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Long-Term Experience of Teaching Life Cycle Assessment and Circular Design to Future Architects: A Learning by Doing Approach in a Design Studio Setting

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Abstract: Architects and urbanists help to shape the built environment, which is both highly impactful and indispensable to support the sustainable development of any society. Hence, they must not only have a basic understanding but also be trained to routinely incorporate sustainability checks into their design practice. Published pedagogical experience with teaching life cycle assessment (LCA) in higher education usually covers students with engineering backgrounds, often at the graduate level. No records of regular courses for architecture and urbanism undergraduates were found. After eight years of teaching, and involving 213 students, this paper shares experience and insights gained in the only undergraduate architecture and urbanism course in Brazil openly dedicated to teaching LCA and circular design metrics within the design studio atmosphere. To encourage and inspire other initiatives, the article emphasizes the last four course offers. The current course design is aligned with recent recommendations and international practice. Still, the total workload is insufficient to adequately tackle complex design objects. Students' final grades across different years show improvements, but actual knowledge retention evaluation requires some post-course follow-up. We confirmed that undergraduate students can successfully apply LCA during design development with compatible additional effort if equipped with adequate tools. An online calculator was developed and is expected to allow expanded design experimentations in future editions.

Keywords: higher education; architecture and urbanism; life cycle assessment; circular economy; cradle-to-cradle (C2C)

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1. Introduction

The education of future decision-makers critically defines humanity's ability to address sustainability challenges [1]. Alongside regulations and political and economic forces, architects' and urbanists' interpretations help to shape the built environment, which is both highly impactful and indispensable to support sustainable development of any society [2]. Hence, future designers must not only acquire a basic understanding over the course of their higher education but also be trained to have command of the necessary methods and tools for conducting sustainability assessments [3] and routinely incorporate them in the decision-making process.

One of the most used techniques for doing so is the life cycle assessment (LCA). LCA is valuable to provide high-quality, multicriterial comprehensive results [4] and has been used as a decision support tool in multiple technological domains. It is a data-intensive approach [5], and LCA application to building and urban assessments is challenging due to the intricacies of these scales, which directly influence the amount of data required [2]. But the mistaken impression that conducting LCAs would be someone else's work, probably a specialist, also plays a role in the limited reported teaching experiences among architecture and urbanism undergraduate courses. Indeed, design is an integrated process involving multiple competencies, but built environment professionals today and in the future should become familiar with such sustainability checks and explore their benefits.

The circular economy (CE) concept offers a framework for acting to reduce environmental impacts. The historical linear paradigm—'extract, produce, dispose'—relies on large amounts of cheap energy and materials, pollutes, and wastes resources. Contrastingly, CE proposes a different design vision to drive the shift towards a more regenerative economy. This model [6] draws on several schools of thought, such as biomimicry [7], natural capitalism [8], the 'cradle-to-cradle (C2C)' design philosophy [9], industrial ecology [10,11], performance economics (functional service economy) [12], and the blue economy systems approach [13].

Despite a considerable number of books on LCA, literature on pedagogical experiences and in-class applications is, in general, scarce [1]. Viere et al. [14] remarked on the lack of a more structured guidance on LCA learning and competency levels and on how teaching approaches and content should match. Both reviews [1,14] provided recent and wide-ranging coverage of the published status. Still, the few examples in scientific literature on how LCA is taught are usually geared toward graduate students. At the time of writing, no explicit records of such teaching experiences in architecture undergraduate design studio settings were found in searchable journal databases. The same applies to circularity of building architectural design, even though the nexus between CE and spatial planning and design has become a prominent issue in academic education institutions, particularly in Europe [15].

Transitioning from undergraduate studies to professional practice involves challenging students with opportunities to address real-life, open-ended problems without clear-cut solutions. This is also the essence of design training. Thus, to increase the number of reported experiences and to inspire other teaching initiatives approaching life cycle assessments and circular design metrics as part of architecture and urbanism undergraduate curricula, this article focuses on the last four offering cycles (2017 to 2020) of the 'Sustainable Architecture and Construction (SAC)' course of the University of Campinas (UNICAMP), in Brazil. In this period the two main learning outcomes (environmental assessment and architectural design) finally became satisfactorily balanced in the studio setting. The complete eight-year action-research is presented by Gomes [16]. Lastly, it discusses improvements introduced and envisioned for the future, through the provision of an automated tool to facilitate LCAs and redirect emphasis toward design experimentations.

2. Theoretical Backdrop

2.1. Life Cycle Assessment and Its Relevance to Environment-Oriented Architecture Design Decision Making

Building regulations enforced over the last four decades have emphasized energy efficiency. With the substantial reduction of operational energy consumption provided, for example, by the European Directive on the energy performance of buildings (Directive 2010/31/EU, Directive 2012/27/EU), the embodied impact has become proportionally more important [17–19]. For new buildings or retrofits, the remarkable reduction of operational impact in temperate and cold climates were usually obtained through the addition of insulating materials, that would embed important impacts literally attached to the buildings.

Hence, studies have increasingly focused on the simultaneous reduction of operational energy and embodied impacts [20,21], estimated through life cycle assessment (LCA). The IEA EBC Annex 57 of the Energy in Buildings and Communities (EBC) Programme of the International Energy Agency (IEA) was established in 2011 to explore procedures for estimating embodied energy and emissions and their indicators [19,22].

LCA is a technique for assessing environmental impacts from the extraction of natural resources to the final disposal of a product or service. To quantify the environmental impacts, all interactions of material and energy flows within the environment (environmental aspects) that occur during the product's life cycle are considered, following the framework standardized by ISO 14040:2006 [23]. The goal and scope definition stage sets the assessment strategy. The product system boundary identifies which processes and phases of the life cycle are included in the study, and the most recommended approach is to analyze the complete (cradle-to-grave) cycle. Hence, the life cycle inventory analysis can be extremely labor intensive. The impact assessment stage is based on science-backed models that relate the inventoried flows to specific environmental impacts. Interpretation occurs throughout the process to provide full understanding of the problem at hand.

For whole building LCA (wbLCA), the European standard EN 15978:2011 framework is often followed [24]. Not only the life cycle stages of the building products, but the life cycle of the building itself must be considered. From the bill of quantities (BoQ) at hand, one needs to find the correct datasets in a building material LCA database. As few countries can count on databases specific for construction products, such data collection often requires substantial extra effort. Hence, while the LCA of products follow the standard four ISO stages, most cases of wbLCA use predefined datasets for the materials or components [25], for which the LCI and LCIA are merged and simplified [26]. The BoQ of the individual materials is multiplied with pre-calculated values from an LCA database and with the replacements needed for the reference service life of the individual components to match that of the studied building. The wbLCA is ultimately the sum of these results.

LCA and building design cross paths when interim environmental assessments are performed for design optimization, and when most potential for improvement can be seized. Whole building LCA has been increasingly used in research, but its application to design practice is still timid, and post-design evaluations driven by certifications like LEED™ or DGNB are more common [25]. This is a complex task, as LCA is a data intensive and time-consuming—hence, costly—technique [27]—partly due to the lack of necessary information for running an LCA in early design stages. As a result, the LCA of buildings is commonly conducted at the end of the design process, when the necessary information is available, but the decision-making process [28] and the design output [29] are no longer affected.

As explained, a building is—from the LCA perspective—a collection of materials, in a collection of building components and elements. Some of these have major impacts in terms of energy and emissions, while others—such as copper and other metals—do not feature so prominently in these categories but have major impacts in terms of human and ecosystem toxicity. Thus, a main strength of an LCA is to provide estimates of impacts in several categories simultaneously, and this is truly essential. By limiting the analysis to just one or two impact categories, this insight is lost, and one risks finding out, later, that relevant environmental loads have been overlooked.

Another important advantage is that an LCA avoids the risk of transferring impacts from one life cycle stage to the next. Imagine that only two materials account for, say, 88% of the mass in a building. This would already give a good indication of the importance of these two items. Now, considering the number of replacements and maintenance interventions, the need for which is a function of the service life of the components relative to the structural system of the building, several other items may become relatively relevant as well. The same applies to end-of-life, for instance: the lack of viable alternatives to avoid landfill disposal may also put several materials as points of attention. These insights are lost if only the product stage is considered.

LCA conceptually works with data in the foreground and in the background. Put simply, foreground data is the data of interest of the analysis, on which one can intervene in decision making. Background data, on the other hand, supports the analysis of interest by supplying data usually extracted from life cycle inventory databases. As not all countries have secondary life cycle inventory databases comprehensive enough to support complete LCAs, large commercial databases like Ecoinvent or GaBi are commonly used in LCA studies worldwide. Construction databases like the Ökobau and KBOB, respectively from Germany and Switzerland, are rare and often used in studies in other countries.

In 2017, a small amount of funding from Switzerland allowed a consortium of Brazilian research institutions to produce the first national construction products datasets inserted in Ecoinvent [30]. With that, assessments of Brazilian buildings could use national data for key construction products, instead of the generic 'rest of the world' (ROW) datasets available in the database, but with limited adherence to the local production context.

If environmental impacts are to be seriously minimized, LCA must be fully integrated to the architectural design process, especially in the highly influential early design phases. Attempts to use building information modelling (BIM) to enable such integration within a design development environment have increased [25,31–34], but teaching initiatives involving LCA integration within the design studio setting are rarely published in scientific literature. The only mention found refers to an experiment in a winter course involving nine students and a 17-student control group [35]. Those authors concluded that even non-LCA experts can apply it during the design phase without much additional effort if equipped with adequate tools.

Hollberg et al. [35] state that two major developments are needed to allow environmental impact analyses during building design: simplified tools that are adapted to the architect's need; and expertise in building physics and LCA—ideally at an early architectural education phase—to prepare students for result interpretation. This paper addresses the latter requirement later on.

2.2. Circular Economy Concepts and Goals

Circular economy (CE) aims to eliminate the concept of pollution and waste generation, maintain the integrity of the product over several use cycles, and focus on closing material and energy loops. A circular economy systems ('butterfly') diagram was proposed by the Ellen McArthur Foundation to visualize the circular economy concept [36]. This economic model distinguishes between biological cycles and technical cycles. Consumption occurs only in biological cycles, where food and biobased materials (such as cotton or wood) are designed to feed the system through processes such as composting and anaerobic digestion. These cycles regenerate living systems, such as soil, which provide renewable resources for the economy. Technical cycles, on the other hand, recover and restore elements, products, and materials through strategies such as reuse, repair, remanufacturing, or (as a last resort) recycling [37].

Underpinned by a transition to renewable energy sources, the circular model represents a systemic shift to gradually decouple economic activity from finite resource consumption, and build long-term economic, natural, and social capital and resilience to meet people's needs within the limits of the planet. Achieving CE involves rethinking and redesigning the way we do things, based on three overarching principles: first, to eliminate the very concept of waste and pollution; second, to keep materials and products in circulation for as long as possible; third, to regenerate natural systems to sustain it all.

Circularity metrics are relevant for monitoring, reporting, and communicating CE implementation progress. Applied to buildings, these metrics deliver structured assessments through standardized indicators, which establish a common language among the agents involved, help implement strategies to assess the circular potential of technical options. Studies dealing with circularity metrics for buildings are still scarce and somewhat variable within an overall common framework [38].

