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A CIRCULAR EDUCATION SYSTEM FOR THE AEC

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Abstract

The contemporary focus on sustainability and specifically on circularity, places new roles, requirements, and responsibilities on AEC professionals. From an educational perspective, this could be addressed by adding circularity concepts for instance into design, modelling, and analysis courses. However, circularity offers more than this; it provides a lens to *re-think* education in the AEC. Traditional courses wherein student work is assessed and discarded; are linear. This paper proposes a *Circular Education System* that reuses student work from one course as future input for itself and other courses. This concept is presented here at a learning objective, course, and program level.

Introduction

Current 'take-make-use-dispose' (linear) approaches developed and deployed for mass production in the previous century are unsustainable. At the same time, cities consume 75% of the world's natural resources (Macarthur Foundation, 2021). The slow realization of these facts in the AEC industry, is motivating innovative thinking about the life cycle of materials and products in buildings as well as the buildings themselves. The circular economy and the 'circular way of thinking' that drive it (Dabaieh et al., 2021), offer an alternative approach to linear (take-make-use-dispose) thinking. 'Circularity' focuses on identifying and then redesigning wasteful linear processes to 'circularise' them. The principles of the circular economy are: (1) eliminate waste and pollution; (2) circulate products and materials; and (3) regenerate nature. Andrews, (2015) likens the circular economy to a 'biomimetic' system in that it is based on the closed systems of nature whilst at the same time, it reminds us to understand a system we must first understand its effect on other systems (Meadows, 2008). Circular thinking is commonly divided into two cycles: the biological and the technical cycles. A major challenge to address is that biological materials which can biodegrade, are often fused to technical (artificial) materials which cannot (bio)degrade but can be reused. From this material perspective, the challenge is how to decouple the two cycles.

In the AEC, this requires our design and engineering knowledge to identify, separate and extend the lifecycles of materials and products. Planned obsolescence and other concepts that provide the antithesis to circularity, make up much of our thinking in the AEC. Circularity provides an opportunity to not just rethink how the AEC industry can support circularity in its physical resources, but as a lens to explore what it means to be an AEC professional in the 21st century. For instance, could it also be applied to our digital design processes? To identify linear design processes and 'circularise' them (McGinley, 2018)? In parametric design, complex relationships are often re-established and reconfigured for each project, could we redesign these systems so that they are more likely to be reused? Can a circular approach be identified to these processes to encourage reuse of previous work and reduce wasted human effort?

Addressing these questions will require the 'formation' of AEC professionals that are capable of 'circular thinking'. Educational systems support this formation of design, engineering, and architecture professionals. Therefore, the circularity paradigm requires changes in the education of AEC professionals to deliver these new approaches and adapt to this new way of thinking. So, how can we integrate circularity into an AEC educational programme? Should we add new circularity themed *content* to a course, start a *new circularity course,* or provide a specific circular learning experience using problem-based learning (PBL) (Duch et al., 2001) supporting the students to design new circular systems (Kirchherr & Piscicelli, 2019)?

Alternatively, could we be even bolder and 'circularise' the *education system* for the AEC? Could this support our students to learn about and normalise the concepts of circularity in their own engineering and design practice and could the education system reinforce this? To answer this, it is necessary to identify the linear elements in our current education system and propose alternative circular approaches.

AEC Education Systems

Education is the *process* of knowledge facilitation and or acquisition. The purpose of an education system in the AEC is to provide future generations with the skills, methods, knowledge, and ethics to make a positive contribution to the future from a specific disciplinary perspective. AEC professionals are 'formed' in university *programmes.* Programmes are divided into *courses* which are composed of *activities*. From a constructive alignment perspective, 'knowledge is constructed through the activities of the learner' (Biggs, 2014). Through these activities, students generate *products* (assignments) that can then be assessed. Teachers and peers can provide *formative and summative feedback*. Formative feedback is provided on the students approach *(process)* to their learning in the *activities* and summative assessment is based on the *product* of the activity. Both types of feedback and assessment are needed to help students understand the alignment of their learning to the *course learning objectives*.

