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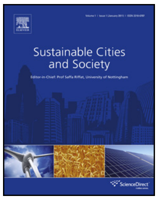

Towards regenerative and positive impact architecture: A comparison of two net zero energy buildings

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ABSTRACT

Regenerative design holds great promise for a new era of sustainable and positive impact architecture, sparking considerable interest among architects, building professionals and their clients. However, the translational arm of regenerative design in practice is in a relatively primitive state. Although a number of theoretical definitions and studies have been initiated, the early returns point to several inherent application problems. In this regard, the professional and scientific potential of regenerative architecture can only be fully realized by the identification of the key barriers to projects design, construction and operation. In this paper, we compare two state of the art buildings to address the critical steps in the transition from the negative impact reduction architecture to the positive impact regenerative architecture, utilizing life cycle analysis. The case studies analysis and comparison can serve as an inspiring eye opener and provide a vision for architects and building professionals in the fields of high performance buildings and regenerative architecture.

1. Introduction

The ecological and economic crises have been present for many years now. The economic system is showing its weak points in a dramatic fashion, unemployment is growing at a fast rate, the end of our fossil energy and other resources are apparent. There are more people who are becoming aware of the consequences of the climate change and the speed at which the biodiversity is diminishing is far beyond human imagination. Historically, buildings and architecture in particular had a central meaning for the sustainable development of the society. Remnants of the built environment of many cultures suggest that architecture played an important role in the social, economic and environmental life, but a review of the last century reveals that architecture tended to diminish in importance while other forms of discourse, such as the political, economic, technological, media had a more definitive impact on culture. Looking today to the challenges for planning and design of sustainable built environment including, carbon emissions, climate change, human health, water problems, biodiversity, scarcity of resources, depletion of fossil fuel, population growth and urbanization; sustainable architecture will play a key role for the sustainable development of society as a whole. Cities and buildings can be seen as microcosms, a potential testing ground for models of the ecological and economic renewal of the society.

Building construction and operation contribute greatly to the resource consumptions and emissions of the society. In Europe, building acclimatization alone accounts for roughly 40% of the total energy consumption (Huovila, 2007). When the effort required for construction, maintenance and demolition adds up, it is safe to assume that roughly half of the overall energy consumption can be attributed directly or indirectly to buildings. According to estimates nearly half of the all raw materials are employed in buildings, and a staggering 60% of all waste is the result of construction and demolition. The great significance of buildings and dwellings is evident in the way the building sector occupies in national economies. Private households spend roughly one third of their disposable income on housing (Eurostat, 2012). In Western Europe, 75% of fixed assets are invested in real estate (Serrano & Martin, 2009).

Thus the resources (land, water, energy, materials and air) we need to provide for decent housing and high quality life in the built environment are in decline because they are being used, exhausted or damaged faster than nature can regenerate them. In the same time, our demand for these resources is growing. The industrialisation exhausted the planet's carrying capacity and destroyed ecosystem functions and services. Populating growth in many regions of the planet has brought with it the need for decent housing with low greenhouse emissions, while in those countries

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Nomenclature

AIA	American institute of architects
ASES	American society energy society
ASHRAE	American society for heating and refrigeration and air-conditioning engineers
BPS	Building performance simulation
DOE	U.S. department of energy
EU	European union
EUI	Energy use intensity
GWP	Global warming potential
HVAC	Heating, ventilation and air conditioning
IEA	International energy agency
IDP	Integrated design process
IPCC	International panel for climate change
LCA	Life-Cycle assessment
LCI	Life-Cycle inventory
LEED	Leadership in energy and environmental design
MINERGIE-ECO	
NRE	Non-renewable energy
NREL	National renewables energy laboratory
NZEB	Net zero energy buildings
PE	Primary energy
PLEA	Passive and low energy architecture
PV	Photovoltaic
RSF	Research support facility
SHGC	Solar heat gain coefficient
Vlt	Visible transmittance
WWR	Window to wall ratio
USGBC	United States green building council
U-value	Thermal conductivity

with consolidated urban development process it is the existing built environment that demands transformation. When setting out the issue of satisfying these needs, we must consider both local and global environmental limitations. However, during the last 50 years architects and building professionals have been mainly concerned by only reducing the environmental impact of the built environment (Meadows, Meadows, Randers, & Behrens, 1972). Even today the dominant operating paradigm to face the economic and ecological crisis remains the same reductions resource efficiency based paradigm.

In this context, it is not enough to aspire to mitigate the effects of human activity. On the opposite we need to increase the carrying capacity beyond pre-industrial conditions to generate ecosystems functions and services to reverse the ecological foot print. This approach is promoted through the regenerative paradigm that seeks to develop renewable resources infrastructure and design building with a positive environmental impact. Therefore, this research explores the two paradigms and presents two state of the art case studies that represent each the efficiency and regeneration paradigm. The purpose of the study is to provide an understanding of both paradigms through practical examples and demonstrate to building designers their adequacy in meeting the challenges of the design and operation of the built environment. The research methodology is based on the life cycle analysis and evaluation of two cases studies through comparison. Comparison is the highest cognitive level analysis involving synthesis and evaluation. The first case study is the Research Support Facility (RSF) of the National Renewable Energy Lab (NREL) representing the reductionist paradigm. The second case study is the Green Offices high performance building representative the regenerative paradigm. The paper explores the difference between two different paradigms regarding their embodied energy and monitored performance. The comparison of two state of the art high performance buildings is valuable because it permits researches to measure constructs more accurately and as a consequence shape an effective theory-building of sustainable architecture. It helps us to answer the main research question of this study: Can the resource efficiency and impact neutrality paradigms help us to solve the economic and ecological crisis we are living? The juxtaposition of both building performance results allowed the research into a more creative, frame breaking mode of thinking. The result was a deeper insight into both paradigms. The significance of the study documents a paradigm shift and its increasing influence on the architectural and building design and construction practice through two state of the art examples.

The results of this study are considered as an eye opener and guidelines for building professionals including designers, owners and architects. The accurate and specific determination of regenerative characteristics of buildings can help designers to make fundamental choices in the design and construction of sustainable architecture. Choices that achieve thermal comfort, occupant's well beings enhance sustainability by working together toward a positive footprint. On the long term this article can lead to reformulating and rethinking the definition of sustainable architecture while increase the uptake of positive impact buildings in practice and consequently lead to a paradigm shift. The paper is divided into section sections. The first two sections introduce the research problem and explore the historical background of sustainability in the architectural practice during the last century while setting a definition for negative and positive impact built environment. The third section explains the comparison methodology and the assumption used for the life cycle assessment (LCA). Then, section four and five present the two case studies and their comparison results. Finally, section six provides an extended discussion and conclusion on the paper findings.

2. Definitions and paradigm shift

In order to understand the changes that accrued in the field of architectural, building design and urbanisation practices during the last hundred years we must follow the history of sustainability in the built environment. We can classify this history under five major phases that shaped the architectural discourse and practice we are witnessing today. Four out of five of those phases were influenced mainly by a major reductionist paradigm that defined sustainability for architecture and buildings design. The reductionist paradigm is seeking mainly the reduction of negative building impact through environmental efficiency. However, we are on a verge of a paradigm shift that operates from a different paradigm. The following sections describe the historical progress and phases of the modern sustainable architecture and explore the sustainability paradigms associated with those phases.

2.1. Historical background

From the beginning of the 20th century there have been five influential paradigms that shaped sustainability in architecture and the built environment. A review of the last 120 years reveals that the architectural discourse was influenced significantly by the economic and ecological crisis associated with industrialisation (see Table 1). This classification is not rigid and should not be interpreted as a rigid classification that creates borders it is a trial of categorisation of thoughts that aims to provide a better understanding of the evolution and relation between sustainability and the creation of the built environment. Thus for thinking on sustainability we distinguish seven paradigms:

Table 1
Sustainability Paradigms influencing Architecture in 20th and 21th century.

