Alexander Hollberg, Guillaume Habert, Philipp Schwan, Linda Hildebrand:

POTENCIALI IN OMEJITVE OKOLJSKIH VIDIKOV ZASNOVE Z UPORABO ORODIJ ZA OCENO ŽIVLJENJSKEGA CIKLA

POTENTIAL AND LIMITATIONS OF ENVIRONMENTAL DESIGN WITH LCA TOOLS

DOI: http://dx.doi.org/10.15292/IU-CG.2017.05.034-045 ■ UDK: 72.012.1 : 502 ■ 1.02 Pregledni znanstveni članek / Review Article ■ SUBMITTED: July 2017 / REVISED: September 2017 / PUBLISHED: November 2017

IZVLEČEK

Grajeno okolje ima velik vpliv na okolje. Arhitekti v načrtu lahko v veliki meri določijo, kakšne vplive na okolje bo imela stavba v svojem življenjskem ciklusu. Na izbiro materiala in vrsto gradbenih objektov lahko vplivamo že v začetnih fazah načrtovanja. Za merjenje vplivov na okolje se uporabljajo orodja za oceno življenjskega cikla (angl. life cycle assessment – LCA). Članek obravnava rezultate štirih študij primera, v katerih so bila uporabljena štiri nova orodja za oceno življenjskega cikla, in sicer pri štirih akademskih predmetih na različnih univerzah. Rezultati kažejo, da je uspeh orodij za oceno življenjskega cikla v veliki meri odvisen od časa, ko se orodje v procesu načrtovanja uporabi, in strategije za načrtovanje, ki ji študent sledi. Če se ob pravem času uporabi pravo orodje, in to ustreza strategiji načrtovanja, lahko izboljšamo kakovost arhitekture in zmanjšamo vplive na okolje. V večini primerov pa čas uporabe ni bi ustrezen, posledica tega pa so bili dodatni napori ob uporabi orodja za oceno življenjskega cikla. Arhitekturno načrtovanje in izboljšanje okoljske uspešnosti zato med seboj konkurirata. Pri tem pa trpi kakovost arhitekture ali pa se orodje uporabi (pre)pozno in okoljske uspešnosti ni več mogoče izboljšati. Četudi je čas uporabe orodja pravi, je uspeh v veliki meri odvisen od strategije načrtovanja. Število orodij narašča, za vsako fazo projektiranja je na voljo ustrezno orodje. Strategija načrtovanja se moram ujemati z orodjem, to pa zahteva pripravljenost, da pristope k načrtovanju prilagajamo. V preteklosti so bila vprašanja okoljskih vidikov načrtovanja povezana s pomanjkanjem ustreznih orodij, danes pa problem predstavlja pomanjkanje ustreznih pristopov k načrtovanju. Poučevanje o uporabi orodij na seminarjih je enostavno. Strategije okoljskega načrtovanja moramo vključevati v projektiranje in jih razvijati v vseh fazah načrtovanja, da postanejo tudi del arhitekturnega izobraževanja.

KLJUČNE BESEDE

orodja za oceno življenjskega cikla (LCA), okoljski vidiki zasnove, faza arhitekturnega načrtovanja

ABSTRACT

The built environment has a very high impact on the environment. Architects can largely define the environmental impact a building will cause throughout its lifetime through its design. Especially the choice of material and the type of construction can be influenced in early design stages. To quantify the environmental impact, tools for Life Cycle Assessment (LCA) are used. This paper discusses the results of four case studies of applying four different novel LCA tools in four different academic courses at different universities. The results show that the success of applying LCA tools highly depends on the point of time during the design process and the design strategy the student pursues. If the right tool is used at the right moment and matches the design strategy, it can help to improve the architectural quality and reduce environmental impacts. In most cases however, the time of application did not fit, resulting in additional effort for applying the LCA tool. In consequence, the architectural elaboration of the design and the improvement of environmental performance compete against each other. Either the architectural quality suffers or the tool is employed late and the environmental performance cannot be improved. Even if the point in time of the tool application is right, the success depends highly on the design strategy. The number of tools is growing and there is an adequate tool available for each design stage. The design strategy has to match the tool and this requires a willingness to adapt the design approach. The issue of environmental design shifted from a lack of adequate tools to the lack of adequate design approaches. Tools can be easily taught in seminars. Environmental design strategies, however, have to be included in design studios and developed throughout the entire design phase to become part of architectural education.

KEY-WORDS

LCA, -tools, environmental design, architectural design phase,n

1. INTRODUCTION

1.1 Scope of environmental impact by architects

The built environment is responsible for one third of the global greenhouse gas emissions and more than 40% of the world's primary energy demand (UNEP SBCI, 2009). Additionally, approximately 50% of the world's processed raw materials are used for construction (Hegger, Fuchs, Stark, & Zeumer, 2007). Architects largely define the resource demand and environmental impact a building will cause within the next 50 to 100 years. While the energy to operate the building is influenced by user behaviour, the embodied energy and emissions are predefined by the building geometry, material choice and construction. To assess the energy embodied in the material and the emissions released during production and disposal, waste processing or recycling, the internationally standardized method of Life Cycle Assessment (LCA) is commonly used. LCA involves the evaluation of the environmental aspects of a product or service throughout all stages of its life cycle. It has originally been developed in the 1970s to evaluate consumer products such as beverage packaging (Klöpffer & Grahl, 2014). Since then LCA has become a widespread method for environmental impact assessment of consumer products and services. In the last ten years, it has also increasingly been applied for the assessment of buildings, especially in an academic context (Weißenberger, Jensch, and Lang 2014). However, evaluating the building design through LCA is not sufficient on its own, as it does not improve the design (Wittstock et al. 2009). To minimize environmental impacts, an integration of LCA into the architectural design process is needed.

1.2 Architectural Design Stages

In general, the planning process of a building can be divided into three main phases, namely pre-design, design, and execution. According to the plans developed in the planning phase, the building is realized, handed over to the client and the use phase begins. During pre-design the client defines the design task or it is developed in collaboration between architect and client. During the design phase, most parameters that influence the environmental performance of a building are defined. Therefore, this paper focusses on the design stage. In addition, architectural education in universities focusses mostly on the design stage. In most industrialized countries, the design phase is divided into several parts which serve as a basis for the calculation of architects' fees (El Khouli, John, & Zeumer, 2014). For this paper, the structure described by Royal Institute of British Architects (RIBA, 2013) is employed, which divides the design process into three parts, namely:

- Concept design
- Developed design
- Technical design

The main tasks of each phase are described in the following. In concept design the general design idea is developed, functional requirements are described and the design tasks are defined by geometric parameters including volume, orientation, etc. The developed design can include decisions on the type of construction, for example whether a skeleton structure or monolithic walls will be used. Definition of the building materials, the connections between different materials, and the HVAC systems occur in the technical design with increasing level of detail. The circularity (re-use or recycling potential) is defined by the type of connection and the material choice in these phases.

In general, decisions made in the early stages of the design process, have the greatest influence, as they set general conditions for the subsequent design process (Paulson Jr. 1976, p.588). As such, the concept and developed design phase have the highest influence on both operational energy demand (Hegger et al. 2007, p.180) and the environmental impacts (Schneider 2011, p.39). This highlights the important role architects and designers play in climate change mitigation and resource efficiency even if they might not always be aware of it. Clearly, there is the demand for integrating environmental aspects in the design process.