It is therefore essential that students work on activities that motivate them and that they can see the links to the course learning objectives which should align to the graduate qualities of the programme. The required alignment of assessment, activities and objectives takes more effort from the teacher in the beginning (Biggs, 2014), but with this structure in place, and if clearly communicated to the students, the aligned activities can support the student's motivation to learn. It can also provide the teacher with a greater ability to monitor the students learning within the course and allow them to reflect on course adjustments in following semesters as required.

Towards a Circular Education System

Sustainable education typically focuses on the content of the education system rather than the sustainability of the education system itself. For instance, the UNESCO definition of sustainable education is *"a learning process or approach to teaching based on the ideals and principles that underlie sustainability and is concerned with all levels and types of learning to provide quality education and foster sustainable human development"* (cited in (Helmers & Ilchmann, 2019)). This does not investigate the sustainability of education as a process. For instance, is the education process wasteful, does it use and reuse resources responsibly? To address this, we need to investigate the sustainability of the education system. However, 'sustainability' is a wide lens with multi-faceted considerations (environmental, social and economic for instance). Therefore, we focus on a subset of sustainability.

Circularity provides a relevant focus area of sustainability for the scope of this paper. Circularity in the AEC focuses on how the industry can support a shift to a circular economy. The circular economy is driven by three principles. (Ellen MacArthur Foundation, (2014):

1. Design out waste and pollution
2. Keep products in use
3. Regenerate natural systems

Can we use these principles to define a sustainable, or more specifically, circular education system? Are elements of our current education systems already circular? If so, from whose perspective? From a learners' perspective, perhaps it is. The activity combined with the feedback enable the student to construct their own methodology which they can reuse and adapt to address similar problems in the future in their own lifecycles. Additionally, the teacher will also have learnt more about how the students approach the activities and can adjust these in the future. So, from the perspective of the students and the teacher, this is a *regenerative natural system*.

In circular economy a distinction is made between the biological and technical cycles. So how can these concepts be applied in an education system? Perhaps, the student and teacher perspective are analogous here to the *biological cycle* in the classical construction of circularity. In that case, *the technical cycle could be the product* / evidence of the student's learning. It is also true that when analysing an education system; the distinction between the learning (biological) and the product / assignment (artificial) can be difficult to decouple. An example of this can be the challenge of early career teachers confusing learning objectives and tasks, in their course syllabus.

In the AEC, 'technical cycle' learning products typically address real world problems. However, this is not always the case and when it is, this work is not always used in the real world. This is the first example of waste in the technical cycle of the education system. Typically, the work that students produce (the *products* of the courses) follow a 'take-make-use-*store*-dispose' linear process. The use phase of the product (analysis by the teacher) is small and then it is stored (unused) for many years before finally being disposed (Figure 1).

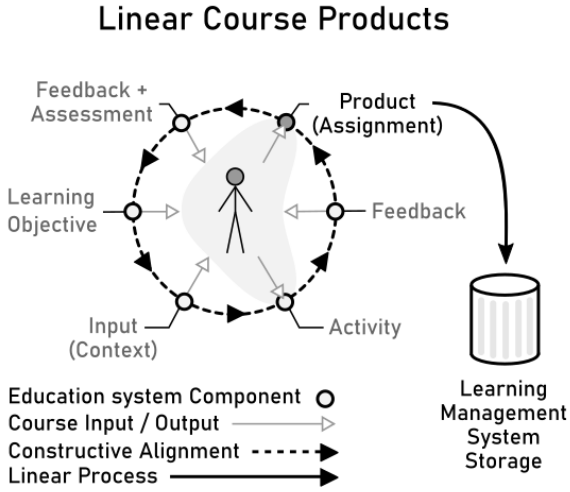

Figure 1. Circular (aligned) education with linear course products

An example is a student producing an LCA (Life Cycle Analysis) of a building as a learning product (assignment) in an activity in a course. LCA is chosen here as an example because it requires a significant grasp and synthesis of many different concepts. LCA is also a skillset and knowledge that is in high demand currently in the AEC. Furthermore, it can support our understanding of a systems sustainability throughout its lifecycle. To illustrate this example, let us say that the students on the course all produce the same LCA for the same system, and this is repeated by new students every year. So, if;

- there are 100 students on the course
- the course has 2 assignments (one formative and one summative)
- all students submit all assignments
- the university require that their assignments are stored for 5 years
- and the course is run every year

Then, in 5 years, 1000 LCAs will have been produced and, following assessment, stored in a Learning Management System (LMS) in an energy intensive data centre for years, before being discarded. Whilst the LCA calculation itself may only be a small excel file with negligible file size it would be derived from a BIM model which could be much larger that would also have to be submitted to enable the assessment.