Paradigm	Years	Influencer	Paradigm
Bioclimatic Architecture	1908–1968	Olgay, Wright, Neutra	Discovery
Environmental Architecture	1969–1972	Ian McHarg	Harmony
Energy Conscious Architecture	1973–1983	AIA, Balcomb, ASES, PLEA	Energy Efficiency
Sustainable Architecture	1984–1993	Brundtland, IEA, Faust	Resource Efficiency
Green Architecture	1993–2006	USGBC, Van der Ryn	Neutrality
Carbon Neutral Architecture	2006–2015	UN IPCC, Mazria	Resilience
Regenerative Architecture	2016–Future	Lyle, Braungart, Benyus	Recovery

The first paradigm named *Bioclimatic Architecture* was dominated by ideas of Frank Lloyd Wright (1906) on organic architecture (Uechi, 2009), Corbusier and Breuer (1906) on sun shading (Braham, 2000), Atkinson on hygiene (Banham, 1984), Meyer (1926) on the biological model (Mertins, 2007), Neutra (1929) on bioregionalism (Porteous, 2013), Aalto (1935) on health and precautionary principle (Anderson, 2010) until formulation of the *Bioclimatic Architecture* paradigm by the Olgay Brothers (1949) (Olgyay, 1953). Buildings of those architects showed a tendency of rationalism and functionalism while being fascinated by the beauty of nature. Bioclimatic adaptation, hygiene, safety and the notion of experimental and empirical design was not developed. Until the brothers Olgay set up the first architecture lab in the 1950ies combining academic research and practice. This is was a major change that moved architecture into the scientific world.

The second paradigm named *Environmental Architecture* was dominated by the ideas of Ian McHarg (1963) on design with nature (McHarg & Mumford, 1969), Ehrenkrantz (1963) on systems design (Ehrenkrantz, 1989), Schumacher (1972) on appropriate technology (Stewart, 1974) and Ron Mace (1972) on universal design (Thompson, Johnston, & Thurlow, 2002). Buildings of those architects showed a tendency of inclusiveness of environment and biology from the building interior to urban and planning scale.

The third paradigm followed the first energy crisis and was dominated by the ideas of the American Institute of Architecture (AIA) (1972) on *energy conscious architecture* (Villecco, 1977), the American Solar Energy Society (ASES) including the work of Balcomb (Balcomb (1972) on passive and active solar architecture (Balcomb, 1992), the Passive and Low Energy Architecture (PLEA) society (1980) and Thomas Herzog (1980) (Herzog, Flagge, Herzog-Loibl, & Meseure, 2001). Buildings of those architects showed a tendency of inclusiveness of solar and energy saving design strategies. The first ideas of energy neutral buildings and renewable energy integrated systems were introduced in several building prototypes and concepts. The use of empirical simulation and measuring based technique to quantify building performance was based on energy codes and standards that were created in this phase.

The fourth paradigm named *Sustainable Architecture* was dominated by the ideas of Brundtland (1987), ranging from Baker on sustainable designs (Bhatia, 1991), Fathy's congruent with nature designs to build architecture from what beneath our feet (Fathy, 1973) to Sam Mockbee. Along with many others, they expanded the purview of sustainable design by embracing aesthetics and human experience in addition to environmental performance.

The fifth paradigm named *Green Architecture* was dominated by the ideas of the US Green Building Council (1993) on green and smart design, Van der Ryn (1995) on ecological community design (Van der Ryn & Calthorpe, 1991), ARUP (1996) on integrated design (Uihlein, 2014) and Faust (1996) on Passive Haus Concept (Feist et al., 1999). With the emergence of this paradigm the greening of architecture proliferated globally with more complex and broader environmental considerations (Deviren & Tabb, 2014).

The six's paradigm named *Carbon Neutral Architecture* was dominated by the ideas of the Kyoto Protocol (1997) on carbon neutrality (Protocol, 1997) and UN IPCC report (2006) on climate change. The work of Bill Dunster on Zero Energy Development and Ed Mazria on the 2030Challenge had a strong impact on architectural research and practice. With the EU 2020 nearly zero energy targets for 28 member states, energy neutral architecture became a reality embracing resilience, dynamism, and integration.

In the coming 20 years we will be on the verge of the seventh paradigm named *Regenerative Architecture*. This paradigm will be dominated by the ideas of Lyle (1996) on regenerative design (Lyle, 1996), Michael Braungart and Donald McDonough (2002) (McDonough & Braungart, 2010) on cradle to cradle design and Benyus (2002) on Biomimicry (Benyus, 2002). We are on a verge of a paradigm shift that operates from a positive impact creation through environmentally effective sustainable buildings. One of the presented cases studies in this reach is a showcase for a positive impact creation.

In conclusion this classification allows us identify the ideas and trends in the field of sustainability of architecture and the built environment. In the last hundred years architecture was influenced by the sustainability discourse and many architectural and building innovations were tied to progress of ideas listed earlier. The influence of the seven phases was profound on architectural practice, driven by new construction technologies such as insulation materials, renewable systems and efficient heating and cooling technologies. Sustainability represented a vision for new practice and performance driven architecture and resulted in new production and performance calculation indices and methods. Several paradigms dominated the architectural and building practice. The most recent two are: ultra-efficiency and effectiveness. Being in a transitional verge between both paradigms the following two sections explain the different between both paradigms.

2.2. Negative impact reduction via increased efficiency

With the emergence of the ecological and economic crises during the last hundred years the architectural, engineering and construction community realized the negative impact of the industrialization of the built environment on the planet. Buildings are responsible for 40% of carbon emission, 14% of water consumption and 60% of waste production worldwide (Petersdorff, Boermans, & Harnisch, 2006). According to the European Union Directive, land is the scarcest resource on earth, making land development a fundamental component in effective sustainable building practice (EU, 2003; EEA, 2002). Worldwide over 50% of the human population is urban. Environmental damage caused by urban sprawl and building construction is severe and we are developing land at a speed that the earth cannot compensate. Buildings affect ecosystems in a variety of ways and they increasingly overtake agricultural lands and wetlands or bodies of water and compromise existing wildlife. Energy is the building resource that has gained the most attention within the built environment research community. Building materials are another limited resource within a building's life cycle. In contrast to energy and water, materials circulate within a near closed-loop system. The regeneration period of most materials used

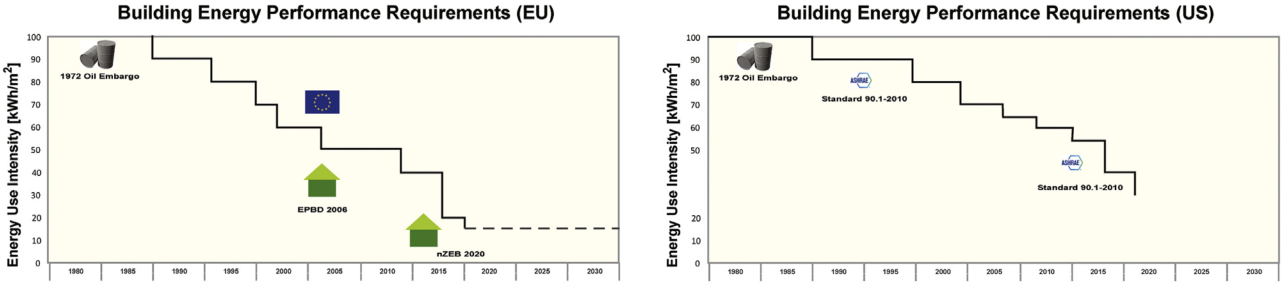

Fig. 1. Evolution of building energy performance requirements in the EU and US.

in current building construction is extremely long since they were millions of years in the making. Water is a key resource that lubricates the building sector as much as oil does. Buildings require water during construction and during occupancy. The enormous negative impacts of ecology and the deteriorating ecosystem functions and services and the large ecological footprint, due to fossil fuel consumption and pollution resulted in large environmental deterioration.

As a result of these problems the resources efficiency paradigm dominated the practice aiming to the reduction of the negative impact of the built environment. For example, the energy crisis in 1973 resulted in the development of energy efficiency measures in the built environment. The International Energy Agency (IEA), European Union (EU) and the American Society for Heating and Refrigeration and Air-conditioning Engineers (ASHRAE) legalized and published standards and performance targets for the energy consumption of buildings have improved by a factor of five to ten since 1984 (see Fig. 1) (EU-Directive, 2005). In trying to achieve an environmental friendly built environment through reduction, the sustainable architectural and building practice for a resource efficiency goals meaning to reduce the consumption and use resources efficiently. However, the changes that influenced the field emerged all from an efficiency paradigm focusing on the reduction of the use of depleting or polluting resources. Even the zero energy buildings and zero carbon buildings goals that seek maximum efficiency derive from the notion of neutralizing the resource consumption and define this as zero energy consumption (Marszal & Heiselberg, 2009). In fact, the "break even" approach is very limited. Restricting the building impact boundaries to 'zero' or "net zero' is misguided, the 'zero' goal limits achieving long-term sustainable building practices. If energy generated on site prove to be an abundant resource, why then should we limit our objectives to zero? Moreover, the efficiency paradigm discourages the potential to reach fossil fuel independent buildings. The decline in the availability of oil, gas and coal and the danger of nuclear energy means that the cost of black fuels will become increasingly volatile. Peak oil will have a huge impact throughout the economy. Thus the energy efficiency paradigm has reached its limit by proposing zero energy or zero emissions as the 'holy grail", because this reductionist approach operates within a black fossil fuel paradigm that does not recognize the importance of renewable, regenerative resources and building design mechanism that can reverse the climate change root cause.