Currently, the most recognized and globally adopted indicator for the built environment is the material circularity indicator (MCI), also known as the theoretical circularity indicator of a product. The MCI tool is part of a broader 'Circular Indicators Project' developed by the Ellen MacArthur Foundation and ANSYS Granta, and evaluates the input type, output type, and the technical useful life of the materials [39]. In Verberne's adaptation [40], MCI is the basis for subsequent nested calculations at product (PCI), system (SCI), and building (BCI) levels. PCI incorporates product disassembly possibilities and can be referred to as the practical 'product circularity indicator'. In the past few years, some BCI improvements have been suggested. Van Vliet [41] proposed to omit the building layers in the PCI calculation; Alba Concepts developed a new BCI based on product, element (instead of 'system') and building [42]; and van Schaik [43] slightly modified it to apply to building foundations.

Some building circularity assessments combine metrics on reversibility and durability [44], the building circularity indicator (BCI), the new predictive BCI [42], and the circular economy key performance indicators of the construction industry (KPIs) to determine to what extent a company implements CE in the different construction projects phases [45].

Finally, the European framework for sustainable building—Level(s)—serves as a starting point for applying CE principles to the built environment [46]. Level(s) is based on 6 macro-objectives and 16 indicators. Not all sustainability indicators need to be included initially, but reporting can rather evolve from, e.g., estimating (Level 2) to recording (Level 3). Within macro-objective 2 "Resource efficient and circular material life cycles", indicators estimate and record purchases of *material quantities* and costs (indicator 2.1), *amounts and types of construction and demolition waste* and their *final destinations* (indicator 2.2), and extent to which *design for deconstruction* principles were applied (indicator 2.4), using eight end-of-life alternatives as proxies to calculate circularity scores, by mass.

Both the Level(s) and the MCI-based approaches can be potentially applied in learning environments, according to the design development stage, e.g., by starting with Level(s) and evolving to BCI. Based on the information the students would have at hand from the LCA database provided, for the course cycles described herein, two metrics were selected as an entry point to begin transitioning towards design circularity reporting within studio practice. First, the "circular content indicator", which relates the virgin resources to the total materials used, in a simplified version of the MCI. Second, the "closed-loop indicator", which describes the fraction of construction and demolition waste that can be theoretically diverted from landfill and return to new economic cycles, similar to Level(s) indicator 2.2.

2.3. LCA Teaching in Higher Education Institutions

Though many higher education institutions teach LCA, those teaching experiences are seldom published [47]. Viere et al. [14] recently searched JSTOR, Science Direct, and ResearchGate for relevant literature on LCA teaching in higher education. Most of the papers (26 out of 28) reported an experience at specific universities, with predominance in European countries and North America (11 and 8 studies, respectively). Only two papers described experiences in Brazil.

The studies reflect the educators' individual narratives, without comparisons across their experiences, which Viere et al. [14] then attempted to provide. All 28 papers referred to student backgrounds in engineering and technical sciences. Though 6 papers also mentioned business and social sciences or non-specified backgrounds, none of them referred to future building professionals. These two pieces of information reflect the way LCA has evolved over the years, propelled by its adoption by the industry in the global North, or spreading through professional networks. They also explain the general lack of retrieved hits from searches in Brazil and in the architecture field, in particular.

Course designs, detailed lectures, and learning outcomes are occasionally presented, but no framework explicitly based on learning outcomes and teaching methods can be devised from the available literature [14]. Project-based learning often underpinned course designs, seldom detailed, involving a LCA project using commercial software, sometimes collaboratively with industry partners. Although appropriate pedagogy is highlighted as essential for student engagement [48], and content and complexity level should be adjusted to the students' backgrounds [49], the described approaches rarely detail these topics.

Widely used in higher education—including in the LCA teaching context (see [14,50–52])—Bloom's taxonomy categorizes learning outcomes based on their complexity and specificity. Originally devised to aid in learning measurement and rubric development, it includes six cognitive domain categories: knowledge, comprehension, application, analysis, synthesis, and evaluation [53]. The most used revision of the taxonomy adds 'creation' as a new cognitive category that represents the learner's ability to generate new knowledge, thereby achieving a high level of understanding of a given subject [54]. Within this revised frame, Viere et al. [14] derived four broad conceptual levels of learning outcomes and cognitive competency for teaching LCA to undergraduate students (Figure 1). Only MSc and PhD courses are expected to reach the top cognitive category ('create'), which includes advancement of LCA methods and extensions on specific methodological aspects, like inventory and impact assessment.

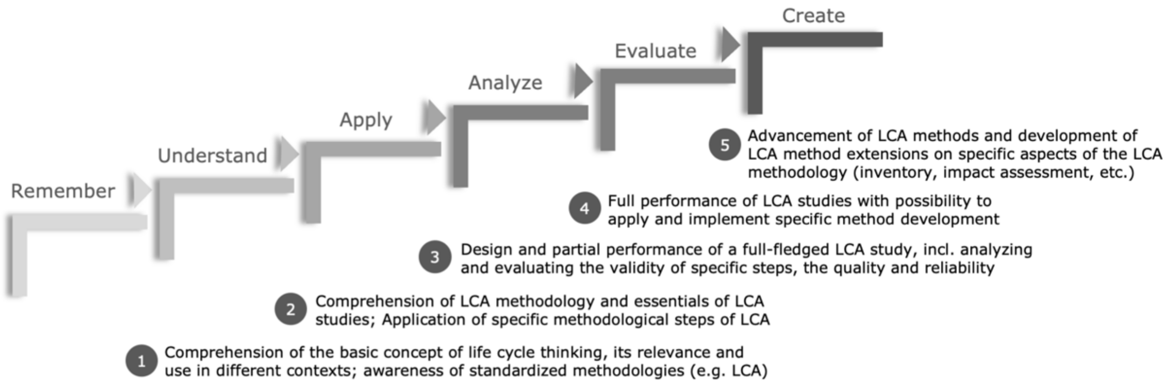


Figure 1. Learning outcomes and competency levels within the frame of a revised Bloom's taxonomy [14].

Another critical aspect of LCA teaching is determining how much software to use. Four groups of LCA software have been used [14]. Spreadsheet exercises (type 1) support simple case studies or calculations by multiplying LCA results derived from simplified inventory data by precalculated emission factors. Streamlined software applications (type 2) typically focus on a single application, such as ecodesign or footprinting, limited system boundaries, or specific sectors. These two classes of tools can examine illustrative, small LCA computations otherwise hidden in specialized software. Professional LCA software packages (type 3), such as SimaPro, openLCA, GaBi, and Umberto, allow modelling of any product's life cycle and calculation of associated environmental impacts using a variety of LCI databases. The fourth category advanced use of LCA software via programming (type 4), like Brightway2 and COM-interfaces to automatically run LCA software from third-party applications. Both are currently limited to highly specialized graduate training.

Case studies and projects are a centerpiece of LCA training and appear at all levels of Viere et al.'s framework [14]. In the lower two levels, case studies have been either embedded into teaching basics as 'pre-made' cases to reflect upon or guided exercises on simplified material, or followed introductory lectures, often supported by some sort of LCA software. At the higher levels, students are trained to interpret and compare full-fledged LCAs, and to plan and execute their own, including some data collection and system modeling in specialized platforms, and seeking to collaborate with external partners in real-life cases. Groupwork and project work approaches are key to achieve desired learning outcomes. In fact, project-based and problem-based learning approaches are at the core of most LCA teaching concepts [14], and a frequent element in design studios as well.

Hollberg et al. [35] was the only scientific publication found that describes a design task explicitly related to LCA. Over the winter semester 2014/15, nine students at the Bauhaus University of Weimar (Germany) and students of the University of Mersin (Turkey) developed a design for a building with a use scenario of their choice, in one of three possible sites in Turkey. They were then asked to analyze the life-cycle environmental impact of their design on a weekly basis, from the first sketches to the final design. All decisions (e.g., urban setting, window sizing) should be made by relating design variants to their corresponding environmental impacts. At the end of the semester, the students handed in optimized versions of their design proposals and explained their decisions based on the LCA results. The ultimate goal was to improve the understanding of the relation between design and environmental impact [35].

Though the students did not perform the LCAs but were rather consistently informed by automated hidden computation, and despite the limitations—e.g., small number of students, being a single course offering, and using German data for design assessment in Turkey—both the parametric tool and the overall environmentally infused design learning outcome are highly illustrative. The software used (Rhino/Grasshopper) shows significant potential to support this kind of application in an environment that designers are increasingly becoming familiar with.

Design studio teaching experiences are, in general, seldom reported in detail. Swann [55] alerted about the limited number of case studies on design education two decades ago. Best practice cross-study analysis is still impaired by incomplete descriptions.

Design education is classically based on the 'studio system' or 'project method' [56]. To address the various demands of design problems and to culturally enrich the design studio environment, a variety of design and flexible teaching methods are needed. Multidisciplinary knowledge synthesis is a challenge in traditional design studio learning environments, as students must develop reflective skills, expand, and, at times, reject responses in a studio design dialogue [57,58].

A multidisciplinary background is required to handle design concerns that range from site, urban, and legal issues, to climate, environmental comfort, energy and water efficiency, resources, specification of materials, landscaping, and interior design. As sustainable architecture gains increased attention in the literature, an integrated and collaborative design process should be encouraged at the learning studio setting, not only to satisfy codes and certifications, but to create actual sustainable design thinking [59] able to solve complex aesthetic, ethical, and technical issues.

Two important cognition factors influence problem-solving capacity: repertoire (facts, principles, concepts, examples, and experience) and problem-solving heuristics (insight systemization). Furthermore, analysis skills are required for design synthesis abilities. Problem-solving also entails a delicate 'from whole to part' and back again in a conscious and efficient manner [60,61]. If future professionals are to be held accountable for their design decisions´ impacts, teaching methods combining studio projects with in-depth environmental analyses should be disseminated and developed at architectural schools. In fact, students should be reminded regularly that future architectural planning will not be possible without considering environmental impacts. Hence, teaching concepts should include LCA and building performance analysis; LCA tools should be taught early in the period of study, just like CAD tools are, and the analysis should have a noticeable effect on the evaluation of the students' designs [35].

Experience shows that what works well in one situation does not necessarily achieve comparable results in a different setting. Before incorporating new approaches, design instructors need to try these out in ways that can be analyzed and reflected upon. In this sense, action research (AR) can be valuable in pursuing useful insights to continuously improve course design and learning benefits [62].

3. Method

3.1. UNICAMP's Sustainable Architecture and Construction (SAC) Course

The 'Sustainable Architecture and Construction' (SAC) course foundations date back to 2004, with the first offers in the Civil Engineering undergraduate program, as design support regarding environmental aspects in design decision making, amid a novel discussion among built environment educators worldwide, and completely innovative in Brazil at the time. Though a couple of graduate courses existed, no regular discipline was inserted in undergraduate curricula nationally.

In 2008, the course was also launched for architecture and urbanism students, this time in design studio format with one 4 h weekly session over 15 weeks. This course has reached all 213 students regularly enrolled between its first offering in 2013 and the 2020 edition. Over the years, the course experimented with different content approaches and design objects, which ranged from social housing to public administrative buildings. The design topic was gradually changed to limit the design object complexity until an optimal balance between the two main learning outcomes (environmental assessment and architectural design) was found.