From a biological circularity cycle perspective, 500 engineers have been formed that are capable of producing LCAs. That is circular, but what about the technical circularity cycle, and the products / assignments of the course (the 1000 LCAs)? How can we increase the (useful) life of the products such as these through reuse and ultimately make them more circular? Could this also increase student motivation for the activities? How can the reuse of the products support the students' understanding of ethics in the AEC for instance?

In the LCA example, the resource of the student's work (the product of their learning) or the teacher's assessment and feedback are not reused and are reproduced each time. From a circularity perspective this is wasteful, and waste should be eliminated. Therefore, this paper aims to identify approaches to increase the circularity of the *product* of the learning activities to support a ***circular education system.*** So how to increase the circularity of the products of the learning activities? Should we try and design *circular learning objectives* for a course, or *circular courses*, or *circular programmes*, or does circularity lead us to a new approach to education?

Circular Programmes

This exploration is conducted at a Technical University in an Architectural Engineering programme, within a Civil and Mechanical Engineering Department. From a programme perspective, the products of one course could be fed into the input of another course, creating a closed loop at the programme (degree) level. This link could be synchronous or asynchronous. Typically, each degree programme has a capstone interdisciplinary design project that aims to teach students 'real-world' skills in a 'realistic' environment. The programme level perspective helps us to think about the links to industry and how, for instance, the students construct their learning to achieve the graduate qualities through constructive alignment throughout the programme.

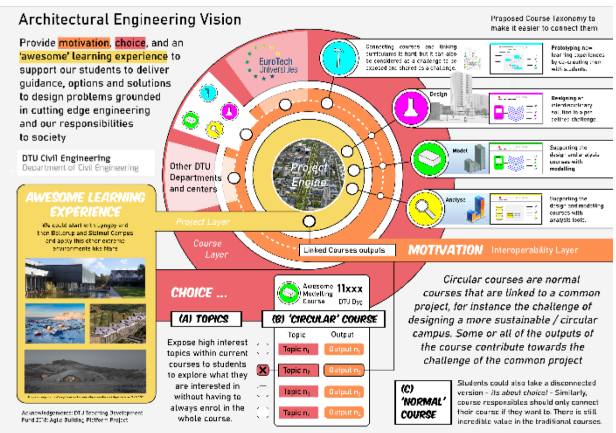

Figure 2. An Architecture Engineering vision, describing the integration of inputs and outputs in different types of courses.

An aim of circularity is to eliminate waste therefore if linear courses are wasteful these should be adapted to become circular for the program to be considered circular, therefore it would be difficult to focus on the programme level. So could there be a single course on a programme that mined and reused all products developed in that programme (if it had permission to reuse those products from the students) and fed them back into other courses where needed. To simplify this process, it might be necessary to develop a simple ontology of courses for instance at a high level they could be described as design, modelling, analysis and prototyping courses for instance.

Circular Courses

From a course perspective the products of one course could be fed into the input of the same course the following year, enabling a circular process of iterative improvement inside a course. as shown in Figure 3.

