, 2 = uncomfortable, 3 = neutral, 4 = comfortable, 5 very comfortable

4.3 Responses with change in an undesired direction

Table 4 presents the pre-test means, mean paired differences, and confidence intervals for items where students' responses changed, but in an undesired direction. Immediately after the curriculum and at one year, students agreed less that there was value in spending professional time improving design and disagree less that the culture of architectural design makes it easy to deal constructively with design errors. At one year, students agreed less that spending time in architectural school learning how to improve regenerative design was an appropriate use of time, were less likely to be open about design errors they witnessed, and were more likely to believe, that no design errors did not require disclosure.

4.4 Assessment of self-reported behaviours

A substantial proportion of students completing the questionnaire at one year answered 'Yes' to whether they had certain behaviours in the year following curriculum completion. 28 (77%) students reported having used what they learned in the curriculum and 32 (88%) reported observing a design mistake. Of these 32 students, 8 (32%) had disclosed a design mistake to fellow student, and 16 (50%) had disclosed a design mistake to a faculty member.

4.5 Jury Evaluation

Three project juries, in 2014, 2015 and 2016, were held by experts and invited speakers to the studio and were attended by the entire class. The evaluation was based on assessing each student's project global vision and detailed project solutions. Since the studio is adopting a student centred education through a project-based approach, the jury had to assess the possibilities of multiple solutions for the building design problem. The jury revealed the importance to define design projects that are stronger linked to the real world with real stakeholders. The jury evaluation is not the only evaluation here because the learning level of the students varies significantly and not all students are aware about sustainability science including regenerative design and circularity in the built environment. Therefore, the studio instructors provide also an additional evaluating on the effort made by students, and how they receive the teaching feedback and support and motivation to evolve and improve their design all over the whole project design process.

4.6 Curriculum Evaluation

At the completion of the curriculum, 31 (86%) of students agreed that the studio content improved their ability to meet the learning objectives either well or very well. Eighty-five percent, on average, agreed strongly that the curriculum and learning modalities were useful in their architectural education. Ninety-two percent, on average, agreed or strongly agreed that the curriculum would be of benefit to their future career, and on average 78% recommended that the curriculum be continued for future architectural school classes. Topic mentioned as the most important thing students gained from the curriculum were an understanding that everyone makes design errors, how to address those errors at the root cause, and the mistake reporting and disclosure are important. Suggested improvements included changes in the timing of the curriculum, shorter sessions, less lecture and more personal follow up sessions, and feedback more guidance on communication issues.

Table 4: Questionnaire items with Change in an Undesired Direction, from a Study of the Effects of a Regenerative Design Architectural Studio Curriculum on Third-Year Architectural Engineering Students' Knowledge, Skills, Attitudes, Liege University, Faculty of Applied Sciences, 2014-2016.

Item	Mean Change (95% CI)		
	Pre-Test mean response	Pre-Test to Post-Test	Pre-Test to Two-Year Post-Test
Attitude Questions*			
Students should routinely spend part of their study time to improve their design.	4.21	-0.29	-0.25
The culture of architectural studios makes it easy for students to deal constructively with design errors	1.68	0.25	0.36
Learning how to integrate regenerative design in the project is an appropriate use of time in architectural school	3.21	-0.11	-0.18
If I saw a design mistake, I would keep it to myself	1.82	0.12	0.19
If there is no harm from a design mistake, there is no need to address the mistake.	1.85	0.23	0.31

* Scale: 1 strongly disagree, 2 = disagree 3 = neutral, 4 = agree, 5 = strongly agree

5 Discussion

Higher education institutions have a responsibility to lead societal changes and promote innovations. The call or resource efficiency and circularity y became essential that academic faculty members, researchers and students can create a sustainable future. A multitude of international declarations have been produced in an effort to stimulate the transition and change to face the ecological and economic crisis. After performing our case study at Liege University we present in this section the results of our study. All members of the engineering academic world, including architectural engineers, should be able to recognize the importance of applying the regenerative design, resource efficiency and circularity concepts in concept in their curricula. Students should be able to systematically apply those concepts and principles in a project oriented format with a thorough understanding of students problem solving and creativity skills. Our results demonstrate regenerative design and circularity in the built environment curriculum was well received and led to some changes in third-year architectural engineering students 'knowledge, skills, and attitudes. However, not all of these changes were for the better, nor were all of the positive changes sustained after the design studio or supported by students' self-reported behaviours on the long term.

We believe there are several sets of factors that contributed to these results. The first is the curriculum itself, including the course content, instructors' effectiveness, educational modalities, timing and integration topics within the overall curriculum, planned redundancy, and evaluation methods. The second comes from other formal or informal learning experiences within the pre-architectural and architecture study years, including hidden curriculum. The third set of factors includes the study design, questionnaires, and evaluation tools used. We discuss each of these three areas below.