With the advent of the 2013 IPCC report it became evident to the scientific and public community that the efficiency paradigm is failing to solve the problem. Even in architecture we witnessed several manifestations regarding its changing role and crucial character to our survival (see Table 1). The accelerated impact of climate change and the increasing negative impact of the built environment are exceeding the planets capacity by six times (Stevenson, 2012). The efficiency paradigm can no longer face the problem. We need to reverse the negative impact of the built environment and go beyond the efficiency paradigm.

2.3. *Positive impact via increased regenerative effectiveness*

From the discussion above we can conclude that the increasing population growth and ecological destruction requires increasing the ecological carrying capacity beyond pre-industrial conditions. We are looking for sustainable positive development that incorporate maximizing the viability of harnessing renewable resources and become independent from depleting and polluting resources. In order, to achieve positive building footprint we must move from the cradle to grave paradigm that aims to reduce, avoid, minimize or prevent the use of fossil energy to a regenerative paradigm that aims to increase, support, and optimize the use of renewable (Lyle, 1996). As shown in Fig. 2, the previous efficiency strategies have been operating within a carbon negative or neutral approach that will never reach a positive and beneficial building footprint. Even the existing net balance approach assumes a fundamental dependence on fossil fuels. Therefore, we define the positive impact of the built environment from a renewable self-efficiency paradigm.

A regenerative sustainable building seeks the highest efficiency in the management of combined resources and maximum generation of renewable resources. It seeks positive development to increase the carrying capacity to reverse ecological footprint (see Fig. 3). The building's resource management emphasizes the viability of harnessing renewable resources and allows energy exchange and micro generation within urban boundaries (Attia & De Herde, 2010, 2011). Over the past years, regenerative positive development paradigm has been garnering increasing influence on the evolution of architecture. The progress is dramatic: plus energy plus, earth buildings, healthy buildings, positive impact buildings. This new way of thinking entails the integration of natural and human living systems to create and sustain greater health for both accompanied technological progress.

3. Methodology

In order to answer the research question in broad terms on the effectiveness of the efficiency paradigm versus the effectiveness regenerative paradigm it is important to build theory from case studies. Two specific case studies were selected to represent the paradigms. We looked for selecting two appropriate high performance buildings with extraneous variations to define the limit for generalising the findings. The two selected buildings provide examples of two polar types classified as state of the art high performance buildings in US and Switzerland. The goal of the selection to choose cases which are likely to replicate. Indeed the US case is LEED Platinum zero energy building and the Swiss case is a MINERGIE-ECO ecological building. The comparison focused mainly on energy during the phase of construction, operation and demolition in order to avoid the overwhelming volume of data. The two cases were meant to be used as a source for a firmer empirical grounding for answer the research question. The analysis was carried out in two steps:

Fig. 2. Paradigm shift towards a beneficial positive impact footprint of the built.

Fig. 3. A regenerative sustainable building seeks the highest efficiency in the management of combined resources and a maximum generation of renewable resources.

- Screening and analysing both building so that we can see the magnitude of impacts.
- Performing a detailed LCA especially for carbon emissions and primary energy.

For the first part of the study multiple data collection methods were combined to compare the two cases studies. The data collection included literature reviews, interviews, observations, field studies and access to simulation models and monitored performance data. The researcher had the chance to interview the design teams and visit both buildings and perform for both buildings a modelling analysis and post occupancy evaluation.

3.1. Life cycle standards and system boundary

The second part of the study comprised a life cycle assessment analysis. The interest in evaluating energy use, consumption of natural resources and pollutant emissions, especially for new and low energy buildings is increasing (Hernandez & Kenny, 2010; Leckner & Zmeureanu, 2011). One of the most important environmental impacts of buildings is materials and resources. According to the USGBC Projects Database materials count for 35% of the total energy consumed during the building life cycle (Turner, Frankel, & Council, 2008). A more recent study pointed out that embodied energy can be up to 60% of the building life cycle (Huberman & Pearlmutter, 2008). Therefore, we opted for a life cycle assessment to compare the energy consumption, material embodied energy and CO^2 emissions according to ISO 14040 and 14044 standards (ISO14040 ISO, 2006; ISO14044 ISO, 2006; Vogtländer, 2010).

The CEN/TC 350 "Sustainability of Construction works" standard recommends consideration of four life cycle stages for building: product stage (raw materials supply, transport and manufacturing), construction stage (transport and construction installation on site process), use stage (maintenance, repair and replacement, refurbishment, operational energy use: heating cooling, ventilation, hot water and lighting and operational water use) and end-life stage (deconstruction, transport, recycling/re-use and disposal) (Blengini & Di Carlo, 2010; CEN, 2005). Table 2 illustrates the life cycle subsystems conducted for this study. To facilitate the comparison of resources for architects we classified our analysis under energy use (operational energy) materials (embodied energy).

3.2. Functional unit, year, tools and indicators

The functional unit to compare both buildings was 1 m^2/year. For the calculation model we expected the occupancy for 100 years. In Switzerland the usual value of LCA lifetime is 100 years. Numerous examples of using LCA for 100 years can be found (Fay, Treloar, & Iyer-Raniga, 2000; Bribián, Capilla, & Usón, 2011; Pajchrowski, Noskowiak, Lewandowska, & Strykowski, 2014). Also global warming potential are available for different time horizons, and a choice of 100 years is usually assessed on this basis (Forster et al., 2007). The cradle to grave LCA was made on the basis of directly collected data from the design-build teams and integrated with literature data. An inventory dataset for materials was developed and completed using the Ecoinvent 2 database. The life cycle inventory was performed using the SimaPro 7 software applications. In order to calculate the environmental impact resulted from the biogenic CO2 circulation, an approach of CO2 storage in the buildings for 100 years was used. The negative values of the global warming indicator results were obtained for a cradle (forest) and positive ones for the final disposal stage of wooden waster (incineration and reuse). The LCA indicators were summarized in a group of three energy and environmental indicators as follow:

- Primary energy (PE), as an indicator of life cycle energy use
- Non-renewable energy (NRE), as the non-renewable part of PE

Global warming potential (GWP), as an indicator of greenhouse emissions, including the contribution of biogenic carbon dioxide. Biogenic CO2 is captured in biomass during the growth of a plant or tree and, consequently, in a biologically-based product.

3.3. Life cycle inventory

Within the scope of the LCA an inventory have been created, which referred to building materials of the four life cycle stages mentioned earlier. During data collection, the expertise of architects and building engineers have been used extensively as described in Table 2. For the Case Study 1 and 2 the as built drawings were used to size most building features and their size and weight. The energy consumption was collected from monitored data between 2010 and 2014 and simulated in two models with the same legislative requirements (in Switzerland and the US) of envelope and HVAC systems to neutralize the climatic variability and estimate average operation energy using Energy Use Intensity (EUI) Index. The main difference between both case studies is those relevant to the building material, envelope thickness and type of insulation and glazing. Also the HVAC systems are very different and the fuel type has different associated carbon emissions. The simulation models helped in elaborating the building components and weights and later feed in the Ecoinvent data inventory.

Table 3 lists data concerning the weight of major building materials for both buildings. By inspecting the material structure of the RSF we can see that concrete is dominating the total building weight reaching almost 80% of the weight share. The precast panels that make up the exterior walls of the RSF were fabricated in Denver using concrete and aggregate from Colorado sources. The building cores, basement thermal labyrinth and basement and floor slabs are responsible for this high value. This includes recycled runway materials from Denver's closed Stapleton Airport used for aggregate in foundations and slabs). Metals represent 4% and include steel bars for concrete reinforcement and reclaimed steel gas piping used as structural columns. In the case of the Green Offices building materials are also dominated by concrete produced from a local concrete mixing plant 30 km from the site. Concrete has almost the highest weight share constituting mainly foundations. Wood is the second most common material reaching almost 14%. Table 4 presents the basic assumptions related to the durability of elements subject to replacement and repairs. Flooring and finishing is carried out with the highest frequency but it was assumed that the previous finishing layers are not removed before subsequent painting. Wooden doors and windows are subject to replacement and are calculated within the use stage. The assumptions include the calculated mass flows of materials and waste generated in 100 year period and resulting from the replacement and repair.