To give readers some perspective on the changes introduced, the first building rating systems were launched in Brazil in late 2007 and remained as a trending topic, at the students' request, until 2014. The originally detailed focus on certification was gradually reduced to a single theoretical lecture complemented by seminars, to give room to more environmentally conscious, relevant final projects. Life cycle assessment (LCA) aspects were gradually introduced. The 2015 and 2016 AR cycles showed that—despite the students' dedication—the final project needed more time, preferably in the design studio. This limitation is particularly delicate in night courses—like that at UNICAMP—especially for students attending the final years, with limited availability for team meetings.

Hence, in 2017, the course was redesigned to introduce a 'semester project' (design case study) to crown the learning experience. Such a project would take 50% of the studio hours and comprised a wbLCA for the first time. Standard design models for public school buildings were chosen as the course topic because all drawings needed for the simulation and the bill of quantities needed for the LCA were freely available. The students modelled the assigned schools in Sefaira energy software and simulated them in different locations and climates. Both operational energy and impacts embodied in materials, construction, use, and end-of-life were estimated through LCA. The students would first analyze the original designs and based on assessment outputs, propose interventions to reduce at least 10% of their overall impact. Theoretical classes were reduced to allocate seven classes for the semester project. In 2018, the same approach was repeated for national standards for public-school design developed for the National Fund for the Development of Education (FNDE, https://www.fnde.gov.br/index.php/programas/par/eixos-de-atuacao/infraestrutura-fisica-escolar, accessed on 3 April 2022).

In 2019, the theoretical topics on ecological footprint, LCA, and design for circular economy were fixated by exercises of incremental complexity, culminating in the semester project. Complexity of the design object was controlled, to provide the opportunity to explore insights offered by LCA and by tracking circular design goals, set as priority design objectives, in the redesign and optimization of the proposed solution.

The teaching teams were composed of one faculty member and at least two teaching assistants. In line with the AR observation step, teaching team members acted as 'class observers' of each other. Before classes and activities were observed, the instructors discussed the points to pay particular attention to. During the post-observation debriefing, feedback was given and received, and possible goals and a development plan discussed for the next offer cycle. The students were informed of this dynamic in the first class, as well as about the AR underpinning continuous improvements, to which all of them individually agreed upon.

Student feedback complemented the continuous observation by the teaching team throughout the semester. In 2019 and 2020, a blind, non-graded diagnosis survey in the Socrative platform was used for background knowledge assessment; the same assessment was reapplied at the end of the course, to assist in progress tracking. The 2020 survey specifically addressed the distance learning imposed by the pandemic. These *pre-post* surveys referred to (1) what was assumed that students would already know; (2) questions that would help to confirm those assumptions; (3) common misconceptions or myths related to the course subject; and (4) questions that would indicate if and at which point environmental concerns were considered in their design thinking. The joint discussion of answers worked as icebreakers for introducing new topics.

Student feedback consists of guided in-class discussions (see "knowledge progress and course design survey" in Appendix A) held in three moments of the course: (1) at the beginning of the main course blocks, when expectations [63] and environmental performance targets were collectively set; (2) at the official mid-term feedback session; and (3) at the end of the course. The progress survey content corresponds to the course's learning outcomes, and to the underlying research questions posed by the instructors. Goals and expectations were revisited throughout the semester to check with students if they still applied or if adjustments would be necessary. If needed, a blind Google form was kept open to receive anonymous feedback.

In line with the AR reflection step, Google Classroom has been used as a teaching portfolio to collect and document relevant course information (evaluations, teaching reflection notes, mid-semester feedback, and class observation materials) to be reflected upon and reported for instructional development and permanence.

3.2. Action Research Framework

Action research (AR) is a method of systematic enquiry that teachers undertake as researchers of their own practice. It offers an interactive, cyclical method of gathering information, when exploring the dialogue between research and practice in educational settings. 'Action' refers to intervening in existing practice in specific social contexts (e.g., a course offering) to bring about change and improvement. 'Research' (or reflection), in turn, involves the systematic observation and analysis of changes due to specific interventions. This cycle offers opportunities to explore teaching practices, curriculum development, and student behavior in a real teaching-learning environment, with continuous reflection to improve processes [62].

The enquiry involved in an AR is often visualized as a cyclical process (Figure 2), which begins with the identification of a problem (1), followed by the postulation of potential solutions, from which an action plan is developed (2) and implemented (3) [64]. The observation stage comprises data collection and results analysis (4). Afterwards, the whole AR process is reflected in (5): the problem is re-evaluated, and the results are interpreted to verify the success of the intervention. A new cycle can then begin, until the problem is solved, allowing researchers to be an active part of an experiment [62].

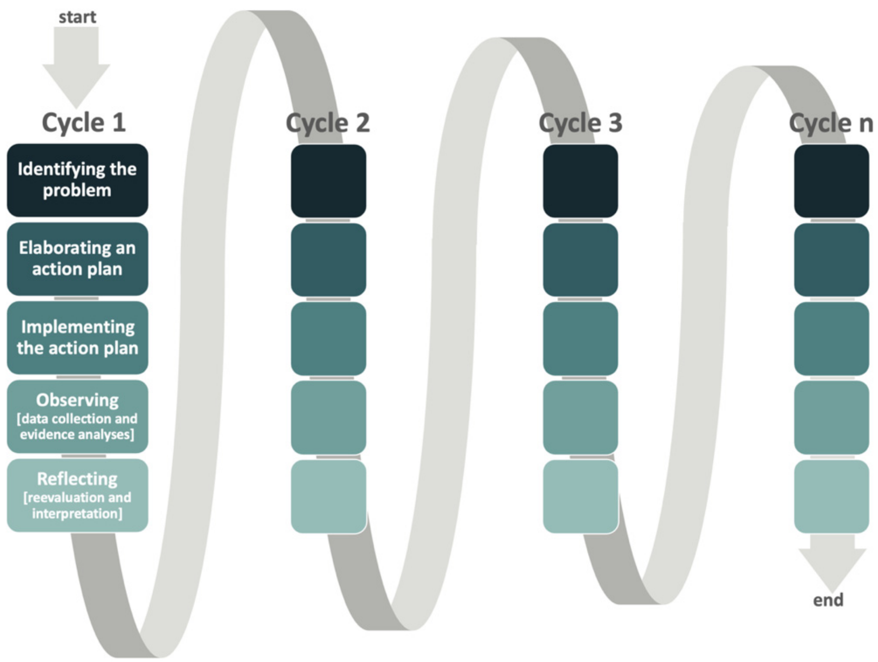


Figure 2. Action-research interactive, cyclical framework.

For being widely perceived as a viable approach to help instructors develop their teaching practice while enhancing their professional competence, AR has been increasingly applied in higher education institutions [65–67]—including sustainability-related topics [62,68]—and was chosen as a formative study of progress in the eight-year investigation [16], which paved the way for the research segment emphasized herein: the past four editions of the course (2017–2020). This period covers about half (122 out of 213) of the architecture and urbanism students who took the SAC course at UNICAMP over the years, and corresponds to the phases described by Gomes [16] as the "Elephant in the room", which refers to defining the approach to insert a highly complex topic—LCA—to non-experts that will become key users of its outputs to orient their future designs—and "Attracting butterflies" phases, the latter in a reference to the Ellen

McArthur Foundation's butterfly diagram, when CE goals were added to the semester project (Figure 3).

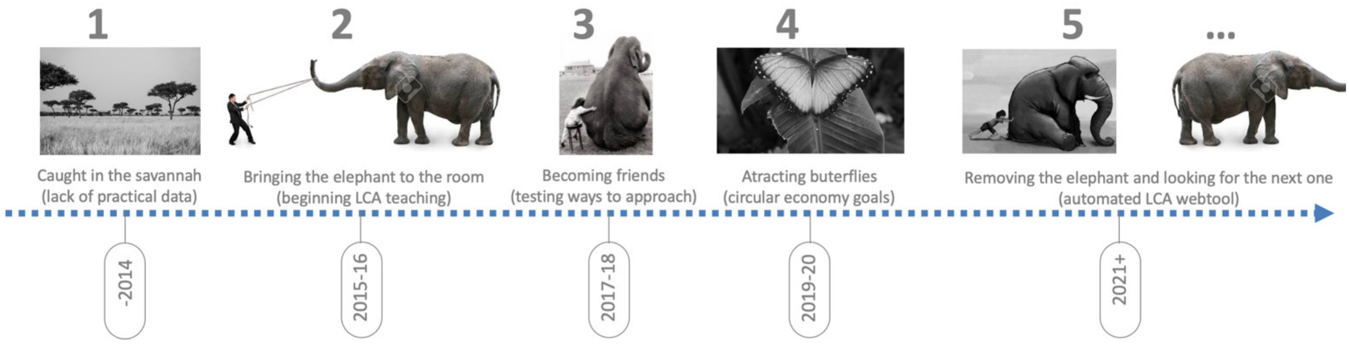


Figure 3. Phases of approaching LCA within architectural design studio described by Gomes [16].

In each offer, the five-step AR protocol (Figure 2) enabled continuous testing of additions, suppressions, and modifications of the previous course design. Four broad research questions underpin the long-term course tailoring:

- What are the minimum and sufficient theoretical contents for the transmission of the necessary basis for the development of the exercises and the semester project (to free the maximum space for application in the development of the project and its evaluation)?
- What are adequate workloads and teaching-learning dynamics to raise awareness and provide training in life cycle modelling *compatible with architecture and urbanism students* and with application to buildings?
- How to balance formative and summative assessments to ensure apprehension of concepts and development of expected competences? What focus should such assessments have?
- How to awaken the perception and stimulate the dynamics between performance estimation and feedback into design development decision-making process?

More specifically, the last two offers were concerned with the following:

- Are lecture contents and (intensive) formats adequate and sufficient to support development of a semester design project?
- What is the best balance between complexity and comprehensiveness of modelling for the semester project?
- Would a preliminary presentation assist in identifying critical issues, problem understanding, and modelling deviations; strengths, difficulties, and misinterpretations, and opportunities for project improvement, ensuring it is effectively informed by environmental performance results and refined accordingly?
- (Given the restrictions imposed during the pandemic) would the original course design and, particularly, the theoretical content suit well a flipped classroom/remote format?

4. Results and Discussion

4.1. AR Cycles 2017–18: Consolidation of LCA as a Major Learning Outcome

4.1.1. Problem Identification (Stage 1)

Successful LCA applications depend on command of specific tools and are challenged by the amount and quality of foreground and background LC inventory available. Some applications might also lack a standardized procedure, which impairs results comparability. That was the case for wbLCA.

In line with the advance provided by national research activities, students worked with the same raw data that formed the Ecoinvent datasets of construction materials produced in the Brazilian context [30]. Although only 28 datasets had been commissioned, they comprised key construction materials used in the country. This AR phase also largely reflects participation in the activities of the IEA EBC Annex 57 (2012–2016), an international research consortium dedicated to the study of embodied energy and carbon in buildings.

These two drivers enabled that students were exposed to discussions at the frontier of international knowledge. Due to previous experience, SimaPro, one of the most widely used LCA platforms worldwide, was chosen as the LCA tool to explore. The 'elephant in the room' to deal with was the challenge of teaching/learning a complex technique and a relatively complex software, plus developing the design proposal and applying the newly acquired knowledge, all within the design studio setting and one semester timeframe [16].

4.1.2. Development (Stage 2) and Implementation (Stage 3) of Action Plan

At this point, LCA was consolidated within the course plan, but it was necessary for students to know the concept and process better. The hypothesis was that students needed less of a teacher and more time to experiment in a teaching-learning environment. Theoretical classes were reduced to about 50% of the course load. Additionally, there was a substantive change in the semester project, and students started building a spreadsheet from scratch and performing the operational energy assessment, using simple software (Sefaira), sufficient to ensure some basis for discussion, without creating a complexity that would overwhelm the teams.