The decisions taken in each part depend on the strategy of the designer and are individual. The phases introduced provide comparability for the decisions made in the architectural planning process.

1.3 Relevance of tools in environmental design

For the integration of environmental concerns, architects need to be informed about the interdependencies between design decision and environmental impact. They can be advised by engineers or environmental scientist or use tools that calculate and visualise the effects of design decisions. In concept and developed design, architects usually work alone, without advising engineers or scientists. Therefore, they often have to rely on simplified computational tools. In the last 10 years, software programs have been developed to include an increasing number of functions, among them the calculation of the operational energy demand and the integration of energy and emission embodied in the building materials. Due to the increasing use of 3D models and the rapid development of computation power, it is now possible to provide real-time feedback on analysis results during the design. This enables architects to receive quantified information during the design process without much additional effort. To allow for design-integrated application, tools need to match the level of detail of current design stage and support decision necessary according to the process of the project.

1.4 Student course as case studies for environmental design

Architectural education has a long tradition of teaching in design studios. The students develop solutions, receive feedback from professors and other students and refine their solutions based on the feedback (Kvan & Yunyan, 2005). In the last two decades, design studios have increasingly focussed on environmental aspects in a qualitative way, for example energy efficiency (Heidenreich & Schütz, 2010), eco-design (Suau, 2013) and reuse projects (for example the student design and built projects "Recycling Mies" (designbuildxchange, 2016) in Aachen or "Die Lücke" (Baunetz, 2016)) in Weimar). The approach of research-lead teaching provides advantages for both,

Table 1: Overview on courses.

Case study	I	II	III	IV
Course name	Sustainable Construction	Cycle-oriented Construction	Link-in-Energy	Environmental Design Strategies
LCA tools	Lixcel	rb-tool	PLCA-tool	CAALA, rb-tool
Assignment	Design of an office building, optimisation using LCA	Optimising type of construction and material choice using LCA and recycling aspects	Definition of design task, Design of a building, optimisation using LCA	Design of student housing, optimisation using LCA
Design stages	Concept design, developed design, technical design	Developed design, technical design	Pre-design, concept design, developed design	Concept design, developed design
Number of students	49	28	36	11
Stage of education	Bachelor	Master	Master	Master, Bachelor
University	Detmolder Schule für Architektur und Innenarchitektur, Germany	RWTH Aachen, Germany	Bauhaus University Weimar, Germany; University of Mersin, Turkey	Bauhaus University Weimar; ETH Zurich, Switzerland; RWTH Aachen
Month /year the course was held	Sep./10 to Feb./11	Oct./16 to Jan/17	Oct./14 to Jan. /15	August/17

teacher and students; Students gain access to latest findings and lecturers and researcher receive feedback on questions they are working on. In this context, the student courses presented in this paper have not been specifically designed to answer the research questions. Years of using LCA tools in student education reflected the interaction of the design phases and the LCA tool. To evaluate the relationship between the design process and the LCA tools, case studies where selected which used different tools in different phases of the design process. The student courses as case studies embody the advantage to include the phases from concept to technical design. The completeness in a defined time period mimics the design process in an architectural office.

While environmental aspects of the project can be collected and quantified by the LCA tools, the architectural dimension is non-quantifiable and up to the creativity of the designer. The evaluation of architectural quality is always a complex task and part of any design assignment in architectural studies. In the scope of this research, the critical feedback of professors and lecturers of the student courses are taken as bases for the integration of architectural design.

This paper discusses the potential and limitations of applying different LCA software programs in the architectural design process based on four student courses. It characterizes different tools and reflects the stage of its useful application. It discusses the relevance of each design phase and the depth of information in different tools needed for each stage. The findings can improve the education in architectural design courses. The suitable combination of LCA tools and design phase can help to develop sustainable buildings including a reliable review of the environmental quality. Additionally, the insights can be used for practising architects who want to apply LCA tools in early design phases.

The paper is structured in three parts: The first provides background and motivation. The second introduces the three case studies (chapter 2) and shows their results (chapter 3), while the third and last includes the discussion (chapter 4) and the conclusion (chapter 5).

2. CASE STUDY DESCRIPTION

In this chapter, the case study courses are described regarding their content, the assignment and goal, the number of students and the university as well as the LCA tool used. Table 1 provides an overview of the basic parameters of each course.

The case studies are chosen to provide a variety of LCA tools and stages in which they were introduced. Beyond that, the knowledge levels of the students differed (in some courses the assignment was embedded in lectures on sustainability and LCA in particular others came without any prior knowledge) and different time spans to work on the project, too. The focus on environmental design and the focus on the design stage was common for all courses.

2.1 LCA tools

LCA software programs in architecture became common in the last decade as environmental data on building material was increasingly available in the form of Environmental Product Declarations (EPDs) (Passer et al., 2015) or national databases. Institutions provide open access to databases like Ökobau.dat (BBSR, 2016) and Wecobis (Haas & Asam, 2014) and with knowledge on the method of LCA, the data can be linked to the building substance. The first software programs providing this link were based on spreadsheets. The second generation of LCA tools are based on 3D CAD models and include functions like the export of volumes and finally the integration of LCA databases.

Bach & Hildebrand (2017) describe differences in LCA software products in architecture by the eight categories product origin, data source, required user's knowledge, default settings, accessibility, entry format, level and life cycle settings. A brief overview of the tools is given structured according to these differences (Table 2). The tools used here have the same origin (Germany) and use the same data source (Ökobau.dat). The required user's knowledge on environmental design varies among the tools and is related

UVODNIK
EDITORIAL
ČLANEK
ARTICLE
RAZPRAVA
DISCUSSION
RECENZIJA
REVIEW
PROJEKT
PROJECT
DELAVNICA
WORKSHOP
NATEČAJ
COMPETITION
PREDSTAVITEV
PRESENTATION
DIPLOMA
MASTER THESIS

Table 2: Overview on LCA tools.

	Lixcel	Rb-tool	PLCA-tool	CAALA
Product origin	Germany	Germany	Germany	Germany
Data source	Ökobau.dat 2011	Ökobau.dat 2016	Ökobau.dat 2013	Ökobau.dat 2016
Required user's knowledge	High	Basic	Medium	basic
Default settings	No	Yes	Yes	yes
Accessibility	Free	Free	Free	Free (educational version)
Entry format	Spreadsheet	3D model	3D model	3D model
Level	Whole building	Building component	Whole building	Whole building
Life cycle settings	Production End-of-life	Production, use End-of-life	Production, use, End-of-life, recycling	Production, use, End-of-life, recycling
Life cycle modules (EN 15978)	A1-A3 C3, C4	A1-A3, B4, C3, C4	A1-A3, B4, B6, C3, C4, D	A1-A3, B4, B6, C3, C4, D

to the default settings. Lixcel needs very detailed information and delivers reliable results only when all data is filled in correctly which leads to a comparable high level of user knowledge. The rb-tool, PLCA and CAALA include default settings and the user needs only basic knowledge. The accessibility is less relevant in this context as the software products were made available to all students. The format to enter information is geometric for the three tools rb-tool, PLCA and CAALA. Lixcel works spreadsheet based. Lixcel, PLCA and CAALA calculate the environmental performance on building level. Rb--tool only looks at the materials and construction on building element level. Lixel considers the life cycle phases production and end of life, PLCA and CAALA include production, building operation and end of life while rb-tool contains the use phase and the end of life.