3.4. Limitations

Although ISO 14040 recommends that LCAs end with a set of mid-point environmental indicators we proposed the narrow set of indicators listed above. Architects often express their need for practical and simple performance indicators that might simplify the decision making. The LCA scope was limited to the subsystems mentioned in Table 2. Also we had limited quantitative information on the actual demolition process. Therefore, we referred to few studies that contain some quantitative and methodological information on the role of end-of-life in buildings in the US and Switzerland (BAFU, 2016; Thormark, 2002, 2006; Werner & Richter, 2007; Spoerri, Lang, Binder, & Scholz, 2009; Boschmann & Gabriel, 2013; Spiegel & Meadows, 2010).

For this study we excluded water installations and sewage installation including roof gutter systems were excluded from the study. Also the damage categories such as human health, ecosystem quality, climate change, resources and impact categories (carcinogens,non-carcinogens, respiratory inorganics, ionising radiation, ozone layer depletion, respiratory organics, aqterrestrial ecotoxicity, terrestrial acidification/nitrification, land occupation, aquatic acidification, aquatic eutrophication, global warming, atic ecotoxicity) were excluded. Needless to say, the energy mix of both buildings was taken into account for calculations in regard to the electricity mix and will be elaborated in following case studies sections.

4. Case studies

The selection of both case studies was based on their similar office function and the awards they received in the USA and Switzerland. Both projects represent the excellence in sustainable architecture and green construction in their countries obtaining the highest green rating certification LEED Platinum and

Table 2
Life cycle phases and data sources.

Life cycle phase	Subsystem	Case study 1	Case Study 2
Product Stage	–Shell and building services materials production	–Quantities estimated from building drawings	–Quantities estimated from building drawings
	–Analysis include gross amount, i.e. including the material loss during building process	–Literature data (Guggemos et al., 2010)	–Unpublished data from University de Lausanne (Lehmann, 2011)
		–Inventory information process for most materials has been collected from ecoinvent database.	–Inventory information process for most materials has been collected from ecoinvent database with exception of wood and cellulose insulation for which specific data have been available.
	–Transportation and Building Process	–Information about the type of means of transport used for transporting individual types of building materials has been based on personal communication with Design-Build team	–Unpublished data from University de Lausanne (Lehmann, 2011)
	– Distances from the production location for the main materials to the building location based on calculated weight	–Distances have been calculated	–Distances have been calculated
	–Type of transport and means of transport		–Information about the type of means of transport used for transporting individual types of building materials has been revised through a presentation of the architect
Construction Stage	–Construction of building components and construction of the whole building	–Assumptions about construction machinery have been made based on the literature	–Assumptions about construction machinery have been made based on consultation with architect
	–Energy consumption by construction machinery	–Calculated with the software application SimaPro	–Calculated with the software application SimaPro
Use Stage	–Energy use for HVAC	–Literature (US DOE, 2012) and monitored data from NREL (Carpenter and Deru., 2010)	–Literature (Lehmann, 2011) and monitored data from architect Conrad Lutz between 2010 and 2014
	–Energy use for lighting and plug loads	–Data concerning HVAC have been collected between 2010–2014	–A simple simulation model was created to assess the energy consumption and fuel breakdown and neutralize the climate varaiablity
		–A simple simulation model was created to assess the energy consumption and fuel breakdown and neutralize the climate varaiablity	
End-of-life Stage	–Dismantling, demolition, recycling/reuse/landfill	–Literature data(Carpenter and Deru., 2010)	–Literature [(BAFU, 2016)] and unpublished data from University de Lausanne (Lehmann, 2011)
	–Type of waste disposal	–Type od means of transport used for transporting building materials has been based on literature	–Type od means of transport used for transporting building materials has been based on literature
	–Distances from demolition site to the final disposal sites		
	–Type of transport and means of transport		

Table 3
Weight share of material groups in the analysed buildings.

Building Material Category	RSF		Green Office[a]	
	Amount [kg]	Share [%]	Amount [kg]	Share [%]
Concrete	32500000	79	788650	73.4
Brick	–	–	10890	1
Gravel	6000000	14.6	50000	4.6
Ceramics	84000	0.2	–	0
Mineral binding materials	82600	0.2	2000	0.1
Wood and wood based materials	10000	0.2	144200	13.5
Insulation materials	110000	0.3	55000	5.1
Metals	1904762	4.7	12600	1
Glass	53460	0. 1	5680	0.05
Paints and Preservatives	48240	0. 1	1340	0.1
Plaster and Gypsum board	229680	0.5	2000	0.1

[a] *Annex 1.1* Lehmann (2011).

Minergie-P-ECO. The RSF received the award of Excellence for Green Construction from the American Concrete Institute AIA. Also it received the 2011 AIA/COTE Top Ten Green Project Award. The Green Office received the Watt d'Or 2008 and Prix Lignum Holzpreis 2009 in Switzerland. More interestingly, both projects represent the reductionist and regenerative paradigm and are seen as pilot projects by the professional communities in two different continents.

Table 4
Durability of elements subject to replacement and repairs in 100 years.

Building	RSF		Green Office	
Inventory element	Durability [years]	Number of replacements	Durability [years]	Number of replacements
Construction elements	100	0	100	0
Windows	25	3	25	3
Internal doors	30	3	30	3
External doors	30	3	30	3
Wood flooring	–	–	50	1
Heating Installations	30	3	30	3
Ceramic tiles	20	4	20	4
Electric installations	50	1	50	1
Ventilation system	25	3	25	3
Roofing	50	1	50	1
Roof insulation	50	1	50	1
Walls insulation	60	1	30	2
Building Facade	60	1	60	1
Painting internal walls	5	19	5	19
Painting external walls	25	3	25	3
Varnishing of Floors	25	3	25	3
PV panels	30	2	30	2

4.1. *Case study 1: efficiency paradigm*

The research support facility (RSF) is a state of the art office building to host researchers of the National Renewable Energy (NREL) Lab. The RSF in Golden, Colorado was designed and constructed between 2006 and 2010, after a process of proposals calls and selection. The vision of the selected project operates within the energy efficiency paradigm aiming to build an energy neutral office building or a NZEB. The design brief emphasized an integrative design approach to design, build and operate the most energy efficient building in the world. The call had a design-build acquisition strategy that connects the building to the electricity grid for energy balance through a power purchase agreement. The Design-Build Team comprises Haselden Construction, RNL Architect and Stantec as Sustainability Consultant and MEP engineering. The design process involved an integrative approach looking to:

1 avoid needs for energy by integrating passive heating and cooling and ventilation;
2 improve energy efficiency and
3 incorporate renewable energy and green power.

The building is located in latitude 39.74 and longitude −105.17 and is 151 m above sea level. The site receives 660 mm of rain per year with an average snowfall of 1371 mm. The number of days with any measurable precipitation is 73. On average, there are 242 sunny days per year in Golden, Colorado. The July high is around 30° and January low is −8 while humidity during the hot months, is a 58 out of 100. The building is a 20.400 square meter hosting 800 person. The building energy use intensity had to perform less than 80 kWh/m^2/year and additional 20 kWh/m^2 per year was allowed for a large data centre that serves the entire NREL Campus. The RSF facility had to perform 50% better that ASHRAE 90.1-2007 energy performance requirements. The project is a net zero energy building and obtained the LEED Platinum Certificate (V.2) and Energy Star Plus certification. The design brief also required maximum use of natural ventilation and 90% of floor space fully daylit.

With the help of building performance simulation (BPS) several passive design strategies were optimized. The building form and mass was shaped to host the main building functions influence by an energy saving approach. The RSF building has two wings sized and positioned to allow natural ventilation and lighting. The orientation of the two wings is elongated on the east-west axe to allow an easy control of solar access during summer. To achieve energy performance goals, the workspace layout is open, with low cubicle walls and light-coloured furniture that allow air to circulate and daylight to penetrate into the space. The aspect ratio is 13.5 and the window to wall ratio is 25% with a low-e triple vision glazing (U-value 0.17, SHGC 0.22). The daylight glass is a low-e double pane day lighting glazing (U-value 0.27, SHGC 0.38, Vlt 65%). The envelope comprises modular structural insulated panels of 2.5 cm exterior concrete with rigid foam insulation (polyisocyanurate R-13) and an internal thermal mass of 15 cm interior concrete.