In the 2017 edition the case studies consisted of Rio de Janeiro's municipal standard school projects and standard projects from the National Fund for Education Development—FNDE, assuming pairs of equal projects implemented in the cities of Rio de Janeiro and Campinas. The aim was to demonstrate the influence of climate and supply logistics induced by the location of the projects, with two main focuses. The first focus was on collaboration and teamwork, and the performance of pre-determined roles that reproduced a real work organization: in each team, there was a group of analysts and a group of simulators. The second focus was on comparing results based on LCA: students made the diagnosis, proposed their intervention, and evaluated it again. With this already intense scope, no intervention was proposed in the original project.

To balance the work demanded with the time available for the semester project, and to allow the desired focus on analyses and discussions, the teaching staff (teacher + teaching assistant(s)) tabulated impact factors per declared units of basic construction materials and ran additional assessments as required. Feedback from students' designs gradually increased this list of materials.

The students were responsible for conducting the computer simulation tasks and had to assemble the MS Excel sheet that described how the inventory flows were computed over the building's life cycle, according with EN 15804 + A1 [69] and EN 15978 [24] standards and IEA EBC Annex 57 recommendations [22]. Teams of about six components proactively and the coordinator indicated those involved in each activity. Besides the intra-teamwork, the team coordinators, planners, and simulators held transversal meetings with their peers in the teams studying the case in another city, for the development of comparative analyses and corrective synthesis.

4.1.3. Observation (Stage 4) and Reflection (Stage 5)

The 2017 AR cycle showed that the students had acquired the expected competencies, but little reflection remained as to the applicability and possibilities of influencing the project and its use. Thus, the next cycle (2018) kept the focus on collaboration and teamwork and the roles played but was specifically aimed at generating information to inform a decision-maker, e.g., a public manager who had to choose—from an environmental perspective—between building a school with 12 classrooms or three schools with 4 classrooms, based on the application of the LCA technique.

If, from a management point of view, it may seem more attractive to inaugurate three schools, would this also be the best alternative from an environmental point of view? Three schools are three inaugurations, they serve more neighborhoods with less displacement, putting less strain on the local road structure, and cities usually have more land available. On the other hand, a school with 12 classrooms takes advantage of the same basic infrastructure to serve a larger number of students.

The students were challenged to (i) carry out the energy simulation; (ii) assemble the inventory data spreadsheet for the models of 4 and 12 classrooms, with and without sports court and, based on their results, draw conclusions to (iii) support the option for one or another school model, and (iv) point out three critical points that could be improved to reduce impacts. This exercise with a restricted number of intervention points aimed to highlight the benefits and consolidate the incorporation of LCA in the design process, given the limited time available. Additionally, the way of communicating results needs to be made understandable by decision-makers and other non-specialist information users, as the public manager in this case.

The product stage inventory spreadsheet follows the same classical structure consolidated for construction budgets, starting with the preliminary services up to the roof. The building inventory is then completed according to the following stages of the life cycle: construction, with the respective losses; use, with the respective maintenance; and end-of-life. Estimates beyond the life cycle in question (Module D) were not requested.

Insightful perceptions soon emerged, like: "... if I add more rooms, the increase in impact is small...". Or: "... adding a sports court to a small school increases the impact by 1/3. For a larger school, the increase is only by 10%... perhaps smaller schools can share sports equipment with each other or with larger schools...". Or even: "... by tripling the number of classrooms, the impact does not increase in the same proportion... there is an apparent gain when a larger number of children are concentrated in these schools". The same could be observed for emissions, showing their proportionality with the energy flow (Figure 4). The students proactively came up with ways of expressing the impact of energy consumption per year per child—and the corresponding greenhouse gas emissions—more tangibly than non-experts (Figure 5).

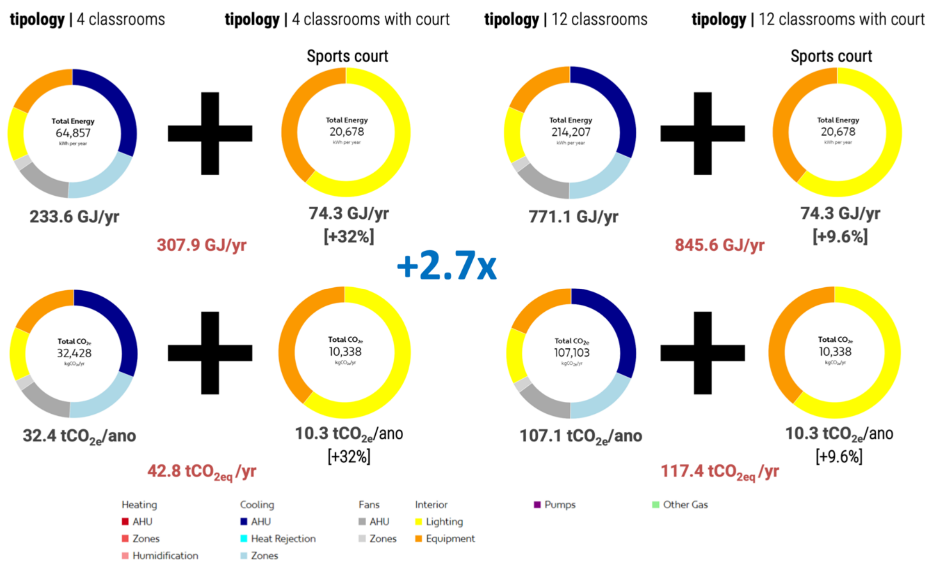


Figure 4. Annual operational impacts (primary energy on top, embodied greenhouse gases) for the two school typologies studied, considering 30 students per classroom. Adopting the 12-classroom typology triples the number of children served, while increasing the impact by 2.7 times. The contribution of the sports court is proportionally more important for smaller schools, suggesting design and management alternatives.

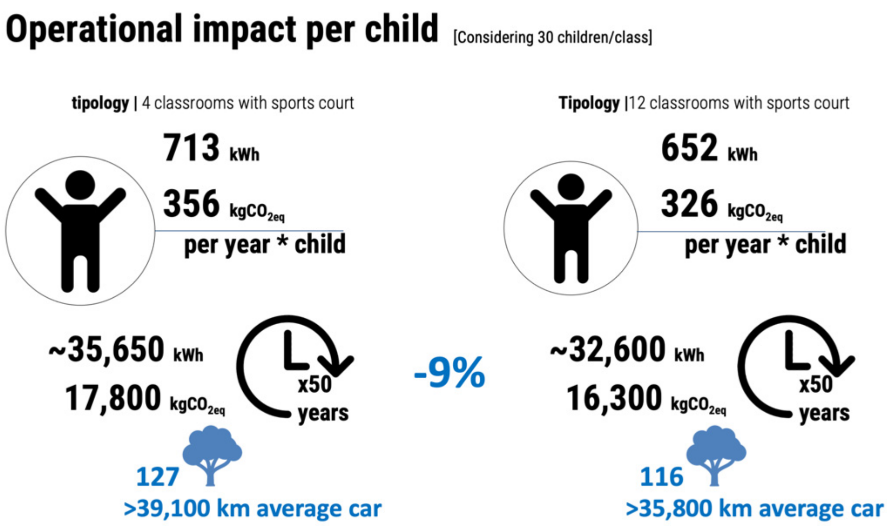


Figure 5. Reporting of annual impacts per child: Keeping one child studying in a 4-classroom school for the expected 50-year lifespan requires the planting of 127 trees to neutralize the effect of these emissions, equivalent to driving nearly 40,000 km in an average car, whereas in a 12-classroom school the individual impact would be approximately 1% less.

Finally, the students identified the type of cement and the material of the window frames and the temporary sheds used on the building site, and made proposals for changes which would result in a 15% reduction in the original impact, greater even than that which motivated the discussion on the most appropriate size of the school structure. Once again, new skills were stimulated, beyond the integrated assessment of operational and embodied impacts: now the students (analysts) were also deepening the use of SimaPro and using it to justify their proposals to intervene on the standard public-school design.

The final presentation included all students in a large group simultaneously and participatively. Individual results of each team and a meta-analysis of all findings were presented. Students and teaching staff considered the results excellent, but the course evaluation still pointed out the restricted time for accomplishment of the semester project, and the limited command of the LCA technique and software itself, for the LCAs were previously performed by the instructors, to gain time.

4.2. AR Cycles 2019–20: Insertion and Consolidation of Circular Design as a Learning Outcome

4.2.1. Problem Identification (Stage 1)

The two AR cycles herein emphasized coincided with participation in the activities of the IEA EBC Annex 72 (2018–2022), which, based on the findings of Annex 57, aims at harmonizing procedures, establishing metrics, and developing benchmarks for life cycle assessment of buildings, not limited to the two categories of embodied impacts (energy and emissions) addressed in its predecessor. The environmental picture provided was thus much more complete. In parallel, we could start to 'attract butterflies', i.e., to shift from the traditional cradle-to-grave cut-off to consider cradle-to-cradle (C2C) aspects. These are dealt with in the LCA 'Module D' ('Benefits and Burdens Beyond the Cycle', in Figure 2) and are at the heart of the CE model (Figure 3).

When transferring these notions to the undergraduate design course, possibly the first big surprise for students—bigger even than the size of the inventory sheet—is to discover that recycling, from a circularity point of view, is not the first or the best option. Their second shock is to find out that less than 9% of our economy is circular [70], that is, very little of the 92.8 billion tons of materials used on the planet annually returns to productive uses. Almost half of this mass goes to the construction and maintenance of houses, roads, and infrastructure.

In a circular logic, products are banks of materials; each product has its value, and, above all, design decisions must be guided by what happens after the useful life. Students should be activated to incorporate circular design thinking in their own methods and processes.

4.2.2. Development (Stage 2) and Implementation (Stage 3) of Action Plan

The experience of the 2018 AR cycle pointed towards students being able to carry out a project from start to finish, whose design process was fed by both cradle-to-cradle (C2C) and circular design concepts, and LCA information, dynamically reinserted into the project development. Thus, actions were taken on four main fronts: (1) further review of the minimum required theoretical content; (2) control of the design object complexity, to expand the space to explore insights offered by LCA results and the selected circularity metric; (3) environmental targets to meet learning outcomes for approval, that would be collectively by faculty and teams; and (4) introduction of a preliminary, formative presentation to allow for cross-group discussions and faculty feedback for improvements before final delivery.

To free up time to add the observation of circularity targets (closing cycles), theoretical lessons were reduced to the inevitable minimum, and a spreadsheet calculator was provided, so that it was sufficient for the teams to insert the materials used in their designs. With this, it was possible for the students, since 2019, to go through all the basics of the expected skills development: understanding LCA and the inventory spreadsheet; practicing the LCA platform, to assemble the missing datasets and complement one or another item of the inventory purposely not provided. Also, mainly focusing on the only summative assessment kept a 'circular design challenge' with feeding the decision-making process, since the beginning of the project conception, by the environmental performance obtained by LCA and circularity metrics.

The theoretical content has been refined for the best adherence to the semester project. The theoretical topics—on ecological footprint, LCA theory, tutorial and practice of specific LCA platform (SimaPro), LCA of complete buildings, LCA at meso-urban scale, and design for circular economy/cradle-to-cradle (C2C)—were fixed by exercises of incremental difficulty, which culminated in the semester project. Complexity of the studied object was controlled by limiting the number of materials/processes to model, to allow greater familiarity with modelling in SimaPro, without overloading the time available to develop the semester project.