5.1 Curriculum characteristics

Our analysis identified aspects of the curriculum that worked well for our third-year architectural engineering students. We believe that presenting the studio content at Bloom's (1956) taxonomy of higher order thinking skills (understand, apply, analyse, evaluate, create) and the interactive nature of the learning modalities contributed to the improved responses after students participated in the curriculum and after two years. For example, the most improvement was seen in items addressed by interactive sessions, such as the debate and the weekly follow up corrections, where students applied knowledge and practiced skills. Conversely, students' improved mastering of content delivered solely by lecture, such as design principles and guidelines reported in the body of literature, but this knowledge was not sustained at two years. These results and the curriculum evaluation suggest that application-focused learning and case-based interactive or narrative sessions may achieve more lasting impact of students' knowledge, skills, and attitudes, as well as improved student satisfaction with the curriculum. In addition, when we covered topics multiple times using several educational modalities during the curriculum, as in the inevitability of design errors, students' learning was sustained.

On the other hand, several topics let to no change in students' knowledge, skills, and attitudes. For many of these topics, students were already familiar with the concepts that were taught, such as the quality gap between ideal regenerative design philosophy and actual application limitations and it takes more than architects to determine the causes of design errors. Students' prior experiences and baseline knowledge may eliminate the need to cover this material in a curriculum. Alternatively, this lack of change in students' responses might indicate that curricular timing and integration should be improved for these topics. For example, the curriculum did not convince students that regenerative design and circularity in the built environment is a priority at Liege University. This may be due to a lack of clear messages and planned redundancy with the curriculum about our institutional focus on circularity, sustainable development and regenerative design.

Based on these results, when we presented the curriculum to the next class of third-year architectural engineering student in 2015 and 2016, we decreased the amount of time spent on introductory material, substituted a required reading for a background lecture, and focused more on the interactive, application-based aspects of the curriculum, including the time allotted for students to apply the project requirements in the project design.

5.2 Other learning experiences

Calling to mind the effects of the informal and hidden curricula, our study shows that students' responses to the two items describing secrecy about architectural design errors weakened after one year of architectural practice. Additionally, responses to two items on the value of learning about improving design quality during the study period and working to improve design quality as part of their professional life.

Surprisingly, students appreciated the site visits that took place during the studio more than the theory courses. Students visited a series of projects over the three consecutive studio study years 2014-2016. The illustrated project in Figure 3, represent building with exemplary sustainable performance. Each of those building was documented through walkthrough visits, interviews with architects and table critique. Students reported the value of learning from those values and appreciated the concrete representation of the circularity into physical buildings.

Figure 3, a) Passive House Standard Collective Housing, Marcinelle, Belgium, b) Wijk Van Morgen, regenerative building, Heerlen, The Netherlands, c) Business Park 2020, Cradle to Cradle Certified, Amsterdam, The Netherlands, and d) Strowijk Project or Straw Bale Social Housing Project, Nijmegen, the Netherlands.

5.3 *Study design, questionnaire, and evaluation tools*

Limitations in our study design, questionnaire, and evaluation methods also may have blunted the effects of our curriculum on student's learning. A stronger study design would have included a control group of Liege University students or students from similar institutions. However, we thought strongly that all Liege University students should be exposed to this content and thus integrated it into the core curriculum. As this was a novel curriculum and likely to be adapted further, we did not seek to implement it at another institution during this phase of the study. Although the response rate was adequate at each time period, our core analysis focused only on those students who completed the questionnaire at all three administrations. The survey instrument was new and therefore limited by its lack of formal validation and reliability testing. Some attitude items were confusing in that they required the students to respond in a way that reflected both what we taught (i.e., in general architects do not report errors routinely) and what we demonstrated to contrary. Ultimately, our study is limited by reliance on students' self-reporting their comfort with skills and behaviours, rather than our using observational methods to determine their actual performance or measuring patient-related outcomes with respect to regenerative design and circularity on the built environment. In addition, students completed the curricular evaluation after the last session, thereby requiring them to recall sessions presented several weeks.

5.4 Lessons Learned to integrate Circularity in Engineering Higher Education

The paradigm of resource efficiency and circularity and the key design concepts and principles of regenerative design were used as a strategy to guide the decision making of architectural engineers during a full semester project oriented design studio in 2014, 2015 and 2016.