Regarding active systems the building has a hybrid operating system. The vision glass is manually operable and gets automatically controlled depending on indoor and outdoor environment. A radiant heating and cooling system is installed in the roof slab. Natural ventilation is achieved during day through manual windows control and during night through automated control for night cooling and thermal mass activation. Mechanical ventilation is demand based and air is displaced through an under floor air distribution system. A heat recovery system is installed on outside air intake and exhaust from restrooms and electrical rooms. The whole building energy use is 283 continuous watts per occupant. Laptops of 60 W with 35 W thin screens are used in workspaces. The artificial lighting system is based on motion and daylight intensity sensors. Sensor controlled LED task light of 15 W are used for workstations lighting. A third party owned power purchase agreement PPA provided full rooftop array of 1.7 MW of mono-crystalline panels of 17% efficiency. The current power purchased from a fossil mix (60% coal, 22% from natural gas, and 18% from renewable energy resources (EIA, 2014)).

The construction life-cycle stage included the full construction of the building. For the LCA data from a proprietary Athena Institute database was used for the construction of similar commercial structural systems (precast concrete, cast-in-place concrete, and structural steel), as well as layers of various envelope materials and interior partitions. Annual energy use was calculated using NREL monitoring results. The maintenance stage includes repair and replacement of assemblies and components of assemblies throughout the study building's service life. The primary source of information was the Athena report, Maintenance, Repair and Replacement Effects for Envelope Materials (2002). Standard recommendations are based on decades of building envelope experience, manufacturers' installation instructions, material warranties, and industry best practice. Generic industry associations' data and publications and North American industry practices were taken in consideration to model the end-of-life stage scenarios.

A literature review and Internet search was conducted but little detailed information regarding construction and demolition waste management practices in Denver urban centre were found and further considered in this study. End-of-life scenarios are being forecast up to 100 years. A more comprehensive description of the production processes and tables for the other varieties can be found in (Guggemos, Plaut, & Bergstrom, 2010). The detailed carbon footprint as well as environmental impact of the various processes for producing the concrete construction system is provided.

4.2. Case study 2: regenerative paradigm

The vision of the selected project was to build the most ecological and regenerative office building. Approached by the French State the architect Conrad Lutz was asked to design and construct an ecologically optimal building with a positive impact. The Green Office building located in Givisiez, Switzerland was designed and constructed between 2005 and 2007. The building is located in latitude 46.81 and longitude 7.12 and is 99 m above sea level. The site receives 1075 mm of rain per year with an average snowfall of 627 mm. The July high is around 25° and January low is −1 while humidity during the hot months, is a 69 out of 100. The building provides commercial office spaces for companies working in the field of sustainable development. The building has three floors with a total area of 5391 square meter and is the first MINERGIE-P-ECO in Switzerland. The building energy use intensity had to perform less than 25 kWh/m^2/year and 10 W/m^2 for thermal air heating should not exceed. The design process involved an integrative approach looking to:

1 avoid needs for energy by integrating passive heating and cooling and ventilation with a focus on compactness;
2 improve energy efficiency and trace the impact of energy resources
3 Sequestration – the capture and storage of CO^2 in the construction material

The high thermal insulation of walls, ceilings and floor and triple glazing was the architect's passive strategy to reduce the need for building heating. The value u-value of the roof is 0.10 W/m^{2}K, façade 0.11 W/m^{2}K, windows 0.5 W/m^{2}K and floors 0.10 W/m^{2}K achieved through wood fibre insulation. The building form is optimised to increase compactness and reduce the envelope surface area and reduce heat losses. The building resembles a cube with a volume of 5291 m^3 and comprises internal partitions that allow several companies to settle, share and grow. Natural light was optimized using daylight simulation for optimal natural lighting and avoidance of overheating during summer. The heating system is a pellet stove with under floor heating. Free cooling using an underground tube that works as passive heat exchanger (puits canadien) is used in summer through ventilation. The hot water is produced with solar thermal panels and the current power purchased from a renewable mix (60% wind, 37% hydro, solar 3% (Lehmann, 2011)). However, the roof is prepared for electricity production and will get equipped with 270 m^2 Photovoltaic. The expected energy generation should exceed 30% of the building electrical energy needs and export the additional 305 to the grid. The plug loads are controlled buy electricity cut off policy and all used equipment and appliances including flat screens are energy star rated.

The construction life-cycle stage included the full construction of the building. For the LCA data from econinvent database was used for the construction of similar commercial structural systems (timber and cast-in-place concrete), as well as layers of various envelope materials and interior partitions. Wood was cut in Semsales Region. The raw wood was transported on a direct path to Givisiez, while the laminated timber made along the way to Burgdorf. The distances have been calculated from Switzerland's maps. Most material sources were located based on the architect's identification of products names and their manufacturer. Annual energy use was calculated using Green Offices monitoring results (Lehmann, 2011). Today, most materials are buried at the end of life of a building in Switzerland. For Green Offices, the timber construction and cellulose insulation was assumed to be burned in a municipal incinerator for electricity generation, and the other district heating. In 100 years, the efficiency of energy recovery may be increased by reusing timber as chips or pellets in heaters. Concrete was assumed to be buried in the ground, or be crushed for reuse as gravel under roads or under construction. Manufacturers indicated that glass panes are not recycled in Switzerland, but buried with other construction waste. Generic industry associations' data and publications and Swiss industry practices were taken in consideration to model the end-of-life stage scenarios. A literature review and Internet search was conducted but little detailed information regarding construction and demolition waste management practices in the Swiss urban centres were found and further considered in this study. End-of-life scenarios are being forecast up to 100 years. A more comprehensive description of the production processes and tables for the other varieties can be found in (Lehmann, 2011). The detailed carbon footprint as well as environmental impact of the various processes for producing the timber construction system is provided.

5. Results

The results of the LCA applied to two high performance buildings in the US and Switzerland is highlighted below. When assessing the sustainability and environmental performance of high performance buildings it is very important to use universal indicators and consider carefully all life cycle phases and subsystems.

5.1. Case study 1: efficiency paradigm

The Research Support Facilities Building (RSF) at the National Renewable Energy Laboratory (NREL) in Golden, Colorado achieved a 67% reduction in energy use (excluding the solar PV offset) at zero extra cost for the efficiency measures, as the design team was contractually obliged to deliver a low-energy building at no extra cost (Torcellini, Pless, Lobato, & Hootman, 2010). Torcellini and Pless (Pless & Torcellini, 2012) present many opportunities for cost savings such that low-energy buildings can often be delivered at no extra cost. Other examples of low-energy buildings (50–60% savings relative to standards at the time) that cost less than conventional buildings are given in McDonell (2003) and IFE (2005). New Buildings Institute (2012) reports examples of net-zero-energy buildings that cost no more than conventional buildings. Even when low-energy buildings cost more, the incremental costs are often small enough that they can be paid back in energy cost savings within a few years or less (Harvey, 2013). The keys to delivering low-energy buildings at zero or little additional cost are through implementation of the Integrated Design Process (IDP) and the design-bid-build process. Vaidya et al. (2009) discuss how the traditional, linear design process leads to missed opportunities for energy savings and cost reduction, often leading to the rejection of highly attractive energy savings measures.

5.1.1. Energy

The building energy consumption and production has been monitored since its construction. The average annual consumption is 109 kWh/m^2/year including data centre serving 1325 occupant. See Table 3 for comparison of monitored performance data.

5.1.2. Materials

Materials used in the RSF contain recycled content, rapidly renewable products, or were regional, meaning they were procured within a 500-mile radius of Golden (DOE, 2012). The precast panels that make up the exterior walls of the RSF consist of two inches of rigid insulation (R-14) sandwiched between three inches of architectural precast concrete on the outside and six inches of concrete on the inside. The panels, which were fabricated in Denver using concrete and aggregate from Colorado sources, constitute the finished surface on both the inside and outside of the wall except that the interior is primed and painted. Wood originates from pine trees killed by beetles used for the lobby entry. Recycled runway materials from Denver's closed Stapleton Airport are used for aggregate in foundations and slabs. Reclaimed steel gas piping was used as structural columns. About 75% of construction waste materials have been diverted from landfills (DOE, 2012). Table 4 summaries the mid-point environmental indicators relevant to the life cycle of the RSF. Pre use and maintenance impacts are higher than those relevant to the use phase.

5.2. Case study 2: regenerative paradigm

The building complies with the MINERGIE-ECO® certificate which is a complementary standard to that of MINERGIE® and MINERGIE-P® seeking to ensure, in addition to a building satisfying the energy efficiency requirements, an sound environmentally friendly construction.