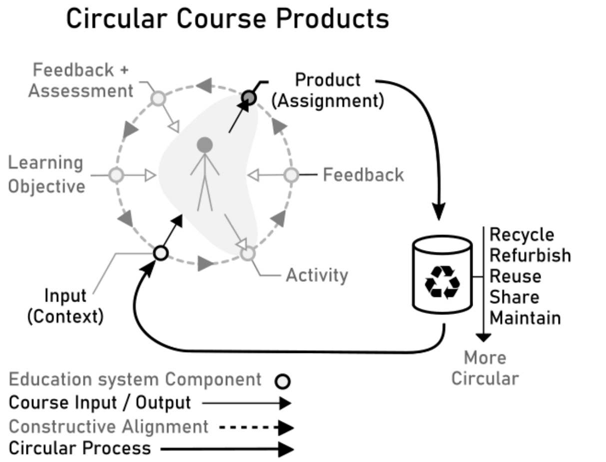

Figure 3. Circular (aligned) education with circular course products

To support this, we could (1) extend the lifecycle of the course product, (2) we could make the product of one course the input to an activity in another course, or (3) previous student work could be reused in the same courses for future students to learn from and improve (Figure 3). From a circularity perspective it is important to define how circular a course is, one way to do this would be to map it to the different levels of circularity (recycle, refurbish, reuse, share and maintain) (Figure 2). For each of these levels an example of how that would work as a course is described in Table 1.

Table 1. levels of circularity in course products

#	Level	Approach
C0	**Reproduce**	This is not circular, it is reproducing the same products every year.
C1	**Recycle**	Build a new course every year based on the materials of the previous course
C2	**Refurbish**	Make improvements to the same course each year
C3	**Reuse**	Reuse examples of previous student assignments in the same or different course
C4	**Share**	Share the student work products for other students to learn from.
C5	**Maintain**	Maintain and improve the products of previous semesters

The initial level of reproducing is the least circular and most linear. At this level, students are asked to do the same task every year. The next two levels (recycle and refurbish) focus on the course. Reuse then focuses on extending the lifecycle of the learning products beyond the initial assessment. A potential challenge of this is that the quality of the product used as input could affect the quality of the work of the receiving students, is quality control required for the products? In the higher levels of circularity, the learning products are shared on the courses to support specific inputs (Figure 3). Finally, the maintenance level suggests that students would actively maintain and further develop the work of previous students on the course. This could lead to an evolution of course products. Thereby increasing the quality of the products and building an ecosystem of tools and methods for the students to use that have been developed by them. This approach would reinforce their formation as autonomous learners. To develop this, we first need to see how learning is constructed. To view the education system at its atomic level, the learning objective.

Circular (Learning) Objectives

Finally, a learning objective perspective allows the education designer to focus on the atomic unit of learning. From this perspective, courses are containers of learning objectives. From a circular perspective it may be possible to directly link the products and or feedback on learning objectives between different courses in the same programme. Although this could be difficult to manage and maintain, this low-level intervention may be easier to align than whole courses. Further exploration is required to identify if this is possible.

Methodology

This paper seeks to identify the principles of a circular education system for the AEC. It reports on an approach to link the products and inputs of multiple courses at the programme level previously explored in McGinley & Krijnen, (2021). That paper explored 4 courses described below in Table 2.

Table 2. The four courses from (McGinley & Krijnen, 2021)

Code	Description
UG1:	An undergraduate BIM course generally taken in the second year of a more scientific engineering programme
UG2:	An undergraduate BIM course generally taken in the first year in a more applied programme
PG1:	A postgraduate interdisciplinary design course generally taken in the 3rd semester of the MSc
PG2:	A postgraduate (Advanced) BIM course generally taken in the 2nd semester of the MSc.

McGinley & Krijnen, (2021)'s BIM focussed paper identified 5 principles to promote a shift in BIM education from students learning *howto* to BIM to learning *from* (Open) BIM. These included to (1) provide a live design experience; (2) provide a focus on standardization of processes; (3) provide a living lab for the development of new analysis tools; (4) provide a focus on Industry Foundation Classes (IFC); (5) integrate real-time analysis and feedback through the LMS (Learning Management System). These principles focused on reducing waste and supporting student and professional learning by identifying and eliminating wasteful processes and approaches from a BIM perspective. This is relevant to the current question of developing a circular education system. Having now run the courses in 2021 based on proposals in that paper, we are now able to reflect on them here from a circularity perspective. This paper uses the 3 principles of circularity (1) eliminate waste and pollution (2) circulate products and materials (3) regenerate natural systems; as guiding principles of 'circularity' to explore the use of the four courses to guide the proposal of a prototype circular education system.