In the following, the programs are introduced by brief description.

2.1.1 Lixcel

In the beginning of this century, a variety of excel-based spreadsheets was developed to calculate the embodied energy and embodied global warming potential of buildings. Their main purpose was the connection of a database with environmental information referring to one kilogram or one square meter of material and the volume or mass of the material in the construction. The spreadsheet tables could be customised to the scope of the task. Factors, like the life span of materials and the building, the indicators and the information depth could be adjusted. *Lixcel* was developed at the Detmolder Schule für Architektur und Innenarchitektur, Chair for Building Construction and Design specifically for student application.

Lixcel consists of three spreadsheets; results, entry format and life span of buildings materials. The entry table is organised in cost groups following DIN 276 (DIN, 2008).

Lixcel was subject to a high error rate and eliminating these made the use time-consuming and inconvenient. It was limited to university use only from 2009-2014 when 3D programs with LCA plug-in where insight but the embedded LCA was not reliable yet.

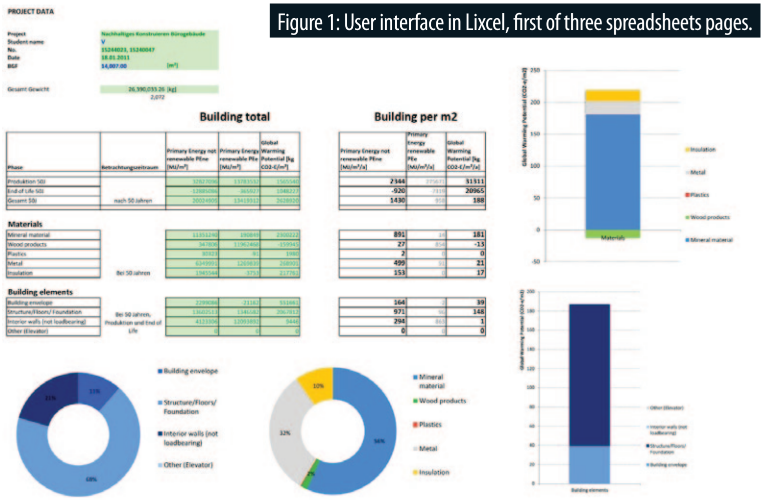


Figure 1: User interface in Lixcel, first of three spreadsheets pages.

2.1.2 rb-tool

The capabilities of 3D CAD software programs grew in the last years and plug-ins for different functions were programmed. The *rb-tool* was developed at RWTH Aachen University, Institute for Reuse in Architecture as a plug-in for Autodesk Revit for student application. The aim is to calculate the embodied energy and embodied global warming potential of building elements and indicate the ability for further use, namely reuse, recycling and landfill. The tool includes LCA values from the Ökobau.dat (2014) for the production phase and connects the further use scenario and on the LCA results in one graph (Figure 2). It includes the Revit user interface and graphical illustration which provides results in real-time. The building elements are drawn in 3D, the materials are chosen from a library and so are the type of connection between material layers. The students did not need basic knowledge of the LCA method and of reuse and recycling scenarios as the library automatically associates LCA data and information on further use scenario based on material and type of connection.

Figure 2: User interface of the rb-tool in Revit.

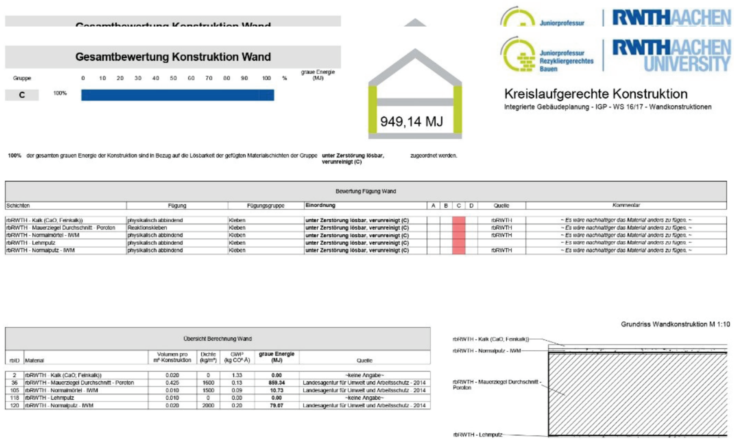


Figure 5: Visualization of results in Rhino.

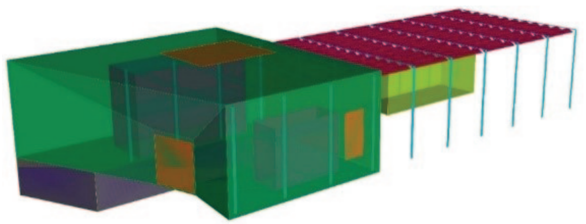
2.1.3 PLCA-tool

To make LCA applicable for parametric design, a method named *Parametric life cycle assessment* (PLCA) has been developed (Hollberg, 2016). The prototype tool was developed in Grasshopper, a parametric plug-in for the 3D CAD software Rhinoceros. The main difference to other LCA or building energy performance tools is the combined calculation of operational and embodied energy (and other environmental indicators). The 3D model is drawn in Rhinoceros (Figure 3). The materials and HVAC systems are input in Grasshopper using drop down lists and sliders (Figure 4). The simulation of the operational energy demand is based on the EnergyPlus (DOE, 2015) engine. A self-develop script calculates the embodied impact using the German Ökobau.dat database 2013 (Hollberg & Ruth, 2016). The results are visualized in a Rhinoceros viewport showing the non-renewable primary energy and global warming potential (Figure 5).

2.1.4 CAALA

A cloud-based plug-in for SketchUp called *CAALA* was developed based on findings from using the PLCA-tool. The software automatically collects the areas of different building components from SketchUp and calculates both, operational and embodied environmental impacts. For the operational energy demand calculation, a simplified monthly quasi-steady approach based on DIN V 18599 (DIN, 2011) is employed (Hollberg, Lichtenheld, Klüber, & Ruth, 2017). The embodied impact is calculated using the database Ökobau.dat 2016 and the simplification rules of the DGNB system (German Sustainable Building Council, 2015) are employed.

Figure 3: Geometry model in Rhino.