5.2.1. Energy

The building energy consumption and production has been monitored since its construction. The average annual consumption is 8 for heating plus 28 kWh/m^2/year for electricity. A building of the same size would have the right to consume 25 kWh/m^2/year for heating according to MINERGIE-P® standard. The total impact of the building would be relatively low when compared with other buildings same functional unit. Building materials and renewable source of heating decrease mainly the impact on resources and climate change.

5.2.2. Materials

The requirements for human health and the immaterial impact on the environment are obligatory. Therefore the architect used wood as raw materials that is widely available and with the least possible impact on the environment. 450 cubic meter of wood were transported from a 20 km close wood forest. The forest wood is sustainably managed and each tree was selected explicitly with the lower possible moisture content to reduce the energy of the wood kiln. As shown in Fig. 4, the use of wood resulted in a carbon negative footprint. By carbon negative we mean a negative outcome of the carbon footprint of wood, i.e. when carbon credits through carbon sequestration and energy production at the end of life phase are higher than the emissions caused by production and transport. The architect design prefabricated wooden panels filled with wood fibre insulation. The structural elements were mainly glued laminated timber trusses and beams. The whole construction was designed to be easily dismantled easily and in addition to materials that could be for the most part, reused or recycled. The compactness of the building space was not only strategically achieved heat loss reduction but also to reduce the material total quantity and reduce the embodied energy of building materials. MINERGIE-ECO® required the use of an exclusion list that prevents materials that end up in the landfill and are not compatible with a healthy indoor environment. Concrete was used in the foundation from a cement factory 100 km away and other materials were transported from maximum 1000 km distance. All materials from a distance less than 500 km were transported with 3.5–20 t trucks materials transported from further away came on 32 t trucks. A more comprehensive description of the production processes and tables for the other varieties can be found in Van der Lugt (2008) and van der Lugt et al. (2009a, 2009b). The total scores (carbon footprint as well as eco-costs) of the various processes for producing the industrial bamboo products are provided in Chapter 6. Fig. 4 shows the important contribution of the building life cycle which corresponds to the two different design objectives and paradigms (Table 5).

5.3. Case studies comparison

The results in the most general view are presented in Fig. 4 and Table 6. The impact shown here relates to the functional unit, therefore the production and transport of the amount of materials necessary construct both buildings and use them, including replacements repairs, demolition, as well as transport and disposal of the demolition waster after 100 years.

In Table 6, the derived breakdown of embodied energy, operational energy and carbon emission values during the different life cycles are compared for both building components considered in the analysis. These indicators are listed in terms of energy per square area (MJ/m^2) of the given material, as well as unit mass per square area (kgCO2/m^2) to account for varying associated material emissions. Table 6 presents the embodied energy (pre-use phase) in materials of the entire building based on the as built drawings. The Green Offices building materials are at least 85% less energy intensive in their production as the RSF. These reductions are mainly due to the wooden construction compared to the reinforced concrete and steel construction system. It is interesting to note that even though the embodied energy is calculated over an assumed 100-year life span, the building embodied energy remains significant in the RSF (23%) and Green Offices (10%). This is due to the large energy consumption during the complicated production process of building materials that happen indoors.

On the other side, the table revealed surprising findings regarding operational energy. Two different analyses were performed in order to validate the final results. The operational energy outcomes were based on the monitored data tracking and the calculation of the energy mix in both states/cantons. Since both buildings were on-grid and achieved a net zero energy annual balance we had to take into account the primary energy of the imported energy. The RSF (66% of primary energy is due to operational energy) depends on natural gas for heating and electricity to meet other loads and Green Offices (86% of primary energy is due to operational energy) depend on pellet furnace and electricity. The most prominent difference seen between both buildings was the relatively high operational energy consumption of RSF, which exceeds that of Green Offices by over 7 times if calculate the end use energy and by over 40 times if calculate the primary energy. There are two reasons for this remarkable performance differences. First of all, the Green Offices is complying with the MINERGIE –ECO one of the most stringent building performance standards and could be compared to the Passive House Standard. The second reason is that the imported energy for the RSF over the course of the year is coming from a black energy mix, while Green Offices imported energy is originating from a green energy mix. Despite that both facilities are recently built as high performance zero energy buildings sharing the same function as office buildings, however, the performance level and operational energy consumption difference is unjustifiable.

Another representation of the LCA results can found in Fig. 4, where the weighted results of impact category indicators have been presented based on Table 6. The primary energy and carbon emissions calculations and provide a new perspective for the overall life cycle assessment of both buildings. While both buildings succeeded to achieve the zero energy annual balance, the carbon emissions

Table 5
Comparison of monitored performance of the RSF and Green Offices buildings.

	RSF	Green Office
Estimated Annual Energy Consumption	100 kWh/m2/year including data centre	25 kWh/m2/year
Annual Energy ConsumptionMonitored	109 kWh/m2/year including data centre	36 kWh/m2/year
Occupants/Surface	1325/20400 m2	50/1299 m2

Table 6
Mid-point environmental indicators relevant to the life cycle of the RSF and Green Offices buildings.

Case Study 1	Carbon Sequest.	Pre-use	Operation	End of life	Life cycle
PE MJ/m^2/a	/	274 (23%)	785 (66%)	131 (11%)	1190
NRE MJ/m^2/a	/	274	785	131	880
GWP kgCO2 equiv./m^2/a	/	56 20 (%)	197 (71%)	25 (9%)	275
Case Study 2					
PE MJ/m^2/a	/	27 (10%)	168 (86%)	−14 (4%)	181
NRE MJ/m^2/a	/	27	56	5	88
GWP kgCO2 equiv./m^2/a	−5.9 (−13%)	6.5 (14%)	40 (90%)	3.4 (7%)	44

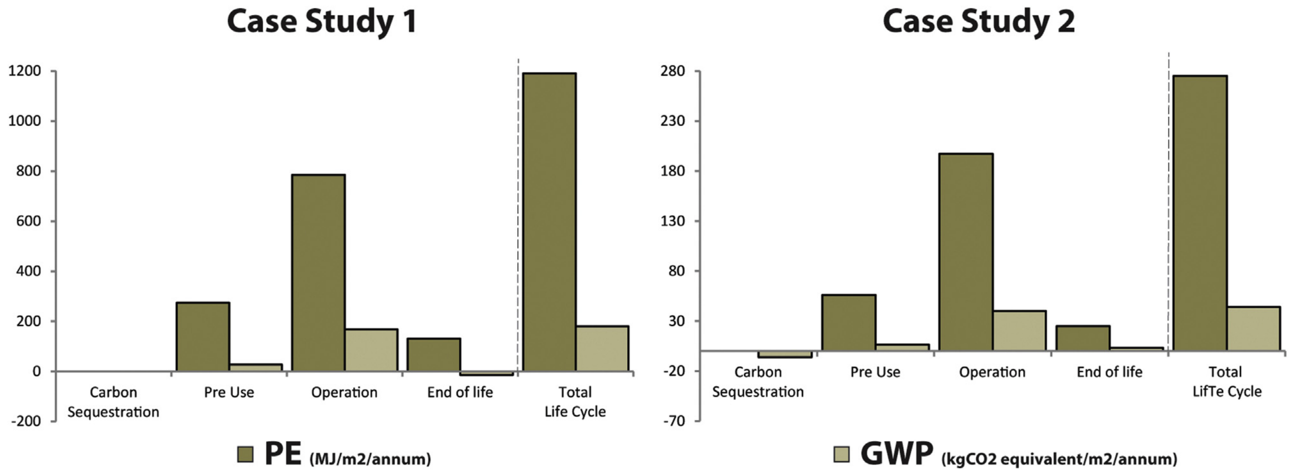

Fig. 4. Comparison of the primary energy balance and global warming potential for both case studies.

associated with the generation and importing of energy was positive. This means that at this degree of results aggregation even if a benefit exists, it is neutralized by the dominating negative impacts. As mentioned before, the main reason is due to carbon emissions associated with the energy imported from the grid. Even though Green Offices imported green energy mainly produced from renewables, the use of pellets for heating, maintenance and number of replacements (see Table 4) are expected to generate 90% of the carbon emissions of the 100 year building life cycle. The use of cellulose insulation will require 2 times replacement, which increased the operational energy. Even the use of bio based construction materials like wood or wood fibers was not enough (-13%) to create a carbon negative outcome. However, if we take into account the biogenic CO^2 captured in wood and wood fibers and make sure to have a zero carbon operational energy we mighty reach a total negative balance of carbon. This shows the importance and dominance of operational energy (use stage) on the overall carbon emissions impact. On the other side the RSF is expected to generate 71% of the carbon emissions during operation.