The scope of the semester project ('circular design challenge') was defined from the demand identified by the students themselves during the discussion of the feasibility study seminar for environmental certification, which focused on the School of Civil Engineering and Architecture and Urbanism's building. The chosen object was a covered structure at the main building site access, combining surveillance and bus waiting functions. The structure should observe circular design goals (the maximum possible closing of resource cycles), with the lowest possible LC impact. From the didactic point of view, this object was simple enough, with a limited number of materials, whose LCAs could be performed within the programmed time and help the fixation of the theoretical content and the use of specific software. By the nature of the object to be designed, the need for energy simulation was automatically suppressed. The environmental goals to be met for approval in the discipline were collectively agreed between the teaching staff and student teams. The overcoming of the agreed goals would define a healthy competition for the joint recognition of the best project, to be presented to our faculty's board for appreciation.

As usual, the teaching staff provided a very complete list of materials with pre-calculated impact coefficients, eventually performing the missing LCAs for the version of the project under study. The students were responsible for conducting the computer simulation tasks and for feeding the inventory data into the building life cycle spreadsheet, on which the comparative analyses were based. Teams of 5 to 6 components were organized in the roles of designers, environmental consultants, and a coordinator. Besides the intra-teamwork, team coordinators and environmental consultants (planners) could hold transversal meetings with their peers from the other teams, to develop the analysis spreadsheets. As this time the students would perform the LCA of the materials, after being assured about the fixation of the concepts and calculations involved, the balance made by the instructors consisted in the supply of a spreadsheet containing the calculation formulas for life cycle inventory. The assembly of the inventory spreadsheet from scratch was still requested, but as soon as the formative evaluation confirmed the fixation of knowledge, the calculator, which was very time consuming in its preparation, was passed on to the teams.

To raise awareness among the students, we introduced an investigative exercise/workshop. The students could choose from a set of everyday objects—a toothbrush, a headset, a battery-powered radio, a toy car—and received a toolkit for disassembling them. In groups, they were invited to:

- Reflect on the product's constitution: What materials is it made of, how is it packaged and how does it get into the hands of the consumer? How is the life cycle of each part . . . are there toxic substances involved or risks posed to their recovery?
- Widen their gaze beyond the end users to also consider the wider network of stakeholders: How do they influence each other?
- Examine material flows: Where do they come from and where do they go after use?
- Find opportunities to redesign this system.

After the workshop, a lecture addressed relevant circular strategies to activate students' thinking and stimulate their design. Topics like shifting towards a service economy, modularity, life extension, material cycles closure, and smart choice of materials and inputs (durable, biodegradable, recycled, or recyclable), considering the end-of-life treatment, were explained in detail.

The 'Circular Design Challenge' was inspired by the *"Circular Design Learning Journey"* developed by the Ellen McArthur Foundation, in association with the global design company IDEO (https://www.circulardesignguide.com (accessed on 2 April 2022)). The aim of the exercise was to provide a learning experience challenging students to rethink their design vision (products, services, and systems) for a CE. The brief comprised understanding products by exploring the system it is part of, and imagining how product and system could be redesigned according to the three main points of the CE:

- Eliminate environmental burdens through design;
- Keep products and materials in use; and
- Regenerate natural systems.

The presentation of the circular design challenge introduced the students' mission (design under the circular logic and assess the resulting environmental impacts), the design task, and the rules to be observed. The designed object was the environmental upgrade of the surveillance point in the front access of the School of Civil Engineering, Architecture and Urbanism at UNICAMP, to also encompass a leisure space for the school's community. As rules:

- The function of surveillance support should be preserved, with the possibility of adding new functions such as bike rack and sheltered space, living and interaction area, waiting for vans, among others;
- The usable area was free, as long as it fitted in the available external space;
- Compliance with circular design requirements should be indicated by the share of closed material cycles among the total materials used; and
- Environmental performance should be demonstrated through LCAs undertaken for a preliminary design brief (baseline), and during design reviews until reaching the final proposition.

The design hand-ins should include:

1. Mapping of the system of interest (influence diagram, see e.g., Figure 6), highlighting the system boundary and opportunities for circularity; the forces that may prevent adherence to CE; how new opportunities would make the system more circular; and who would benefit from this. As it is an exploratory process, some iterations might be

necessary and used in the workshops, but only the final version would be delivered, handmade or by free choice software, in the desired visual language.

2. Synthesis of the reflection on the circular opportunities explored. Initiated by formulating the most critical question for system change, specific and action-oriented, that could lead to a better system design: "If you could ask one question to make your project more circular, what would it be?" This would be the very design challenge to address. Where would you like other people to keep their attention?
3. Estimated life cycle impacts and circularity indicators, demonstrating how they influenced project improvement (spreadsheet and corresponding analysis).
4. 'Design Magic' conveyed by the proposition, demonstrating a high-level architectural synthesis outcome, and high degree of creative confidence.

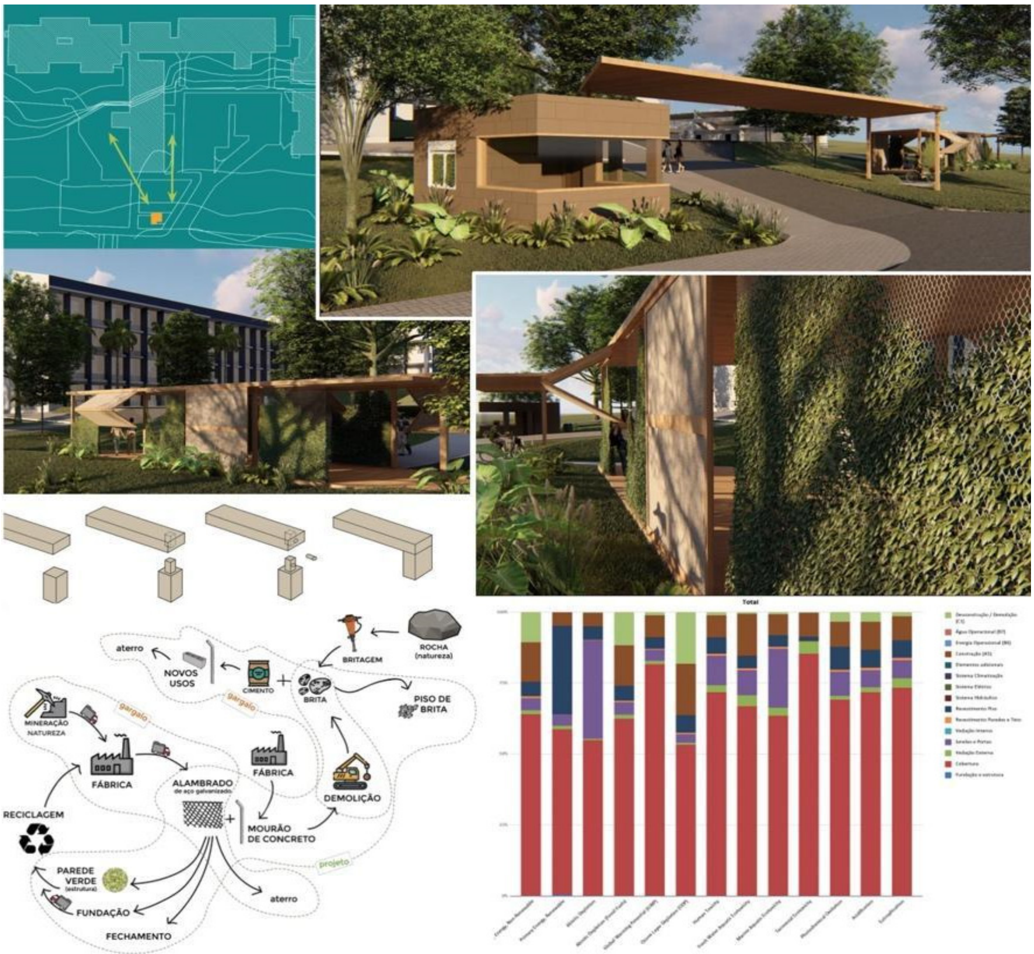


Figure 6. Illustrative excerpt of the circular design challenge hand-in board: urban equipment design, design logic for disassembly, system mapping and identification of circularity bottlenecks, and impact analysis through LCA. Image courtesy: Team A (2020). Original in Portuguese.

Finally, all groups presented their work (Figures 6–9), followed by a peer evaluation session and by a detailed discussion about the design challenges experienced. All evaluations were on the high-grading segment, with occasional deviation more related to failures in the individual partial deliveries than to insufficient design performance.

Figure 7. Illustrative excerpt of the circular design challenge hand-in board: LCA study for a bamboo and adobe structure. Image courtesy: Team B (2020). Original in Portuguese.

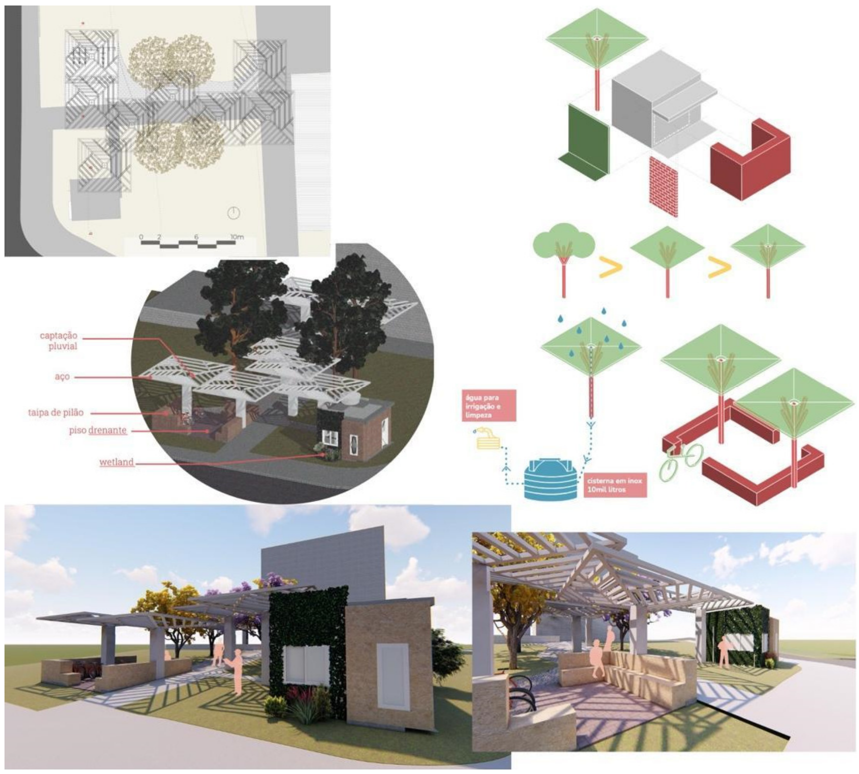
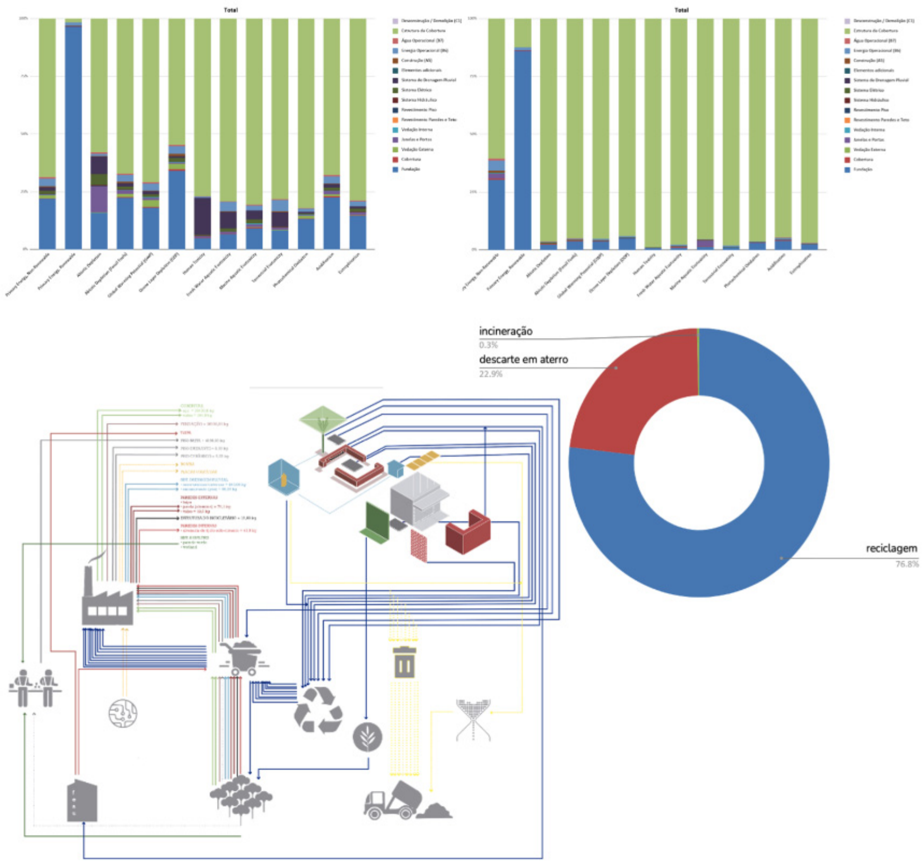