- Complexity and wicked nature of problems
- Uncertainty of circularity science
- Inter and trans disciplinarity
- Institutional reform

The complexity of regenerative design forced students to manage available knowledge and generate knowledge adapted to their project context and multiple objective criteria of sustainability. The debate on the topic of circularity and regenerative design during the studio pushed the students to take a standpoint to defend their understanding and conviction. All students succeeded to integrate renewable energy systems in their design, conserve energy, use healthy and regenerative materials, collect and mange water and create healthy and positive impact buildings with daylight and high air quality. The complexity of applying the paradigm of resource efficiency and circularity and its principals in engineering and architectural practice requires rethinking how to educate engineers. Regenerative design and circularity lie across many disciplines and interacts with various scale levels (Huges et al. 2016).In the same time, the science for circularity is still unstructured and not mature. Students needed to define the building material elements with limited available resources (e.g. case studies, products). There was a difficulty to apply and examine the regenerative design principles in practice. Therefore, there is still work to do to share and amplify practices, principles, and breakthroughs to tackle the wicked nature of design problems.

Also, resource efficiency and circularity involve a large choice of technical and social parameters and is embedded in sustainability science as well as ethical aspects. Even expert knowledge provided through the studio learning material or invited speakers is incomplete, fragmented plural and uncertain. Despite the site visits, student complained from the complexity and lack of agreement on materials sustainability and the deep uncertainties related to life cycle assessment. Also discussions on social life cycle assessment and social concerns took place during the debate and to take care of social considerations closely for societal stakeholders and work with them (Ryu et. Al 2006). Uncertainty of decision making associated the whole design process and students could not find always answers to their questions on how to build with a positive impact. Identifying circular materials, their origin and positive impact in relation to the construction system and the ability to disassemble the building is an uncertain process in the architectural engineering and construction industry. There are no building circularity indicators that guide the decision making process so far. Moreover, the debate generated very interesting questions related to materials volumes. Since a building is a combination of elements. Volume will dominate the circularity result as a normalization factor and will lead to select less materials volumes. However, the characteristics of high performance buildings indicate to highly insulated building with high amounts of insulation materials volumes. The conflict between using more materials for energy conservation and fewer materials for resource consumption reduction is a concrete example on the delicate intellectual uncertainty associated with resource efficiency, circularity and regenerative design.

On the level of academia, engineering educations is trapped in silos and we need to deconstruct those silos. Faculty and students need to have the courage to move out of their comfort zones (Attia 2016c). In the same time, educators need to create safe spaces for interdisciplinary learning and send to students the message that what they do outside their discipline is valuable to the community and outside the campus. Faculty needs to be convinced too on the importance of transdisciplinary. Interdisciplinarity is essential and critical we should move with engineering education towards transdisciplinarity following the medical education. This requires effort, time and an infrastructure to prepare educators and allow them to work with educators from different disciplines. This is the only way to prepare students for a wide spectrum of skills (Murray et, al.2007).

Another key challenge that emerged from our case study was the importance of considering social challenges besides technical challenges, the studio addressed resource efficiency and circularity from a technical approach. The multidisciplinary facets of circularity require academia to reform engineering education and bring professional together to solve societal problems in an interdisciplinary approach. We are looking to prepare T-shaped professionals who can address the circularity problems as specialists in their own disciplinary area but also have an overview on the overall circularity and positive development agenda. We need to raise the awareness on the ecological crisis we are living in and that the engineering field is responsible socially and ethically to address those problems. We need an integrative learning environment that allows engineering educators to find way to allow for greater interdisciplinary in the curriculum to allow comprehensive and interactive problem solving approaches (Brody et al 2006). The outcomes of the case study are in line with the previously published work of Siller et al. 2016 and Trulsson et al. 2016.

Finally, we believe that there is an opportunity to achieve resource efficiency and circularity within a strategy of institutional change and rethinking the role of engineering higher education within the societal and environmental context. Therefore, re-educating engineers should address complexity interdisciplinarity and uncertainties related to regenerative design and circularity.

6 Conclusions

We designed an innovative regenerative design and circularity in the built environment curriculum for third-year students at the at the University of Liege and studied the effects of the curriculum on architectural students' knowledge, skills, and attitudes after their participation in the curriculum and at one year, gathered data on student-reported behaviours regarding use of the curriculum and exposure to and disclosure or errors, and measured students' evaluation of the curriculum.

Our results show that the circularity paradigm can affect the knowledge, comfort with skills, and attitudes of undergraduates engineering students to develop sustainable ideas, solutions and projects. Within several different domains, students demonstrated improvement that was sustained two years later. However, some improvement was not sustained and some changes were not consistent with the learning objectives. Student-reported behaviours at the two-year timeframe demonstrated that although students recognize architectural design errors, the number of students who disclose errors to faculty members is far than those disclosing errors to their peers. In addition, the regenerative design and circularity in the built environment curriculum was well received by students. Students perceived it to be useful, beneficial for their careers, and recommended it for future architecture engineering students. However, resource efficiency and circularity should be achieved within a strategy of institutional change and rethinking the role of engineering higher education within the societal and environmental context. Re-educating engineers should address complexity interdisciplinarity and uncertainties related to regenerative design and circularity.

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