In the case of total life cycle, carbon emissions intensity constituting about 275 kgCO^2 equivalent/m^2/annum for the RSF building and about 44 kgCO^2 equivalent/m^2/annum for the Green Offices building, there is very significant difference. Attention should be paid to the fact that the use of concrete and steel has a very high environmental impact on carbon emissions. Even in the Green Offices building, which has very low emission value, the impact of foundations and concrete walls (average 1400 kg/m^2) has been the highest (73% according to Table 3). However, reaching 44 kgCO^2 equivalent/m^2/annum for the Green Offices building is a very good record because if the emissions associated with operation could be neutralized through a greener grid energy mix where the total carbon emissions might reach a negative balance taking into account the carbon sequestration or bio generation of wood. Therefore, building efficiency improvements (on the level of MINERGIE-P-ECO) and renewable energies must be introduced in the grid and during the pre-use and end life phase. The role of reaching a negative CO2 balance over the whole building life cycle should become increasingly prominent.

6. Discussion and conclusion

6.1. Summary of main findings

The regenerative paradigm was found closer to reverse the ecological foot print and provide a positive impact building. Thanks to the biogenic Co2 calculation approach the life cycle stages responsible for creating the positive and the negative environmental impact related to global warming are presented, eventhough there is no consensus in literature or practice to used carbon sequestration or carbon bio generation. The regenerative paradigm increased knowledge about the materials and embodied energy, generated a more conscious attitude to materials and energy resources selection and almost eliminated the reductionist paradigm in design. The design team who used LCA and who demonstrated a high level of knowledge on materials and resources' environmental impacts, succeeded to create an almost regenerative building with a positive impact. In order to create a positive impact building the building had to produce more than its requirements to compensate the emissions released during for heating and DHW. Moreover, the building has to be built with the maximum possible amount of plant or bio based construction materials. The use of plant or bio based construction materials can help to offset the environmental effects of climate change, provided the wood is harvested from a natural forest or a plantation created to improve degraded lands and is processed using renewable energy (during the pre-use phase). After succession of multiple reuses and down cycling cascade the main insulation and construction material will be fired. On the other side, the zero energy objectives achieved the environmental neutrality only for operational energy and could not guide the design team to focus on the overall environmental impact of the building. After one year of full monitoring of the RSF the bet zero energy balance was not achieved and a new parking lot was constructed to host new arrays of 668 kW. The roof was covered with PV panels that are more than 17% efficient. The rooftop array alone could not offset the RSF's energy needs, so several adjacent parking structures were covered with additional PV. Moreover, the rebound effect associated with the increase of plug loads and panels' efficiency degradation factor of 0.7% per year eradicated the efficiency and impact neutrality paradigms. The results are in accordance with previous studies (Jordan & Kurtz, 2013; Phinikarides, Kindyni, Makrides, & Georghiou, 2014).

The zero energy claims have potential consequences of unsustainable approaches to building and planning. This claim of annual building operation carbon footprint neutrality of zero carbon emissions/year for the RSF building is misleading. Both case studies could not overcome the limitation given by a non 100% carbon neutral grid infrastructure or energy supply. Therefore, maintaining such objective on the short and long term cannot increase the carrying capacity of nature and reverse our foot print.

By tracing the environmental impact of operational energy and embodied energy over 100 years for two case studies we could proof that the choice of building materials comes in the second place of importance and relevance after the operation energy. Despite the slightly different climatic conditions between Golden, Colorado and Givisiez, Fribourg and the different needs for heating, cooling and DHW, it is worthwhile to consider operational energy and the sustainability of grid energy supply followed by building materials when building high performance buildings. With the mandatory performance requirements of nearly zero energy buildings by 2020 in the EU we cannot remain operating under the current efficiency or energy neutrality paradigm (Sartori, Napolitano, & Voss, 2012; Attia, Mlecnik, & Van Loon, 2011). Therefore, this study has demonstrated that the setting the right goals (MINERGIE-ECO as an example) can play in mitigating the effects of climate change and helping architects to create a positive impact of the built environment on their surroundings. By highlighting the potential of regenerative design paradigm it can contribute to sustainable building practices, we also hope to increase the awareness about its impact of operational energy and embodied energy of foundation and concrete construction. Regenerative design can lead to beneficial footprint and positive impact buildings and can inform architects and building designers in accordance with the United Nations Framework Convention on Climate Change. However, in order to maximise its impact, and benefit the greatest number of communicates, its use needs to be promoted amongst the public and buildings professionals. The regenerative approach should be based on maximum efficiency coupled with renewable dominated energy mix. Creating a circular economy means shaping the building regulatory and market frameworks to strengthen regenerative finance and delivery, and to support architects and building engineers with simple environmental indicators, calculation methodologies and national implementation standards and strategies.

6.2. Comparison with existing literature

This research builds on earlier studies that have considered the mitigation of global and local resource depletion and environmental degradation (McHarg & Mumford, 1969; Lyle, 1996; Cole, 2012). Regenerative design and development, as previously noted in the case of Green Offices, has consistently been shown to deliver innovative buildings with beneficial qualities. With respect to Cole who stated the scarcity to find similar built projects can show the capability of expanding our environmental performance targets (Cole, 2012; Waldron, Cayuela, & Miller, 2013; Wolpensinger & nachhaltiges Bauen, 2016). This study is in line environmental assessments made for plant based construction materials (Van der Lugt, 2008; Prétot, Collet, & Garnier, 2014; Ip & Miller, 2012; Wolpensinger & nachhaltiges Bauen, 2016; Waugh, Wells, & Lindegar, 2010). Despite the small sample of case studies, the author tried to go into buildings with a well-defined focus and to collect specific building performance data systematically.

6.3. Implications for research and architectural design practice

The controversy surrounding efficiency paradigm has recently been reignited by several studies, published simultaneously (Ankrah, Manu, Hammond, & Kim, 2013). The large contribution of building to resource consumption is highly relevant, not least because optimisation potential is equally great in the same sector. Whatever the outcome of the technocratic reductionist efficiency debate, the fact remains that the resources efficiency and the reductions approach have significant limitations. Those architects, building designers and owners seeking sustainable architecture in their practice require valuable information in order to make informed decisions. It is estimated that buildings design cost 1% of the percent of the life cycle cost but it can reduce over 90% of life cycle energy cost (Lovins, Lovins, & Hawken, 1999). While during early design phases 20% of the design decisions taken subsequently, influence 80% of all design decisions (Bogenstätter, 2000). However, effort spent to predict or reduce buildings environmental impact should be replaced by high quality regenerative design support metrics, indicators, tools, strategies and framework for net positive development. They need information on how to replace fossil fuel based system and components with passive or natural/renewable sources on the building and grid level. This information will need to be easily accessible, and, as shown in this study, based on well establish predicts and materials life cycle analysis.

This study used Life-Cycle Assessment and carbon footprint calculations to analyse the environmental impact of two states of art buildings. The main limitation of LCA remains in its cradle to grave approach that mainly measures the environmentally damaging footprint. The Green Offices concept was designed for disassembly and adaptation to change of function. The structure had modular dimension systems, the skin is made of demountable facades and the internal spaces allow movable separation walls. Issues such as adjustability, versatility, movability and scalability are of great added value allowing high quality future reuse. However, the LCA approach could not quantify those beneficial design qualities. Therefore, new tools and indicators are needed in the future to assess building's functionally and which environmental, social, and health benefits that can be achieved in particular at the end-of-use phase (reuse, recycling, incineration, landfill) (Bor et al., 2011) (Geldermans & Rosen-Jacobsen, 2015). Needless to say the study was limited to only three energy and environmental indicators. From the results, it can be concluded that bio based buildings can generate energy and are CO^{2} negative. However, without studying the other indicators such as eutrophication, acidification, air/soil/water toxicity and the associated embodied water consumption the results of the wood construction cannot be generalized. On the other side, the aim of the study was not conduct a full LCA but to use the LCA for comparison and highlight the importance of including materials environmental impact in any future green or sustainable building rating. Using LCA we proofed by evidence that the zero energy objective cannot be the answer to our ecological and economic crises.

Finally, in the last three decades architecture was influenced by the sustainability discourse and many innovations were tied to progress in technology. The influence of technological advances was profound, driven by new construction technologies such as insulation materials, renewable systems and efficient heating and cooling technologies. From this study there is a proof that there is change of current practice and that there is a shift in the design and construction of sustainable architecture. This implies that new theories and strategies and performance indicators and metrics will appear in the near future. Sustainability represented a vision for new vision and performance driven architecture and resulted in new production and performance calculation indices and methods. Today the regenerative design paradigm can provide a new vision of a new built environment. Regenerative design will become a necessity to support a healthy and positive ecological built environment.