Figure 8. Illustrative excerpt of the circular design challenge hand-in board: complete circular design challenge delivery: urban equipment design, design logic for disassembly. Image courtesy: Team C (2019). Original in Portuguese.



(**a**)

(**b**)

Figure 9. Illustrative excerpt of the circular design challenge hand-in board: LCA, system mapping, and identification of circularity bottlenecks for steel (LCA I) and for wood (LCA II) structural studies (**a**). System mapping ('50 years and 1 day') and material cycle closure indicator (blue lines on mapping) for refined LCA III (**b**), avoiding 77% of landfill disposal. Image courtesy: Team C (2019). Original in Portuguese.

In the 2020 edition, offered during the pandemic, the same teaching-learning dynamic was repeated, including the semester project exercise. But students carried out the investigative exercise individually, recorded videos of the process, and uploaded them to the Google Classroom platform. A preliminary, formative design proposal presentation was introduced about three weeks before the final delivery. Students were encouraged to voice their concerns and indicate main design points they were not yet satisfied with. The instructors provided step-by-step feedback during the proposal presentations. Summaries and instructions for the next step were immediately published in the Google Classroom environment to guide further developments. The fact that it was a non-graded assessment, with time to improve the project, set a very motivated mood and students were attentive to the instructors' comments and colleagues' presentations.

A breakthrough resulted from an interdisciplinary teaching experience (UNICAMP's Architecture, Economics, and Computing Institutes), including these authors, to meet the demands of the sustainability component of the International Hub for Sustainable Development (HIDS), over the second academic semester of 2020. The online tool is the same Excel calculator developed over the multiple course offerings and made freely available to students, dressed in a web interface for increased outreach: students will be able to test their designs course wide, and future editions of the course will have more time to focus on architectural design. Figure 10 displays the tool's logical structure.

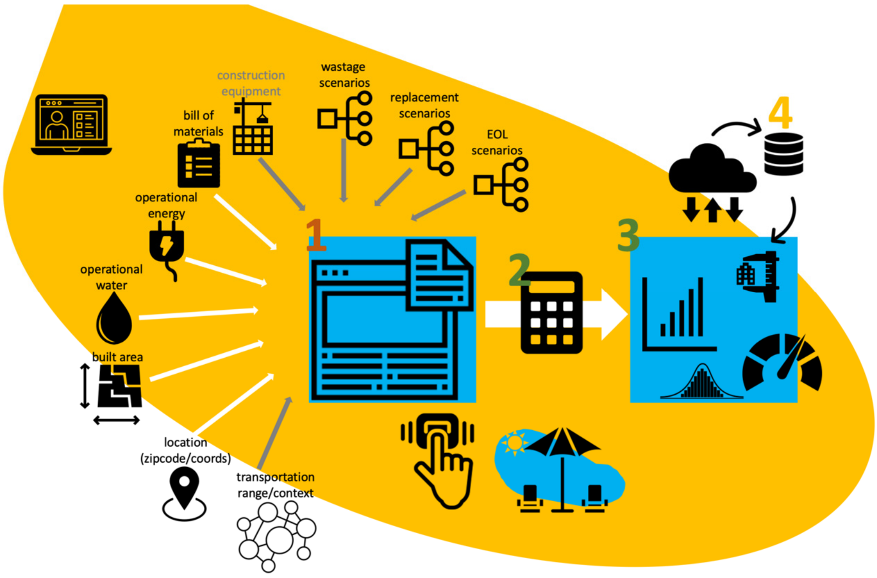


Figure 10. Online tool's logical structure: the Excel calculator developed over the multiple course offerings was dressed in a web interface for increased outreach. Its main strength is to shift time from lengthy spreadsheet preparation and automatization, towards architectural design. All context and building information required are input via a web interface (1); the calculation runs in the background (2) and results allow comparison against benchmarks (3), dynamically stored in the cloud (4).

The tool's interface (Figure 11) allows each registered user to create as many assessments as desired or to edit or delete existing ones. It is possible to adjust aspects such as service life and component replacement factors, considering various maintenance needs. Information can be input manually—by choosing materials from a pre-defined list—or by automatically loading data imported through a MS Excel template. The graphic output generates contribution analyses broken down into building materials and subsystems, as well as per life cycle stage and for the complete cycle. The corresponding data table can be downloaded (.csv file) for detailed analysis. Seed money from the Inter-American Development Bank (IADB) was granted to advance development of the online tool within the HIDS framework. The current version is based on Ecoinvent v.3.2.

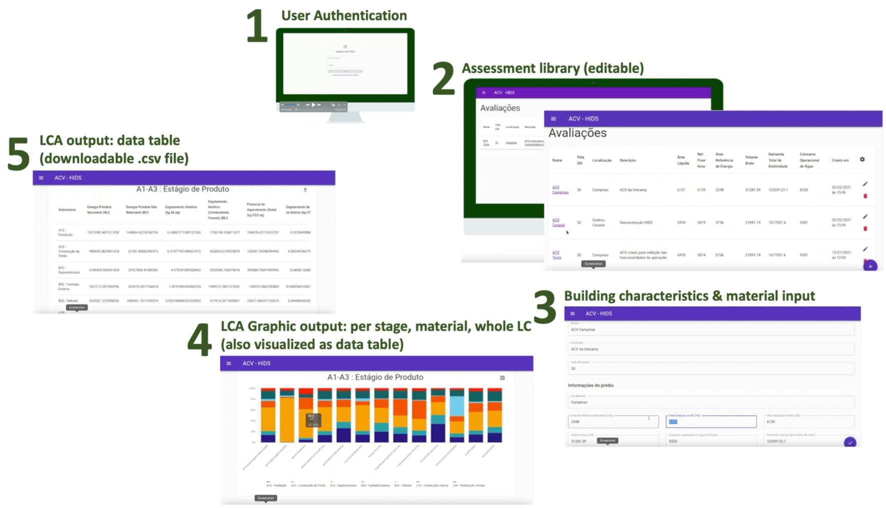


Figure 11. Online tool's interface (in Portuguese): information can be manually input or uploaded and edited as needed. Contribution analyses are broken down into building materials and subsystems, as well as per life cycle stage and for the complete cycle. The corresponding data table can be downloaded (.csv file) for detailed analysis.

5. Discussion

The course gradually evolved after the sequential cycles of reflection on the teaching practices, learning environment, and outcomes. As a result, the current course structure is shown in Figure 12.

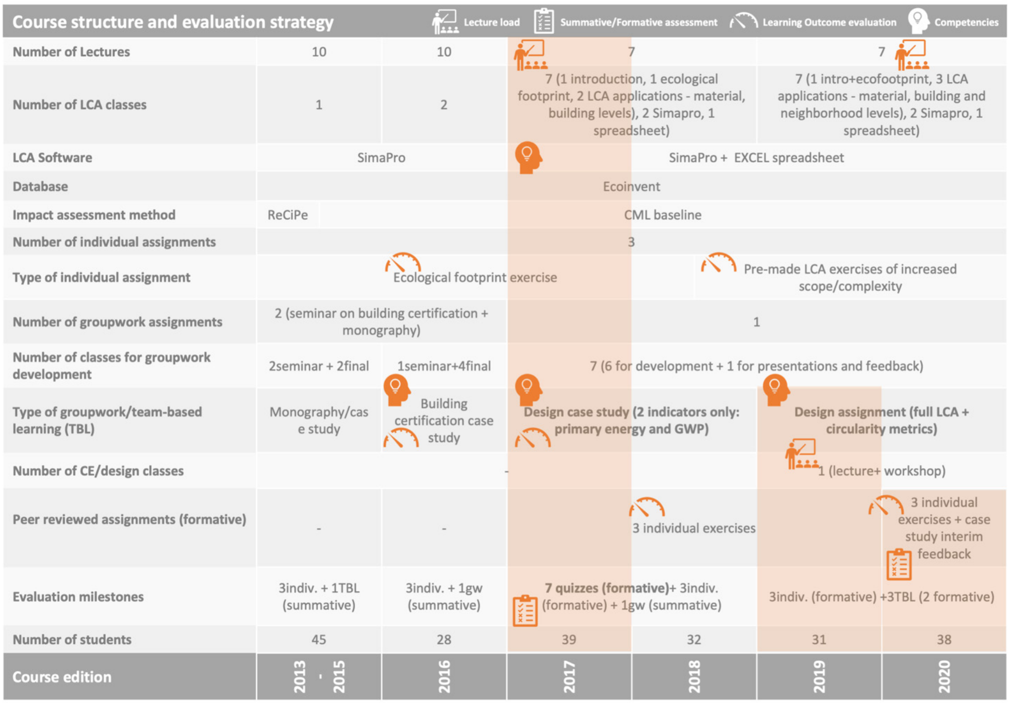


Figure 12. Course design main updates (active/passive learning, environmental assessment/design balance, evaluation focus and type, and competencies acquired) over time: major changes were implemented within the study period (2017–2020).