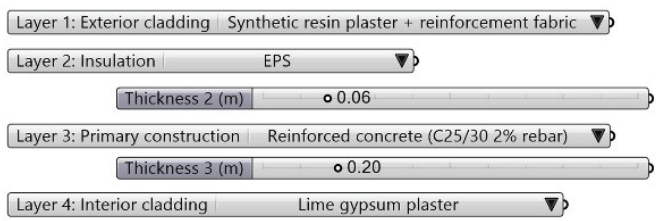
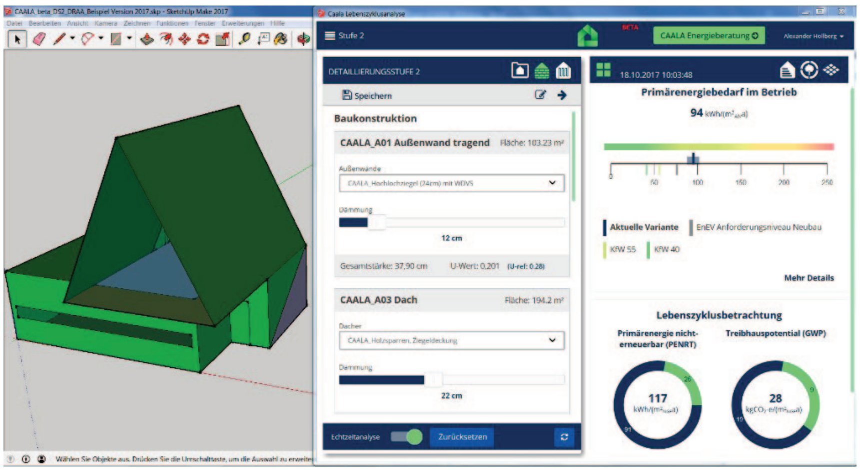


Figure 4: Parametric material definition in GH.

Figure 6: User interface of CAALA (left: SketchUp modelling environment, right: input of materials and visualization of results in browser window).



2.2 The student courses and assignments

All courses aimed at teaching architectural students LCA and its application for environmental design. They were held at and in cooperation with different universities, namely the Bauhaus University Weimar, Detmolder Schule für Architektur und Innenarchitektur, ETH Zürich, University of Mersin and RWTH Aachen University. All courses were supervised by at least one of the authors. The duration of the course varied from semester-long to two full--time weeks. Lectures on sustainable design with different extent accompanied the design assignments. The level of knowledge on environmental design strategies or LCA in particular varied among the students.

2.2.1 Course and assignment – Sustainable Construction

The course *Sustainable Construction* was held between the years 2008-2013 by the Chair of Building Technology and Design for 65-80 bachelor students of architecture at the Detmolder Schule. The students heard lectures on Sustainable Construction and the method of LCA was taught. The students were expected to have basic knowledge of LCA when working with Lixcel. The case study includes the winter semester 2010 after Lixcel underwent its first optimisation cycle. The assignment included the design of an office building and an LCA for the building materials. The course was structured in three parts. In the first phase, the design concept was developed, in the second the type of construction was planned and in the third, the LCA calculation was made. The students worked in groups of two. The assignment was the same during five years with only little variation. In one aspect, this course was different to the others. By mistake, the LCA tool Lixcel was made available to the students during the concept-phase while it was planned to be handed out in the developed-phase. Most of the students used the LCA tool without the supervisor's knowledge, filled in the materials and copied LCA flows from a prepared spreadsheet. The assignment included the definition of the material, the volume, its density and the expected life span. Data were inserted for the LCA phases production and end-of-life. Lixcel then calculated the exchange cycles and showed the results on the first sheet. The level of required information was very detailed.

2.2.1 Course and assignment – Cycle-Oriented Construction

The master-course *Cycle-Oriented Construction* was held in the winter semester 2016. 30 architecture students joined the weekly course for lectures. The assignment was structured in three parts. First, a reference building was defined and the relevant building elements were identified. Each material and type of construction were planned in detail for one square meter of the chosen building elements. Based on this, LCA values for the production were calculated manually and the further-use-scenarios after the end-of--life of the specific building element were defined manually. In this way, the students learn to apply the LCA method and the scenarios for further use. In a second step, the rb-tool was used to do the same, LCA calculation and referencing the further use scenarios. In the third phase, the building elements were optimised regarding their environmental impact by decreasing the LCA values or improving the further-use scenario.

2.2.2 Course and assignment – Link-in-Energy

The third case study is based on the design studio called *Link-in-Energy* held at Bauhaus University Weimar and University of Mersin in 2015 (Hollberg et al., 2016). The 36 students were all in the master programme of architecture. The design task consisted in developing a use scenario and designing a building for the historic city of Tarsus, south Turkey. The environmental aspect was one of the main criteria from the beginning of the project and all students received introductory lectures on sustainability, energy concepts, LCA and the importance of embodied energy in building materials. Nine students (Group 1) took part in a seminar for design-integrated LCA using the PLCA-tool. The students were asked to improve the environmental performance of their building by generating and comparing different design variants. The goal was to lower the environmental impact as far as possible. The first part of the semester focused on the improvement of the geometry. A default material configuration had been provided for the students, which served as a baseline scenario. For the second part of the semester, the students should model their individual materials to improve the environmental performance further. The 27 students that did not take part in the LCA seminar (Group 2) had the same design task and were asked to base their environmental concept based on the qualitative information they received in the lectures. They had to hand in a 3D model of the geometry and a list of materials at the end of the project. The supervisors used the PLCA-tool to calculate the LCA results.

2.2.3 Course and assignment - Environmental Design Strategies

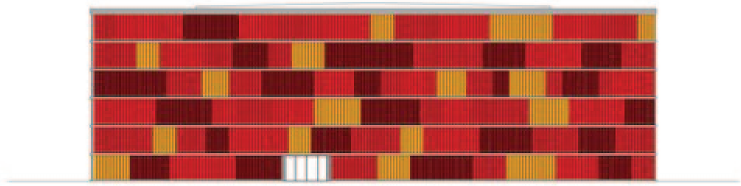
The course *Environmental Design Strategies* took place in Weimar as part of the Bauhaus Summer School in August 2017. During two weeks, an international group of 11 students worked in interdisciplinary pairs of two. The task was to develop an environmentally friendly design for a student apartment house for 45 students in Weimar. The course focused on the environmental aspects of the building design, including an energy- and a material concept. The students received an introductory lecture and then started developing a concept on the first day. This concept was refined on day two after a visit to the building site. On the third day, all students were introduced to CAALA. They presented their projects roughly every second day and could acquire feedback from the supervisors at any time.

3. CASE STUDY RESULTS

The challenge of the course assignments was the integration of both, the design and functional requirements with environmental performance. In this chapter, the courses' results are documented and discussed regarding both aspects.

Next to the description of the outcome, for each course a graph summarizes the environmental performance on the y-axis and the architectural quality on the x-axis. The indicator for the environmental performance depends on the tool applied, for example minimum embodied primary energy. The architectural quality can only be evaluated in a qualitative way. The graphs represent the grades given by the individual supervisors for the

Figure 7: left design by Group 1, right design by Group 2.



architectural design. Clearly, the aim of each course was to achieve results in the upper right quarter – high environmental performance combined with high architectural quality.

3.1 Results - Sustainable Construction

The results for the course included an office design, documented by drawings and the LCA results. Sub-grades were given for the three parts of the assignment "concept and design", "definition of the type construction" and "LCA". Compared to the results from the previous semesters and the ones following, the "concept and design" grades where approximately 30% worse. Partly, the concept was poorly elaborated or the ideas for the building design were lost when using the LCA tool.