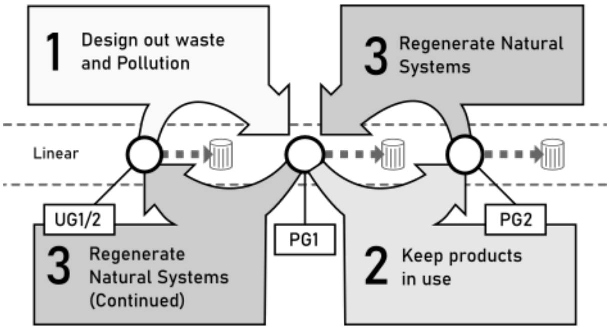

Figure 4 The principles can be combined to create a prototype circular education system connecting the four courses.

The first principle is used to explore the reuse of the student work between the undergraduate BIM courses and the MSc design course (PG1). The second principle (to keep products in use) is used to explore the connection between the MSc design course (PG1) and the postgraduate BIM course (PG2), where students develop tools to support the design course. Finally, the third principle to regenerate natural systems is used to explore both the analysis of the design course BIM models in the BIM course for future students of the design course as well as future iterations of the undergraduate BIM courses. Each principle of circularity is used to frame a discussion of approaches to 'circularise' the courses shown in Figure 4.

Principle 1. Eliminate waste

The first principle of circularity is to eliminate waste. How can waste and pollution be identified in an educational system? Waste has been described as a by-product of a process (Jelley, 2017). Waste could be any unwanted by-products made in the process of achieving an intended product. If the intended *product* of a course is the student's learning (in the biological cycle), then the assignment, they submit (in the technical cycle) is a *by-product*. This paper argues that once an assignment has been assessed it has fulfilled its usefulness. It is then stored on a server; this server uses energy that in most cases will be at least partially from non-renewable sources. This illustrates some of the impact in the 1000 reproduced products from the fictional LCA example course. To eliminate this waste, we could look at why the repeated production of the same learning activity (by)product is wasteful and how could we make it useful? how could this waste be designed out or looped back in? One way would be if the (BIM) model produced in the course could be (re)used by other students, perhaps in another course that could learn from it. Perhaps by extension they could analyse the models and provide feedback to the students who created the models?

This idea is explored here through the lens of two undergraduate BIM courses (UG1 and UG2) (Figure 4). UG1 and UG2 are similar courses targeted at different programmes. These courses had developed efficient and repeatable activities for students where they were asked to model the same specific building on campus. This meant that the teaching material and project requirements could be reused every year. This responds to the *reproduce* (C0) level in Table 1. This focus on reproducing the course, paradoxically meant that great effort had to be made so that the students did not copy the assignment from previous years. Consequently, this meant that opportunities for students to learn from previous years was actively discouraged.

2020

Rather than focus on the modelling and drawing of the building for the whole course, for the 2020 iteration of these undergraduate BIM courses, a second part was introduced which focused on the analysis of the work done in the first part. In this case the students used Solibri Model Checker to analyse IFC versions of the Revit projects they developed in the first part of the course and then make the necessary changes in the native software and repeat the process. The students found this version of course the least motivating and lacking in feedback. So, from a circularity perspective it did take the course from reproduction (C0) to reuse (C3) in the technical cycle but lost the students' motivation and should have provided better feedback to support the biological (circular) learning cycle.

2021

At the same point in the semester that the undergraduates in UG1 and UG2 were modelling the same building in 2020, an interdisciplinary postgraduate design course (PG1) was also modelling a complex building and struggling to complete the modelling by themselves in the time they had available. The PG1 project consisted of 10 interdisciplinary teams designing 10 different buildings in a 'live design environment'. Therefore, the idea for 2021 was for the undergraduates to support the student teams in PG1 to model specific systems of their buildings. The idea being that this would reduce waste, by the undergraduate students producing work that was *useful* for the Masters' students. Interestingly, UG2 thought they had learnt a lot and got more feedback, but UG1 thought the opposite.

The UG students found that the requirements for the design (in a live design project) were unclear, so they were unclear what to do and did not feel that they could make decisions themselves. Furthermore, the PG students were not confident (clear about their own requirements) to brief the UG students or give them meaningful tasks to model, that would have supported the understanding of the PG student. Instead, they either got the UG students to design things (outsourcing their own learning tasks) or to work on low value or decorative parts of the project. So, the new approach missed the clarity of the previous one where the activities and teaching material was repeated every year. This was because it had not run before so both sides of this vertical course were unaware of what was expected of each other. If this were to be attempted again it might require another course to coordinate the specific interaction between the two courses.