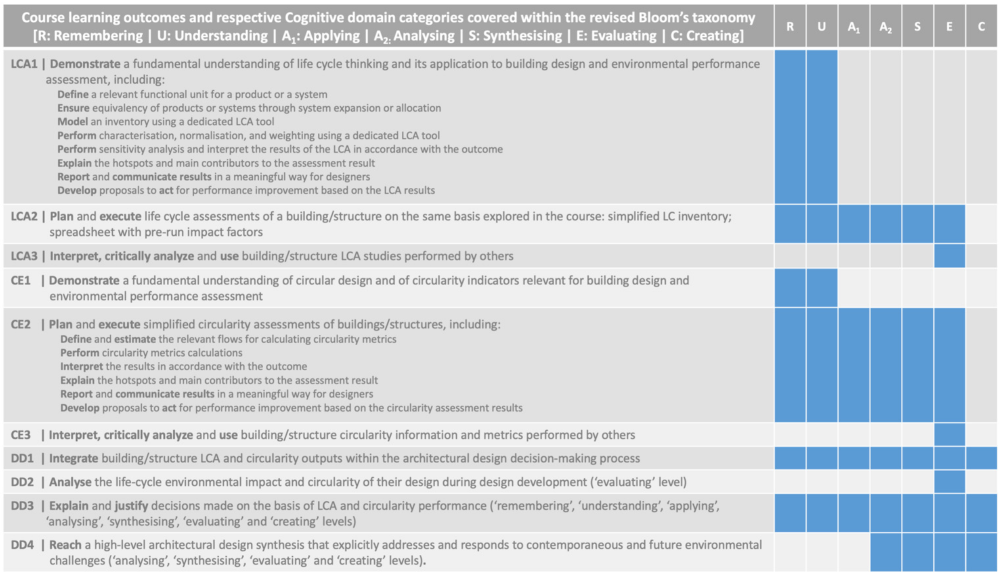
5.1. Course Structure

The course design relies on a structured combination of theoretical teaching, practical assignments, combining use of specialized LCA software for guided exercises with limited scope, and of a simplified Excel spreadsheet for the more complex assignments, explicitly guided by LCA outputs. Throughout the semester, the students design urban structures and perform LCA and circularity studies in groups to inform their design process. The design proposals undergo two LCA iterations: initial screening analyses that enlighten and support redesign opportunities for improvement demonstrated in a second assessment round. The final assessment includes the design thinking approach to achieve the pre-set circularity goals, demonstrated by metrics jointly agreed by instructors and students upfront.

With such an arrangement, and consistently with the pedagogical principle of 'learning by doing', it was finally possible to open space for the realization of a full analysis–synthesis–analysis cycle, valuable for the design activity [62]. In 2020, the course design was reapplied, with the adaptations needed to cope with the remote education mode imposed by the COVID-19 pandemic.

5.2. Alignment of Learning Outcomes and Competencies with International Practice and Recommendations

The course learning outcomes cover the entire range within the revised Bloom's taxonomy of cognitive domain categories (Figure 13), in all three learning axes: life cycle assessment (LCA), circular economy (CE), and design development (DD). LCA and CE learning outcomes focus on the most basic ('remembering' and 'understanding') or advanced ('synthetizing' and 'evaluating') levels. Separately, these also induce integration across the whole taxonomy range.



Course learning outcomes and respective Cognitive domain categories covered within the revised Bloom's taxonomy [R: Remembering | U: Understanding | A_1: Applying | A_2: Analysing | S: Synthesising | E: Evaluating | C: Creating]	R	U	A_1	A_2	S	E	C
LCA1 | **Demonstrate** a fundamental understanding of life cycle thinking and its application to building design and environmental performance assessment, including: **Define** a relevant functional unit for a product or a system **Ensure** equivalency of products or systems through system expansion or allocation **Model** an inventory using a dedicated LCA tool **Perform** characterisation, normalisation, and weighting using a dedicated LCA tool **Perform** sensitivity analysis and interpret the results of the LCA in accordance with the outcome **Explain** the hotspots and main contributors to the assessment result **Report** and **communicate results** in a meaningful way for designers **Develop** proposals to **act** for performance improvement based on the LCA results							
LCA2 | **Plan** and **execute** life cycle assessments of a building/structure on the same basis explored in the course: simplified LC inventory; spreadsheet with pre-run impact factors							
LCA3 | **Interpret, critically analyze** and **use** building/structure LCA studies performed by others							
CE1 | **Demonstrate** a fundamental understanding of circular design and of circularity indicators relevant for building design and environmental performance assessment							
CE2 | **Plan** and **execute** simplified circularity assessments of buildings/structures, including: **Define** and **estimate** the relevant flows for calculating circularity metrics **Perform** circularity metrics calculations **Interpret** the results in accordance with the outcome **Explain** the hotspots and main contributors to the assessment result **Report** and **communicate results** in a meaningful way for designers **Develop** proposals to **act** for performance improvement based on the circularity assessment results							
CE3 | **Interpret, critically analyze** and **use** building/structure circularity information and metrics performed by others							
DD1 | **Integrate** building/structure LCA and circularity outputs within the architectural design decision-making process							
DD2 | **Analyse** the life-cycle environmental impact and circularity of their design during design development ('evaluating' level)							
DD3 | **Explain** and **justify** decisions made on the basis of LCA and circularity performance ('remembering', 'understanding', 'applying', 'analysing', 'synthesising', 'evaluating' and 'creating' levels)							
DD4 | **Reach** a high-level architectural design synthesis that explicitly addresses and responds to contemporaneous and future environmental challenges ('analysing', 'synthesising', 'evaluating' and 'creating' levels).							

Figure 13. Course learning outcomes within the frame of the revised Bloom's taxonomy. LCA: life cycle assessment; CE: circular economy; DD: Design development.

In terms of learning outcomes and competencies, this course conceptually matches the characteristics and competencies expected from Level 2 LCA teaching in Viere et al.'s LCA learning and competency framework [14]. The highest cognitive domain ('creating') is expected for design development.

During knowledge acquisition, lectures are commonly used to introduce specific LCA points [1]. In higher levels of competencies, lectures tend to give room to case studies and group work, and represent less than one third or half of the total course workload [14]. An international panel invited by those authors tentatively proposed a Level 2 typical workload of about 10 h (lectures), 30 h (case study), and between 4 h (spreadsheet) and 12 h (software) for LCA supporting tools.

The main challenge still concerns total course hours. Such courses are recommended to have about 60 h in-class plus 90 h preparation and group work (between 2–5 ECTS). The SAC course has only 60 h in-class, but also aims to develop some design activity to apply environmental assessment. This highlights the benefit of increasing course hours, to imagine a two-course sequence, or to run it parallel to a regular design course and fully integrate content and design assignments. If taught right after an energy simulation course, it would strengthen the environmental axis across the program. Using the students' previous designs to assess a piece of their own authorship might bring some sense of pertaining and activate more interest than the third-party standard design, but would also circumvent the goal of infusing their design method with environmental assessment.

Cosme at al. [1] dive into details of their evaluation approach and strongly advocate for real-life, team-based case studies with external partners. Those authors mix individual graded assignments applied weekly or right after lectures. Contents and learning objectives are in line with the theoretical background given by lectures and reading material. Since the major 2017 update, the SAC course systematically uses peer-graded quizzes covering the lecture contents, that receive feedback by the instructors in the subsequent class. Anonymous (among students) peer correction and grading were introduced more recently for simultaneously offering opportunities for active knowledge acquisition, exercising analytical skills, and self-checking the acquired knowledge [1].

Case studies are protagonists of the evaluation strategy, particularly at higher competency levels. Team-based learning is particularly beneficial, not only to share the considerable workload, but also to stimulate soft skills development. The team members are requested to ensure visibility and accountability of the individual contributions as well as group interactions. Complementarily, the instructors constantly engage students in active discussions during in-class case study/design/assessment development.

Due to time constraints, feedback after quizzes, seminars, and semester project presentations is given collectively. Specific feedback is provided right after grading. Individual feedback is increasingly valued by students and is on the instructors' radar. A similar format transition was also reported by Cosme et al. [1].

5.3. Improving Learning Evidence

The literature shows varied approaches to defining adequate fulfilment of learning outcomes. Hollberg et al. [35], for example, consider a 10% reduction in life cycle energy and CO_{2eq} as a proxy of satisfactory accomplishment. In turn, Cosme et al. [1] present precise grading elements based on the expected abilities to be acquired and used an evaluation scheme that details criteria for those elements, to harmonize grading among instructors and teaching assistants.

In our course, a similar term of reference is used: a comprehensive matrix relates LCA, circularity, and design development learning outcomes (columns) to 5-level criteria described in the lines. This matrix is shared with the students and explained in the first class. Marks are calibrated in a first round of assessment, then cross-checked in a second round before disclosure to students. A companion course schematic, relating learning outcomes to content, activities, and assessments, is made available to students, and maps their way to where concepts and skills are introduced and mastery is expected.

Students' final grades across different years show improvements, but are inconclusive, partly due to the changes dynamically implemented as the courses were being taught, and partly because of how the students embraced the topic. For example, the 2018 class surprised the instructors by presenting their final assignment as a single group, providing integrated analyses that surpassed expectations. The collective analytical exercise was so brilliant that all students reached the highest mark (Figure 14).

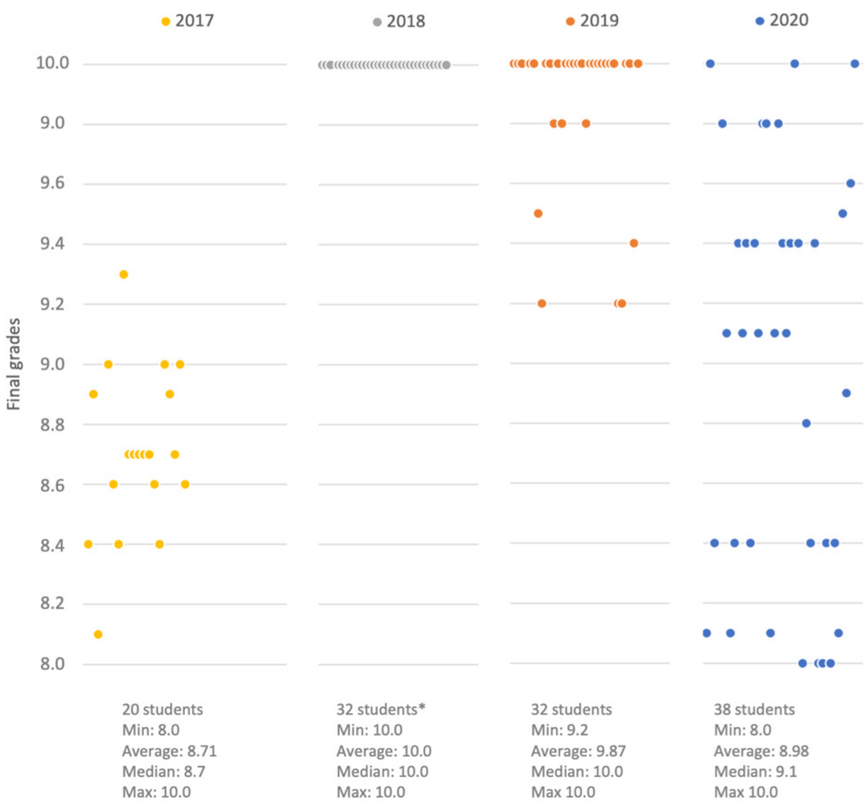


Figure 14. Final grades of classes 2017–2020. * The brilliant analytical exercise of the class of 2018 achieved the highest mark.

Measuring and managing evidence of student performance is not an easy task in the highly subjectivity design studio context. Performance expectations must be observable, include consistent evaluation practices, and use assessments that ensure the right learning outcomes are met. The goal is to capture not only a snapshot of the current performance level, but also the students' trajectory over time (process and progress). In this sense, pre- and post-assessment contrast becomes key to detect where students were initially, and which skills and competencies were acquired as a direct result of the course.