The initial assignment of the course included to first finish the work on the architectural characteristics including volume, openings, organisation of the functions, then elaborating this further on the type of construction and apply the LCA tool to exchange materials or compare different construction types. In this course, often the first design idea was calculated in Lixcel and design parameters, like geometry and orientation, were used to improve the environmental performance. The results the tool provides improve when reducing the building volume and all building elements with high values for embodied energy, like windows. The students did not reflect the consequences this had on the architectural characteristics. Some groups continued working on the initial architectural concept, probably as entering data for design alternatives was time intensive. Entering the building information in Lixel requires the definition of each material with its dimension up to millimetres. In their own judgement, students worked approximately four weeks to integrate one full building alternative in Lixcel. The average time supervisors needed to correct errors in the calculation was three hours, which lead to limited correction cycles.

Student Group 1 used the results in Lixcel to argue for design decisions: The building volume was optimized regarding the area-to-volume ratio, the window area was reduced and the spatial efficiency is very high. The narrow floorplan with endless corridors gave a pressed impression in the interior and provoked the nickname „office machine". Different student groups presented similar designs. Group 2 was an exception to this as they used the LCA tool at the very end of the semester. They started to use it after finishing the drawings. Findings from the LCA calculation were made available too late to be integrated into the construction and material choice. Architectural aspects were well reflected, while the environmental

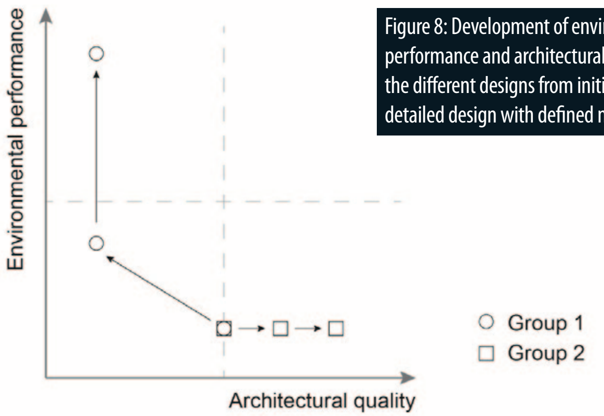


Figure 8: Development of environmental performance and architectural elaboration of the different designs from initial concept to detailed design with defined materials.

performance was under its potential. In both groups only one aspect was considered, either the environmental or the architectural quality. (Figure 8)

3.2 Results - Cycle-Oriented Construction

The results in the course *Cycle-oriented Construction* included a documentation of the chosen building elements and their optimisation regarding the embodied energy (primary energy not renewable), the embodied greenhouse gas emissions (global warming potential) and the potential for further use of the building materials. The diagrams of the further-use scenarios refer to the results of the embodied energy and emissions calculation: If a material has a high ecological impact, it is more relevant to prepare it for reuse or recycling compared to a material which might have relevant weight share but shows low ecological impact. The functions of the building element remained the same. Optimising the environmental performance on building element level included an analysis of the required functions. The most relevant aspects include the surface quality following the interior design (and for the façade the building outside design), acoustics, fire resistance, load-bearing and the thermal capacity. Two approaches could be observed: while some of the students exchanged the materials to decrease the embodied energy and emissions (Figure 9), others worked on the type of connection to improve the share of reusable and recyclable material (Figure10). For the optimisation, different strategies were used. Solid construction was modified to a stick-and-beam system in order to decrease weight and hence, embodied energy and emissions. Integral systems were modified towards a separation of functions. For example, solid walls with render

UVODNIK
EDITORIAL
ČLANEK
ARTICLE
RAZPRAVA
DISCUSSION
RECENZIJA
REVIEW
PROJEKT
PROJECT
DELAVNICA
WORKSHOP
NATEČAJ
COMPETITION
PREDSTAVITEV
PRESENTATION
DIPLOMA
MASTER THESIS

Figure 9: The embodied carbon was reduced by changing to renewable materials.

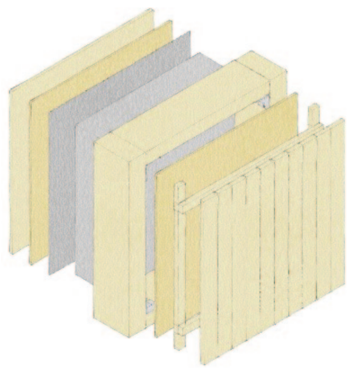
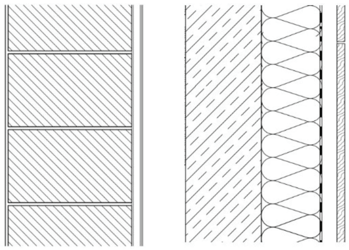


Figure 10: Bevor (left) and after the optimisation (right).



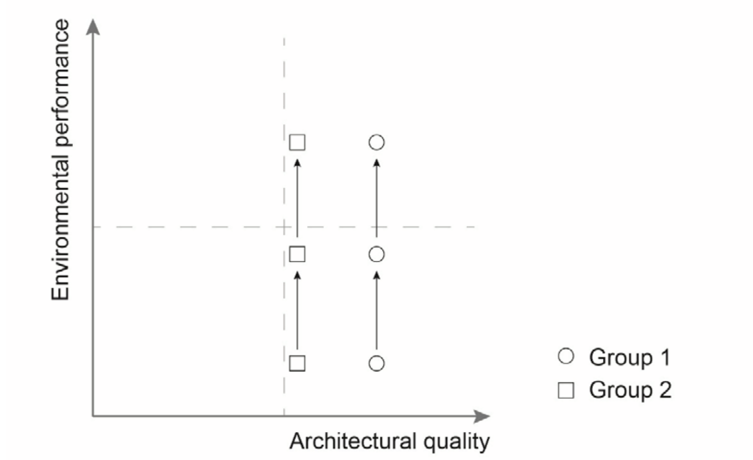


Figure 11: Development of environmental performance and architectural elaboration of the different designs from initial concept to detailed design with defined materials.

and plaster were developed to be separable. Non-renewable materials were replaced with renewable ones. All students achieved a significant optimisation by using the rb-tool. The real-time graphical feedback supported decision making. In the exam situation, this did not necessarily correlate to the level of understanding. While all showed good results only two thirds of the course could explain where the improvement came from and transfer this to other examples. However, integrating an ecological evaluation after the design parameter were set, supported an essential optimisation while not corrupting the function of the building element in the design context.

3.2 Results- Link-in-Energy

In the first phase of the semester, the students of Group 1 used the predefined standard materials to develop their designs. These results were compared to the designs of Group 2. The average of the results of both groups did not diverge. In the second phase, the students of Group 1 chose their individual materials and were able to save an average of 8.2% of primary energy and 16.2% of global warming potential compared to the baseline scenario. However, with the individual choice of material the designs of Group 2 performed worse than using the standard material. In consequence, the designs of Group 1 perform more than 40 % better when using the individual material.

At the beginning, the students taking part in the seminar (Group 1) had some difficulties in modelling the geometry. First, it was difficult for some students to draw abstract 3D massing models. Around half of the students had 2D floorplans of their design including wall thicknesses when they started modelling in 3D. It seemed difficult for them to reduce the complexity of their model for an energy "shoebox" model. Second, many issues arrived from the requirement of a watertight volume for the EnergyPlus calculation. Almost all students needed help in the beginning to fulfil the specific model requirements for thermal simulation. Throughout the semester they learned to find the errors themselves, however, it was a frustrating process for them. Finally, simulation time of one to five minutes seemed to be a problem, because they felt like they had to wait for the results and felt interrupted in their work. In consequence, they seemed to have simulated less variants than they desired, because they wondered whether it was worth investing the time. As such, the idea of an intuitive, playful, iterative optimization did not work out. As a result, the tool was not applied in early design stages and the geometry was not optimized using the tool. This can be seen in the results, because for the standard material the design of groups 1 and 2 perform equally well on average (see Figure 11).