2022

The 2022 results have been included here to provide context because part 1 of the courses was repeated from 2020 but instead of then supporting a live design project they were asked to analyse their own buildings they developed in part 1. UG2 preferred this iteration, but it looks like UG1 preferred the live design experience of 2021. So maybe the students should be able to choose if they model a live or fixed design.

Table 3. BEng BIM course evaluations

UG1	**2020**	**2021**	**2022**
Respondents	*35*	*24*	*33*
learned a lot	3.1	2.8	3.4
LOs aligned	3.5	3.5	3.6
motivated by activities	2.5	2.6	3.2
feedback	1.9	1.8	2.4
Expectations clear	1.7	2.1	2.9
Amount of work	4.6	4.0	3.6

Table 4. Diploma BIM course evaluations

UG2	**2020**	**2021**	**2022**
Respondents	*34*	*12*	*35*
learned a lot	3.4	3.7	3.5
LOs aligned	2.9	3.8	3.4
motivated by activities	2.5	3.6	3.2
feedback	1.7	2.1	2.2
Expectations clear	1.9	2.9	2.8
Amount of work	4.6	3.3	3.7

Future

It is clear also that a main issue with the courses is the lack of feedback. Whilst the 2021 iteration increased the motivation of the students and improved the clarity of the expectations, these still have a lot of room for improvement. The second group also reported that the amount of work had reduced, but they had learnt more. However, UG1 reported that they had less work and also learnt less. Therefore, it is important to focus on feedback and clear expectations as the lack of these might be the biggest 'waste' of the students' time, and the most critical area to improve. It is not enough to focus on the technical cycle for course to be circular, from the perspective of the student both the technical and biological cycles need to be circular.

Principle 2. Circulate products and materials

The second principle of circularity is to keep products and materials in use for as long as possible (at the highest value possible). This is explored through extending the lifecycle of the learning products that result from the technical cycles of two postgraduate courses (PG1 and PG2) (Table 2). PG1 is a postgraduate interdisciplinary design course. The stated aim of the course is to '*give participants knowledge of integrated building design, and how specialised competences can be used in collaboration within multidisciplinary project teams to create a design fulfilling many functional requirements at the same time.'* This was the original educational intention of the course described in (Dederichs et al., 2010), which was extended with an Open BIM approach defined in (Karlshøj, 2016) and then again in (McGinley Krijnen, 2021). The course runs in the Spring.

PG2 is a postgraduate BIM course that runs in the Autumn, it is therefore not possible to create a synchronous link between PG1 and PG2. The simplest approach would be to reuse (C3) the previous assignments or share (C4) them to another course. So, how could the products of these courses be shared and reused? How could we keep these products in use? PG2 (the postgraduate BIM course) followed the traditional methods of 13 assignments (one for each week of the course). These were sometimes repeated and in many cases students were asked to solve the same problem. This was how the course was run in 2019.

2020

In 2020 the students in PG2 (postgraduate advanced BIM course) identified their own use cases and supporting data from an IFC model to develop tools to address the Penn State use cases using Python and IfcOpenShell. This new direction in 2020 was designed to make best use of the students as a resource to promote innovation rather than blindly train them in proprietary software packages (McGinley & Krijnen, 2021). Alternatively, in the new version of PG2, concepts of BIM are taught through the lens of the international standard IFC. This enables the students to develop products in the form of digital tools written in Python using the ifcOpenShell library to analyse the IFC files. The first three sessions of this course were in person and the following 10 sessions were online in 2020. There were only four respondents for 2020 for PG2, so whilst the numbers look good, they are not over analysed here.

2021

The 2021 and 2020 courses for PG2 had the same syllabus, and same teaching assistants. The 2021 PG2 course possibly benefitted from more physical teaching as it had an improved perception from the students in terms of learning objective alignment, the amount they learnt and their motivation (Table 5). In 2021, PG2 again used the Penn State use cases. Perhaps Table 5 shows that it can take a while for a new course to settle in and the students to get used to it. The perception that the learning increased and that the students were motivated by the activities is encouraging, however there is still lots to do on the feedback and clarity of expectations. One student noted that in PG2: *'Sometimes a clearer purpose should maybe be presented'*. Furthermore, PG1 has lower scores in 2021, most significantly in motivation and clarity of expectations. These are two points that should be addressed in the future.