The substantial adjustment made in 2018 is too recent to support elaborate conclusions. Actual knowledge retention into professional competencies can hardly be assessed only within the course timeframe and requires some post-course follow-up of effective application to subsequent designs. The SAC course is offered at the fifth year, with no following design studios. The only missing steppingstone towards graduation is the final design studio (TFG). That studio is a heavy task for students, when they should demonstrate a high level of creativity, theoretical, technical, communication, and design abilities, expected to be mastered by future professionals.

Examining the final TFG handed in by graduates in the classes of 2018, 2019, 2020, and 2021 it became clear that students occasionally run energy analyses, and that only the few of them really connected to sustainability concerns apply sustainability analyses. This is not a failure of this course itself but signals a general flaw in emphasizing the relevance of mastering environmental performance in professional life and locking in this knowledge to design teaching foundations along the undergraduate program. This is notably more emphasized in European higher-education institutions [35]. It might also be related to the point at which it is taught during the students' academic trajectory, when it is too late to influence their design method consolidation.

5.4. Automated Online Tool to Foster Integrated LCA and Circularity Assessment in Design Process

The online tool developed was refined over time for teaching purposes, by teachers and not software developers. Hence, it is non-geometrical, non-integrated, and will require labor-intensive updates whenever the database it is based upon is substantially updated. The design materiality is described in terms of flows—material quantities and corresponding impact factors—and does not offer geometrical results visualization, an important aspect for designers. The calculator does not provide integrated assessments: designs are modelled in Autodesk REVIT©; hence, the BoQ can be automatically extracted from the model to run the LCA that estimates the embodied impacts (Ei) and uploaded to the online tool or inserted manually if not BIM integrated; a (simplified) model is simulated in Sefaira (or other package of preference) for operational energy and corresponding impact estimation (Oi); finally the life cycle impact (LC = Ei + Oi) is automatically calculated behind the scenes, following the logic of the automated spreadsheet.

For design professional design use, an ideal tool would offer geometrical input and real time energy simulations [35]. Most of all, it should be BIM-integrated, so that impacts would be automatically recalculated whenever the model is modified.

6. Conclusions

The teaching experience described in this article illustrates the strategies for reflecting advances in research on the subject within the classroom space, and the search for admissible simplification to move forward in pedagogical and formative terms. The analysis of the evolution at each offering cycle was based on four essential elements: the relationship between the components of theoretical exposition and application; the evolution of formative and summative assessment elements; the focus of summative assessments; and on how effectively environmental information underpinned the decision-making process during design project development.

The design topic was gradually changed to limit the design object complexity until the most adequate balance of the two main learning outcomes (environmental assessment and architectural design) was reached in the last two offerings. Design subjects can change again, as long as they fulfil requirements (complexity of design, complexity of LCA, potential for the circularity challenge) for respecting this balance.

The long-term study pointed to the following main conclusions:

- Non-LCA expert undergraduate students can successfully apply the analysis during the design development with compatible—but not excessive—additional effort if equipped with adequate tools;
- Blindly applying LCA calculators has limited learning retention. Basic LCA qualification and practice in small exercises are needed—and effective—for awareness raising and holistically understanding design implications;
- Formative assessment elements play an undisputable role in ensuring a fruitful and dialogical teaching-learning experience, particularly the intermediate design hand-in followed by immediate instructors' feedback before final design submittal; and
- Design quality results from multiple factors. Though flawed initial ideas would tend to carry those failures up to the end, improved environmental performance was clearly demonstrated by all teams;
- An optimal balance between theoretical exposition and application seems to have been found to effectively support achievement of the established learning outcomes; and
- LCA learning outcomes were quasi-satisfactorily balanced with design learning objectives and should be further explored in future course editions.

The final course evaluation revealed the extremely positive reaction of students to the opportunity to improve their projects and work on the points indicated by the teaching team, instead of just knowing their final grades; and to effectively understand the impacts of their decisions as designers and what should really be considered when naming a project as more sustainable or not. By the end of the semester, it became clear to the students that this procedure could be subsequently applied not only in their Final Graduation Studio, but also in their upcoming professional practice.

The course was not offered in 2021 but will be resumed in the second academic semester of 2022, in person. The automated wbLCA tool will allow students in upcoming offers to finally understand LCA and CE, with more agile analyses that give maximum space to the discipline's core activity: developing projects for sustainability, accounting for and knowing the implications of their decisions, and to exercise with confidence the environmental responsibility that is incumbent on designers. The knowledge acquired in this teaching experience is transferable to other similar design disciplines and practice. When fully implemented, the online tool will be made freely available to any students and should be operational until major changes in databases and average data occur.

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Appendix A

Mid-term and ex-post feedback survey, relating research questions and course design to students' perceptions (class of 2019, 32 students).

RQ1 ["What are the minimum and sufficient theoretical contents for the transmission of the necessary basis for the development of the exercises and the semester project?"]	Do you think that the theoretical contents are sufficient to provide the abilities required for environmental assessment over design development?						
	Totally agree 8/32 (25%)	Mostly agree 20/32 (62.5%)	Agree 4/32 (12.5%)	Neutral	Disagree	Mostly disagree	Totally disagree
	If you disagree at any level, would you please explain the reasons? If you agree at any level, could you please indicate the course highlights? In any case, could you please suggest opportunity for improvement?						
	Do you think that the theoretical contents are sufficient to provide the abilities required for circularity assessment over design development?						
	Totally agree	Mostly agree 22/32 (68.75%)	Agree 10/32 (31.25%)	Neutral	Disagree	Mostly disagree	Totally disagree
	If you disagree at any level, would you please explain the reasons? If you agree at any level, could you please indicate the course highlights? In any case, could you please suggest opportunity for improvement?						
	Are the lectures content sufficient and (intensive) format adequate to support development of the semester project?						
	Totally agree 30/32 (93.75%)	Mostly agree 2/32 (6.25%)	Agree	Neutral	Disagree	Mostly disagree	Totally disagree
	If you disagree at any level, would you please explain the reasons? If you agree at any level, could you please indicate the course highlights? In any case, could you please suggest opportunity for improvement?						
RQ2 ["What are the most adequate workloads and teaching-learning dynamics to raise awareness and provide training in life cycle modelling compatible with architecture and urbanism students and with application to buildings?"]	Do you think the overall teaching/learning/evaluation strategy used ensures that the design outcome is effectively informed and refined based on environmental performance results?						
	Totally agree 2/32 (6.25%)	Mostly agree 10/32 (31.25%)	Agree 8/32 (25%)	Neutral 8/32 (25%)	Disagree 4/32 (12.5%)	Mostly disagree	Totally disagree
	If you disagree at any level, would you please explain the reasons? If you agree at any level, could you please indicate the course highlights? In any case, could you please suggest opportunity for improvement?						
	Do you think the teaching-learning dynamics used effectively raised awareness and provided the needed training?						
	Totally agree 2/32 (6.25%)	Mostly agree 10/32 (31.25%)	Agree 8/32 (25%)	Neutral 8/32 (25%)	Disagree 4/32 (12.5%)	Mostly disagree	Totally disagree
	If you disagree at any level, would you please explain the reasons? If you agree at any level, could you please indicate the course highlights? In any case, could you please suggest opportunity for improvement?						
	Do you think the workload for this course is compatible with the credits sum and timely positioned in your academic trajectory?						
	Totally agree	Mostly agree 4/32 (12.5%)	Agree 8/32 (18.75%)	Neutral 6/32 (15%)	Disagree 10/32 (31.25%)	Mostly disagree 2/32 (6.25%)	Totally disagree 2/32 (6.25%)
	If you disagree at any level, would you please explain the reasons? If you agree at any level, could you please indicate the course highlights? In any case, could you please suggest opportunity for improvement?						
	Do you think the exercises enabled to satisfactorily carry out the semester project?						
	Totally agree 30/32 (93.75%)	Mostly agree 2/32 (6.25%)	Agree	Neutral	Disagree	Mostly disagree	Totally disagree
	If you disagree at any level, would you please explain the reasons? If you agree at any level, could you please indicate the course highlights? In any case, could you please suggest opportunity for improvement?						

RQ3 ["How to awake the perception and stimulate the dynamics between performance estimation and feedback into design development decision-making process?"]	Do you think the evaluation strategy (formative + summative assessments) used adequately reveals knowledge retention and evolution, and skills acquirement over the course?						
	Totally agree 12/32 (37.5%)	Mostly agree 10/32 (31.25%)	Agree 8/32 (25%)	Neutral	Disagree 2/32 (6.25%)	Mostly disagree	Totally disagree
	If you disagree at any level, would you please explain the reasons? If you agree at any level, could you please indicate the course highlights? In any case, could you please suggest opportunity for improvement?						
	Do you think the evaluation strategy (formative + summative assessments) used focuses on the important knowledge elements and abilities?						
	Totally agree 30/32 (93.75%)	Mostly agree 2/32 (6.25%)	Agree	Neutral	Disagree	Mostly disagree	Totally disagree
	If you disagree at any level, would you please explain the reasons? If you agree at any level, could you please indicate the course highlights? In any case, could you please suggest opportunity for improvement?						
	Do you think that complexity and comprehensiveness of the environmental (e.g. simulation, LCA) modelling are compatible with the semester project scope?						
	Totally agree 8/32 (25%)	Mostly agree 12/32 (37.5%)	Agree 8/32 (25%)	Neutral	Disagree 2/32 (6.25%)	Mostly disagree 2/32 (6.25%)	Totally disagree
	If you disagree at any level, would you please explain the reasons? If you agree at any level, could you please indicate the course highlights? In any case, could you please suggest opportunity for improvement?						
	Do you think that complexity and comprehensiveness of the LCA modelling are compatible with architectural design studio practice?						
	Totally agree	Mostly agree 8/32 (25%)	Agree 4/32 (12.5%)	Neutral 12/32 (37.5%)	Disagree 4/32 (12.5%)	Mostly disagree 4/32 (12.5%)	Totally disagree
	If you disagree at any level, would you please explain the reasons? If you agree at any level, could you please indicate the course highlights? In any case, could you please suggest opportunity for improvement?						
RQ 4a [How to awake the perception and stimulatethe dynamics between performance estimation and feedback into design development decision-making process?] and RQ4b [Potentialfor active learning methods"]	Do you think that an interim proposal presentation could improve final design quality (e.g., by assisting in identifying critical issues, difficulties and misinterpretations, and opportunities for project improvement?)						
	Totally agree 32/32 (100%)	Mostly agree	Agree	Neutral	Disagree	Mostly disagree	Totally disagree
	If you disagree at any level, would you please explain the reasons? If you agree at any level, could you please indicate the course highlights? In any case, could you please suggest opportunity for improvement?						
	Do you think that active learning methods (e.g., flipped classroom) suit well the initial topics and ensured effective integration of the learning objectives (LCA and circularity assessment) into the design process?						
	Totally agree 8/32 (25%)	Mostly agree 12/32 (37.5%)	Agree 8/32 (25%)	Neutral -	Disagree 2/32 (6.25%)	Mostly disagree 2/32 (6.25%)	Totally disagree
	If you disagree at any level, would you please explain the reasons? If you agree at any level, could you please indicate the course highlights? In any case, could you please suggest opportunity for improvement?						

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