However, the tool helped to take informed material decisions. Although both groups had the same task and attended the same lectures of sustainable construction and materials, the designs of Group 1 performed 40% better. Apparently, the environmentally friendly choice of material within the complex interactions between building equipment, insulation thickness, operational energy demand and embodied impact is not evident. Figure 11 summarizes the results for the start and end of the project. With the standard material provided as default the design of both groups perform similarly on average. Choosing individual material Group 1 managed to lower the GWP while Group 2 caused high results. However, Group 1 did not compare many variants and therefore did not reach the theoretical optimum of 100% environmental performance.

3.4 Results - Environmental Design Strategies

All six groups were able to model their design and to calculate a simplified LCA with predefined construction elements within half a day. The goal for the next days was to optimize their design through generating and comparing lots of variants, for both, geometry and material. One group did a thorough comparison of several geometries (see Figure 12). Another group compared two different geometric variants; however, the other groups did not generate design alternatives. They kept their initial concept and mainly used the results provided by the tool to argue the supposed environmental benefits of their design. For example, they compared their alternative material choice to the same geometry made of concrete and conventional materials.

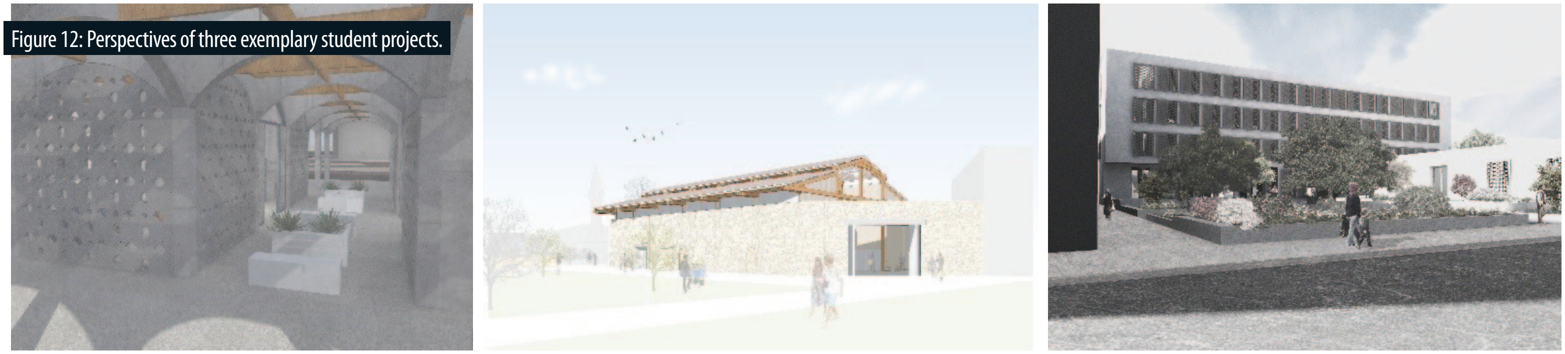


Figure 12: Perspectives of three exemplary student projects.

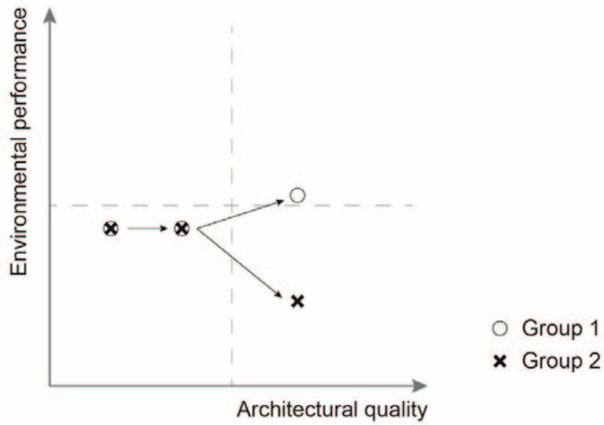


Figure 13: Development of environmental performance and architectural elaboration of the different designs from initial concept to detailed design with defined materials (Group 1 with tool, Group 2 without tool).

There were only minor difficulties in modelling and the application of CAALA in the concept design phase worked well. Nevertheless, only one group (Group 2) did a variant-based improvement process as intended by the teachers. Some groups started with an initial design with low environmental impact, based on their general knowledge or intuition. Group 1 for example chose a compact geometry, well-oriented windows and a combination of timber and earth construction material. Clearly, in this case the optimization potential using an LCA tool is smaller than for other groups that chose conventional materials, such as group 3. Figure 10 summarizes this aspect. Group 2 evaluated many design variants and reduced their impact compared to their initial variant. They even achieved slightly better environmental results than Group 1 that did not improve their initial variant based on the results of the tool. However, the design Group 1 showed the highest architectural quality. Both designs fulfilled the goals of the assignment.

4. REFLECTION ON THE CASE STUDIES

All four project show the aspects for the potentials and limits of the application of LCA tools in the architectural design process. In this section, these will be discussed regarding the following aspects:

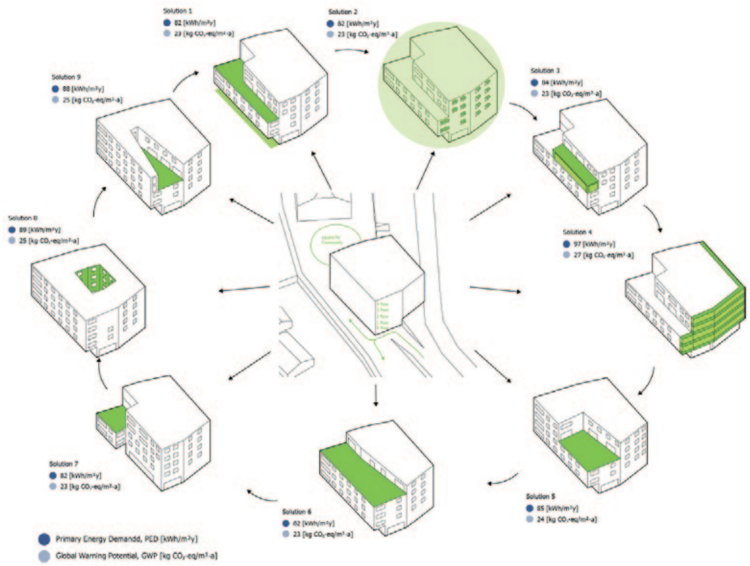


Figure 14: Comparison of the environmental performance of different geometries.

- Integration of tools in the architectural design workflow and
- Relation of environmental performance and architectural quality.

4.1 Integration of tools in the architectural design workflow

The results from the courses presented here show that the quality of decisions based on LCA tools depends on the time of application in the design process. In conventional LCA calculation, the assessed object (the so called functional unit) is defined by its function which remains the same throughout the evaluation process. This is different in architectural design; the function develops over the planning phase and the evaluation needs to be repeated in an iterative process. Integrating environmental aspects into the design phase requires an evaluation of the geometry, type of construction, materials or joints according to the design stages.