Table 5. interdisciplinary design course evaluations

PG1	**2019**	**2020**	**2021**
Respondents	*37*	*4*	*38*
learned a lot	3.7	4.5	3.5
LOs aligned	3.7	4.2	3.0
motivated by activities	3.4	4.0	2.3
feedback	3.7	4.0	3.2
Expectations clear	3.0	3.8	2.1

PG1 scores lowest in the factor of expectations being clear.

Table 6. Course evaluations for PG2 Advanced BIM course

PG2	**2019**	**2020**	**2021**
Respondents	*28*	*26*	*31*
learned a lot	2.8	2.5	3.5
LOs aligned	3.2	2.3	3.3
motivated by activities	2.9	2.3	3.2
feedback	3.2	1.9	2.5
Expectations clear	2.8	1.9	2.4
Amount of work	3.3	3.3	3.4

Unclear expectations were also described in PG2 the postgraduate Advanced BIM course.

Future

Excitingly, most students in the 2021 version of PG2 agreed to share the tools they developed with students in following versions of the course. This means that in future versions it will be possible for PG2 students to maintain (C5) the products developed in previous iterations of the course, creating a truly circular course. In terms of PG1, as the two courses are asynchronous it was initially unclear how they could be linked to share (C4) products between the two courses. The most sensible approach would be for the tools in the advanced BIM course (PG2) (held in the autumn) to be used in PG1 (the postgraduate design course) (held in the spring). However, the most interesting approach will be to take the product of PG1 (the BIM models from the advanced buildings design course from the spring) and share (C4) these with the students starting in PG2 in the autumn.

The PG2 students could then analyse the outputs from PG1 and identify use cases from the products of PG1. Based on this they would the develop new (C0) or refurbish (C3) old tools that could then be maintained (C5) in future versions of PG2 and also used in PG1. This would enable PG2 to become a circular course. PG1 is a much more complex course and will take longer to circularise. In 2022 an additional survey to the students has been asked to get more detailed feedback than is typically provided in the standard course feedback.

Principle 3. Regenerate Nature

The third principle of circularity is interested in regenerating natural systems. The regenerative focus in an education system is the biological cycle of the students learning. So, how can the technical cycle and the products it produces support this? Currently student learning is coupled to the technical cycle of the work they produce to achieve that learning. So how can a students learning be looped back into the education system to help it grow? Should students be invited back in to share their experiences with future students? or by employing previous students as TAs? Or is it about trying to create an 'emergent' education system? Following the principle that from simple systems can be generated great complexity? Figure 4 shows that the investigation of this principle covers the interaction between multiple courses, increasing the complexity encountered in the previous principles. The focus here is on PG2 (the postgraduate advanced BIM) course and PG1 (the postgraduate advanced building design) course with implications for the undergraduate BIM courses as well. As stated in the previous section, the 2019 PG2 (Table 6) course was report based with a focus on teaching a different concept each week with aligned activities. However, this meant that there were 13 activities and assignments, which whilst they offered a good overview of the domain, it was difficult to manage and align all these activities. To address this, the course was changed in 2020 to 5 activities focused on IFC and IfcOpenShell. The first year (2020) resulted in a dip (Table 6), but last year (2021) saw an improvement and most importantly an improvement in the number of students who thought they had learnt a lot. The weakness of the course is still a lack of feedback and expectation management for many students, and these are where it received its lowest evaluations. However, for some, the open and exploratory nature of the course was motivating. *'I really liked the class and the open learning atmosphere. The subject was more of a guided discovery than a goal orientated, outcome specific experience.' (student in PG2:2021)*