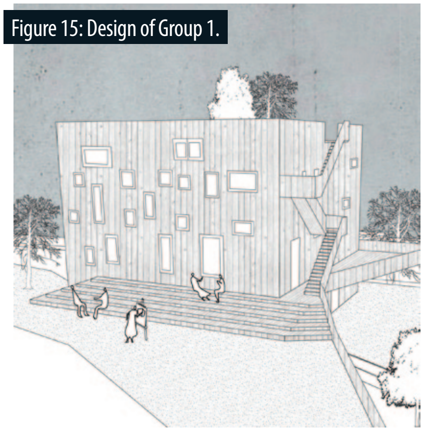


Figure 15: Design of Group 1.

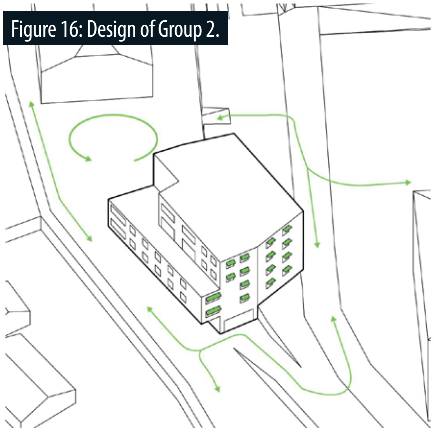


Figure 16: Design of Group 2.

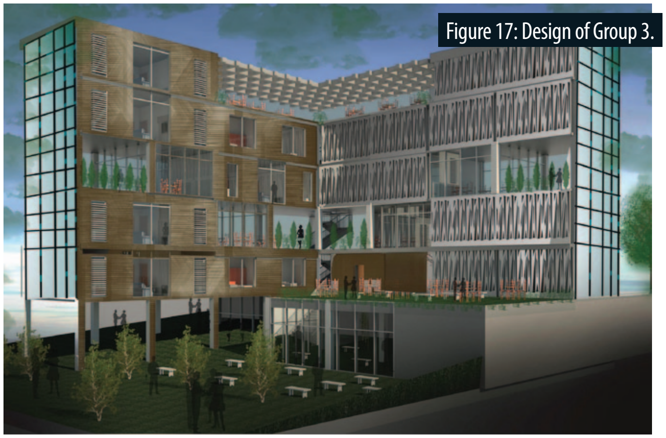


Figure 17: Design of Group 3.

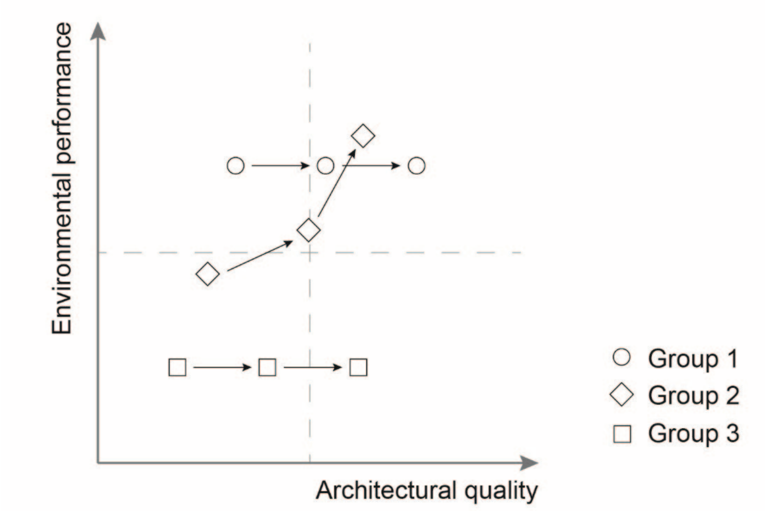


Figure 18: Development of environmental performance and architectural elaboration of the different designs from initial concept to developed design with defined materials.

In general, integration in the early concept design stage allows for more design changes based on the LCA results and therefore for higher improvement of the environmental performance. However, the results of the course *Sustainable Construction* show that very accurate but complex data can result in too much time spent on the assessment. The information required for the tool needs to develop along with the design process. Managing complex data blocks the design process, if very detailed data are required too early. If the assessment is carried out late, changes cannot be integrated, because the iteration cycle would take too much time (for example see Group 2 of the course *Sustainable Construction*).

While during *Link-in-Energy*, the main issues resulted from the tool, the main question during *Environmental Design Strategies* was the design approach. Most students were interested in LCA results to use them as an argument for the supposed benefits of their design solution, but they did not seem interested in using the results to improve their solution. One reason might be that the assignment was to abstract. The supervisors asked to environmentally optimize the designs as far as possible. The results might have been different, if a limit on the global warming potential would have been fixed the same way a client fixes a financial budget for any design project. Furthermore, benchmarks showing how many kg of CO_2-eq/m^2 is "good" or "bad" might have helped to question solutions with low environmental performance.

The course *Link-in-Energy* showed that real-time results are very important in concept design to compare different variants. This is also true for the developed and technical design stage as shown in *Cycle-oriented construction* for defining the type of construction and materials, when the improvement is indicated without export and in real-time multiple alternatives can be tested.

The variety of LCA tools is increasing and the choice for one needs to reflect the design phase it will be integrated in. With the growing number of tools, it becomes even more important to employ the suitable tool at the right time. CAALA proved to be applicable in the very early design stages to compare geometric variants, while more detailed assessment using rb-Tool or spreadsheet-based tool such as Lixcel should be carried out in later stages to define constructions and materials.

4.2 Relation of environmental performance and architectural quality

The design strategies employed are of significance as two examples from the course *Environmental Design Strategies* show. Most students used a top-down approach moving from the building volume, to the detailed geometry and then to defining types of constructions and materials. They employed CAALA first, then moved to rb-tool and finally looked into detailed material databases. The advantage of this approach is that the overall design concepts exists before any tool is used. As such, it will be unlikely that the tool compromises the design concept. Students do not put aspects of architectural design aside as observed in the course *Sustainable Construction* when they focussed mainly on the quantitative

LCA results. The pure optimization towards the highest environmental performance, which means least embodied primary energy demand, in this case, leads to solutions that are not satisfying from an architectural point of view. The environmental performance and the design concept can only be improved through iteration cycles of generation of a variant, assessment, and adaption of parameters. This requires the willingness to integrate the results for the assessment and to re-evaluate decisions previously taken. If this willingness is lacking, no improvement will be possible.

One group of *Environmental Design Strategies* applied a bottom-up approach starting from the materials. They looked at regional available materials and focussed on combining these to building elements meanwhile evaluating the recyclability. Based on these environmentally optimized building elements they developed a design concept. They started their research using material databases, then moved to the rb-tool and finally to CAALA to evaluate the whole building. This approach showed the advantage that the environmental aspects of the material choice are well integrated into the design concept. A potential issue arises if too much time is spent on the material assessment and the architectural design concept is weakened.