For others, this openness was problematic, this is a wider problem that is described by Jensen et al., (2021) that *'students lack specific learning strategies for how, through a curious and investigative behaviour, to create an in-depth analysis of the presented content that leads toward meaningful learning experiences. [so] they often are brought into situations where they do not know what the next step is.* This can be seen in another comment that said the course: *'lacks the opportunity for [feedback] and help to get on the right track in the course assignments'.* Furthermore, some students also require more structure to guide the development of the tools. They require: '*a better overview of what was going to happen each week'.* And also that *'We have learnt a lot and done a lot with our efforts but there were many times we were lost.'* However, ultimately the course requires that students find their own solutions and that these will not be 'spoonfed' to them, this is especially important in interdisciplinary work and is summed up in the comment for PG1:2021 that *'It seems like the teachers are role-playing real life projects, by not interacting with each other, and contradicting each other.'* This is a good example of a regenerative system wherein the role of expert is transferred from the discipline specific teachers to the interdisciplinary students. However, if this switch is not communicated and 'bought into' by the students it can be demotivating.

Future

In reflection with the PG2 students at the end of the 2021 semester we discussed the requirement for them to define two case studies and they thought it was extra unhelpful work. The original justification for two case studies was that it would enable them to switch to a different case study if they hit a dead end with their tool in that study. However, if we take the input from the PG1 course, then the students could identify a single case study in PG2 based on the captured learning (by)products of PG1. This was a good example of waste by 'just in case' thinking.

From a constructivist perspective in PG2 the learning relies on previous experience with coding - and this is a factor in the assessment of the final product - it is therefore important to consider the students prior engagement with code before starting the course. One suggestion for next year could be that at least one person in the group should have taken the python course. This was also true in PG1 where students felt that: *'It seems that the teachers expect you to have knowledge of the subject [..] Therefore, It could be considered whether the students' completed courses should have an influence on which subject one is assigned.'* This suggestion has been incorporated into the 2022 version of the course, but the feedback on this is unfortunately not yet available.

To increase the autonomy of the students learning, since 2021 students in PG1 are allowed to choose their own learning 'KPI's. This allows them to set the relative sustainability of their project for instance and how they weight this against the importance of cost and time and spatial density. A future student could then consider how to reuse and adapt the product and its' learnings to their own criteria. However, the implications of the KPIs and the work required behind them need to be clearly expressed to address the concern of some of the students (in PG2): *'The PMs responsibilities have grown from the beginning till the end and involve a lot of stuff not mentioned in the introduction, like LCA, DGNB-certification and creating a construction schedule.'*

Discussion

This investigation of four architectural engineering courses through the lens of the three principles of circularity provides a starting point to support the development of a prototype circular learning system. The findings for each principle are summarised below from both a biological and technical cycle perspective and are based on the methodology defined in Figure 4.

Eliminate waste

From a biological perspective the biggest waste is students' motivation, which should be supported as much as possible. An approach could be to design and support learning activities to provide continuous feedback on learning objectives. From a technical perspective it is the reproduction of assignments which makes the product of the learning activity wasteful. Activities should be developed in a course, to coordinate the learning inputs and products between and within courses in a programme.

Circulate products and materials.

The discussion of principle 2 resulted in a proposal to share the products of BIM and other assignments with the from PG1 in the spring with the PG2 in the autumn. For this, it is important that the products are developed in a standard format, in our case this is IFC for the BIM files. The PG2 could then build new, refurbish or maintain tools to support analysis in PG1.

Regenerate Natural Systems

Following on from the previous principle, the regenerate natural systems principle was investigated to suggest that PG2 could then use the tools developed in PG1, test them, and give feedback on them back to PG1 in the following semester. This circular link between the courses would support the courses as a regenerative natural system.

Conclusions

Circularity is shown here to be a productive lens to explore an alternative education system for the AEC. Based on this a prototype Circular Education System is described here, that has designed out its waste, reuses the work of its students and continuously generates feedback to support the growth of the next generation of AEC professionals. To support this, three new circularity concepts of are defined. *Circular Programmes:* At the programme level a course could be set up to focus on 'circularising' existing course offerings increase the circularity of the programme. *Circular Courses:* Circular courses reuse the product of the student's learning. Linear courses do not. To make a linear course circular a starting point is to identify how the products of a course can be reused and eventually maintained (Figure 3). *Circular Objectives:* A focus on learning objectives supports the alignment of the students' circular education. This will be explored in more detail in future work.

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