5. POTENTIAL AND LIMITATIONS - CONCLUSION

This paper compares the results from four different academic courses using four different LCA tools during the architectural design process. The results show that the potential of using these tools to improve the environmental impact is very high, but keeping the balance between architectural design and environmental aspects is still difficult. Both dimensions require the other one as there is no architectural quality without the consideration of environmental aspects and there is no sustainable building without architectural quality. Ideally, both architectural and environmental dimensions benefit each other. Conflicts can occur, for example, a big glass area can provide a great view to the outside and benefit the architectural design but decrease the environmental performance due to a high embodied impact. Both sides need to be evaluated and the negotiation process requires a strong architectural concept, which protects the key characteristics and is flexible for optimisation.

The LCA tools can support this negotiation process. However, if the point in time during the design process does not match the tool, the dimensions of environmental performance and architectural quality compete against each other. This highlights the relevance of the choice of tool and time of application. The user needs to be aware about the tools capabilities and balance it to the time when it is employed for optimisation. As in conventional LCA for products, the architectural characteristics and requirements need to be defined first. In the concept stage of the design phase, a geometric optimisation needs to reflect this and show potential within this framework. In the developed stage, different types of construction are compared, followed by an evaluation of materials and joints in the technical stage. All case studies show, that the comparison of different alternatives is key to argue for the best solution. The course results showed that the success of employing LCA tools in the design process highly depends on the point in time and the design strategy followed.

In general, the integration of LCA into architectural design shows a high potential to optimise the environmental performance of buildings. The number of LCA tools is growing, the computation power of PCs is increasing and cloud computing opens new possibilities. The current students are used to work with computers. Furthermore, the application of 3D tools in early design is growing (Köhler, 2016) even if they all have their advantages and disadvantages. This leads to the conclusion that the issue of environmental design now shifted from a lack of adequate tools to the responsibility to develop a design approach that integrates architectural and environmental quality. The use of iteration cycles in designing, analysis, and adaption apparently is not common to many students. This requires the willingness and openness to question and revise decisions already taken. The method of iteration needs to be integrated into the design studios.

Currently, assessment tools in the design phase evaluate only one aspect, e.g. environmental or economic properties. This leads to the emphasis on a single parameter. Even if the environmental aspect is of particular relevance, a sustainable effectiveness develops only, if also functional aspects are integrated. In the future, the software competences will grow and more functions can be integrated in one tool. This stresses the relevance of two main findings and recommendations of this research: A strong design concept is needed that reacts throughout the planning process with flexibility while carving out its key characteristics; and awareness about the tool's capabilities reflects in the choice of a suitable tool in the specific planning stage.

The software market develops continuously and with high pace making it impossible to teach students all available tools. More important is to educate them to understand the scope of a specific tool and the relevance of a design strategy. This will support the next generation of architects to do both, develop buildings with architectural quality and contribute to a more positive environmental footprint.

ACKNOWLEDGEMENT

We would like to thank all participants of the courses. Furthermore, we would like to thank colleagues who supervised the courses with us, namely Prof. Dr. Ulrich Knaack, Prof. Dr. Jürgen Ruth, and the organizing team of Bauhaus Summer School.

References

Baunetz. (2016). Temporäres Restaurant in Weimar. Retrieved December 12, 2017, from http://www.baunetz.de/meldungen/Meldungen-Temporaeres_Restaurant_in_Weimar_3933881.html

BBSR. (2016). ökobau.dat. Bundesministerium für Umwelt, Naturschutz, Bau und Reaktorsicherheit. Retrieved from http://oekobaudat.de/

DIN. (2008). DIN 276-1: Kosten im Bauwesen. Deutsches Institut für Normung e.V.

DIN. (2011). DIN V 18599-2:2011 Energetische Bewertung von Gebäuden - Berechnung des Nutz-, End- und Primärenergiebedarfs für Heizung, Kühlung, Lüftung, Trinkwasser und Beleuchtung - Teil 2: Nutzenergiebedarf für Heizen und Kühlen von Gebäudezonen. Deutsches Institut für Normung e.v.

DOE. (2015). EnergyPlus V8.3. Retrieved October 10, 2017, from https://energyplus.net/

El Khouli, S., John, V., & Zeumer, M. (2014). *Nachhaltig Konstruieren* (Detail Gre). Institut für Internationale Architektur-Dokumentation.

German Sustainable Building Council. (2015). DGNB system. Retrieved October 10, 2017, from http://www.dgnb-system.de/en/

Hegger, M., Fuchs, M., Stark, T., & Zeumer, M. (2007). *Energie Atlas: Nachhaltige Architektur.* Birkhäuser.

Heidenreich, C., & Schütz, S. (2010). *Screenhaus.SOLAR - Ein Kino im Solarkleid.* Bauhaus-Universitätsverlag.

Hollberg, A. (2016). *Parametric Life Cycle Assessment - Introducing a time-efficient method for environmental building design optimization.* (bauhaus.ifex, Ed.). Bauhaus-Universitätsverlag.

Hollberg, A., Ebert, M., Schütz, S., Cicek, B., Gumpp, R., & Ruth, J. (2016). Application of a parametric real-time LCA tool in students' design projects. In *Sustainable Built Environment* (pp. 72–81). Hamburg.

Hollberg, A., Lichtenheld, T., Klüber, N., & Ruth, J. (2017). Parametric real-time energy analysis in early design stages: a method for residential buildings in Germany. *Energy, Ecology and Environment.* https://doi.org/10.1007/s40974-017-0056-9

Hollberg, A., & Ruth, J. (2016). LCA in architectural design—a parametric approach. *The International Journal of Life Cycle Assessment, 21*(7), 943–960. https://doi.org/10.1007/s11367-016-1065-1

Klöpffer, W., & Grahl, B. (2014). *Life Cycle Assessment (LCA) - A guide to best practise.* Weinheim: Wiley-VCH Verlag GmbH & Co. KGaA.

Köhler, M. (2016). Rhinos, Hoppers, CAD-Monkeys. *Competition Online*, 85–90. Retrieved from https://www.competitionline.com/de/magazin

Kvan, T., & Yunyan, J. (2005). Students' learning styles and their correlation with performance in architectural design studio. *Design Studies, 26*(1), 19–34. https://doi.org/10.1016/j.destud.2004.06.004

Passer, A., Lasvaux, S., Allacker, K., De Lathauwer, D., Spirinckx, C., Wittstock, B., ... Wallbaum, H. (2015). Environmental product declarations entering the building sector: critical reflections based on 5 to 10 years experience in different European countries. *The International Journal of Life Cycle Assessment, 20*(9), 1199–1212. https://doi.org/10.1007/s11367-015-0926-3

Paulson Jr., B. C. (1976). Designing to Reduce Construction Costs. *Journal of the Construction Division, 102*(4), 587–592.

RIBA. (2013). RIBA Plan of Work 2013: Consultation document.

Schneider, C. (2011). *Steuerung der Nachhaltigkeit im Planungs- und Realisierungsprozess von Büro- und Verwaltungsgebäuden.*

Suau, C. (2013). Minimum Game Plans: Eco-Design and Low-Tech Fabrication in Studios. *Igra Ustvarjalnosti - Creativity Game, 2013*(1), 034–039. https://doi.org/10.15292/IU-CG.2013.01.034-039

UNEP SBCI. (2009). *Buildings and Climate Change Summary for Decision-Makers*.

designbuildxchange. (2016). Recycling Mies

Haas, S., & Asam, C. (2014). Wecobis- Ökologische Baustoffinformationssystem