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References

Anderson, D. (2010). Humanizing the hospital: design lessons from a Finnish sanatorium. *Canadian Medical Association Journal*, *182*(11), E535–E537.

Ankrah, N. A., Manu, E., Hammond, F. N., & Kim, K. G. B. A. (2013). Beyond sustainable buildings: eco-efficiency to eco-effectiveness through cradle-to-cradle design. *Sustainable buildings conference*, http://www.irbnet.de/daten/iconda/CIB_DC26491

Attia, S., & De Herde, A. (2010). Towards a definition for zero impact buildings. *The proceedings of sustainable buildings CIB*, http://ebooks.narotama.ac.id/files/Towards%200-Impact%20Buildings%20and%20Built%20Environments/3.2%20%20Towards%20a%20Definition%20of%20Zero%20Impact%20Buildings.pdf

Attia, S., & De Herde, A. (2011). Defining zero energy buildings from a cradle to cradle approach. *Proceedings of PLEA*, 205–2010. http://books.google.be/books?hl=nl&lr=&id=ygdAO6_mOCgC&oi=fnd&pg=PA205&dq=attia+c2c+&ots=YU1Gz80RV7&sig=aGCs5-8j8qWgzw5QYpo1y5scv14

Attia, S., Mlecnik, E., & Van Loon, S. (2011). Net zero energy building: a review of current definitions and definition development in Belgium. *Proceedings of passive house 2011*, http://orbi.ulg.be/handle/2268/167481

BAFU (2016). Kompakte bestandsaufnahme: Abfall und recycling in der Schweiz Luzern. Retrieved from http://www.packaktuell.ch/newspool/kompakte-bestandsaufnahme-abfall-und-recycling-in-der-schweiz/.

Balcomb, J. D. (1992).. *Passive solar buildings* (Vol. 7) MIT Press. https://books.google.be/books?hl=fr&lr=&id=L8uAq-7YJooC&oi=fnd&pg=PA1&dq=Balcomb+(1972)+passive+design+douglas&ots=Cg4XgnQY6H&sig=ouZcqbixsvn1dC3oXJmgUX0qazI

Banham, R. (1984). *Architecture of the well-tempered environment*. University of Chicago Press. https://books.google.be/books?hl=fr&lr=&id=kkI5pgQHM7cC&oi=fnd&pg=PA9&dq=Atkinson+on+hygiene+architecture+1926&ots=Ab2EEv-bda&sig=veCEiM7cFP5B7AbU36ILMYdKDwQ

Benyus, J. (2002). *Biomimicry: invention inspired by nature*. New York: HarperCollins/Perennial.

Bhatia, G. (1991). *Laurie baker*. Penguin Books India. https://books.google.be/books?hl=nl&lr=&id=UT0rMM_hrbYC&oi=fnd&pg=PR9&dq=Laurie+baker+architecture+india&ots=9CuJbrj7Up&sig=UXPdb_yQEtzpJ_Wz59R6XoJEQ0s

Blengini, G. A., & Di Carlo, T. (2010). The changing role of life cycle phases, subsystems and materials in the LCA of low energy buildings. *Energy and Buildings*, *42*(6), 869–880.

Bogenstätter, U. (2000). Prediction and optimization of life-cycle costs in early design. *Building Research & Information*, *28*(5-6), 376–386.

Bor, A.-M., Hansen, K., Goedkoop, M., Rivière, A., Alvarado, C., & van den Wittenboer, W. (2011). *Usability of life cycle assessment for cradle to cradle purposes*. Utrecht: NL Agency.

Boschmann, E. E., & Gabriel, J. N. (2013). Urban sustainability and the LEED rating system: case studies on the role of regional characteristics and adaptive reuse in green building in Denver and Boulder, Colorado. *The Geographical Journal*, *179*(3), 221–233.

Braham, W. W. (2000). Erasing the face: control and shading in post-colonial architecture. *Interstices Journal of Architecture and Related Arts*, https://interstices.aut.ac.nz/ijara/index.php/ijara/article/viewFile/96/159

Bribián, I. Z., Capilla, A. V., & Usón, A. A. (2011). Life cycle assessment of building materials: comparative analysis of energy and environmental impacts and evaluation of the eco-efficiency improvement potential. *Building and Environment*, *46*(5), 1133–1140.

Brundtland, G. H. (1987). *Report of the World Commission on environment and development: our common future*. United Nations.

CEN TC 350, (2005). Sustainability of construction work. Executive summary. Retrieved from http://www.cen.eu/CEN/sectors/TechnicalCommitteesWorkshops/centechnicalcommittees/Pages/PdfDisplay.aspx.

Carpenter, A., & Deru, M. (2010). *Green building rating: use of life cycle assessment in determining the sustainability of buildings*. Golden, Colorado: NREL. http://lcacenter.org/lcax/presentations-final /98.pdf

Cole, R. J. (2012). Transitioning from green to regenerative design. *Building Research & Information*, *40*(1), 39–53.

DOE (2012). The Design-Build Process for the Research Support Facility (p 60). Retrieved from http://www.nrel.gov/docs/fy12osti/51387.pdf.

Deviren, A. S., & Tabb, P. J. (2014). *The greening of architecture: a critical history and survey of contemporary sustainable architecture and urban design*. Ashgate Publishing Ltd., https://books.google.be/books?hl=nl&lr=&id=80h0BAAAQBAJ&oi=fnd&pg=PR13&dq=The+Greening+of+Architecture:+A+Critical+History+and+Survey+of+Contemporary+Sustainable+Architecture+and+Urban+Design.+&ots=qxqi-AvG-W&sig=VpNQE8wGZwAj5×6FVk9uV491PcA

EEA. (2002). *Benchmarking the millennium*. Environmental Signals.

EIA (2014). Colorado State Energy Profile: Colorado Quick Facts. Retrieved from http://www.eia.gov/state/print.cfm?sid=CO.

EU. (2003). *Towards a Thematic Strategy on the Sustainable Use of Natural Resources (p. 16). Brussels*. http://eur-lex.europa.eu/legal-content/EN/TXT/?uri=CELEX:52003DC0572

EU-Directive. (2006). *Thematic Strategy on the sustainable use of natural resources. Not published in the Official Journal*. http://eur-lex.europa.eu/legal-content/EN/TXT/HTML/?uri=CELEX.52005DC0670&from=EN

Ehrenkrantz, E. D. (1989). *Architectural systems: a needs, resources, and design approach*. McGraw-Hill Inc. http://dl.acm.org/citation.cfm?id=542274

Eurostat. (2012). *Housing cost overburden rate by tenure status*. Eurostat. http://ec.europa.eu/eurostat/statistics-explained/index.php/Housing_statistics

Fathy, H. (1973). *Architecture for the poor*. Chicago: The University of Chicago Press.

Fay, R., Treloar, G., & Iyer-Raniga, U. (2000). Life-cycle energy analysis of buildings: a case study. *Building Research & Information*, *28*(1), 31–41.

Feist, W., & others. (1999). Das Passivhaus. CF Müller. Retrieved from http://gse.cat.org.uk/downloads/passive_house.pdf.

Forster, P., Ramaswamy, V., Artaxo, P., Berntsen, T., Betts, R., Fahey, D. W., et al. (2007). Climate change 2007: the physical science basis. In S. Solomon, D. Qin, M. Manning, Z. Chen, M. Marquis, & K. B. Averyt, et al. (Eds.), *Contribution of working group I to the Fourth assessment Report of the IPCC*. Cambridge, U.K. and New York: IPCC. http://www.ipcc.ch/publications_and_ data/publications_and_data.htm

Geldermans, R. J., & Rosen-Jacobsen, L. (2015). *Circular material & product flows in buildings*. Delft University of Technology. http://repository.tudelft.nl/assets/uuid:383e09e2-cc4b-44de-8ad1-ed934c56877e/318181

Guggemos, A., Plaut, J., & Bergstrom, E. (2010). *Greening structural steel design, fabrication and erection: a case study of the national renewable energy laboratory research support facilities project*. pp. 46. Colorado: Colorado State University. http://ibe.colostate.edu/Documents/White%20Paper_FINAL.pdf

Hernandez, P., & Kenny, P. (2010). From net energy to zero energy buildings: defining life cycle zero energy buildings (LC-ZEB). *Energy and Buildings*, *42*(6), 815–821.

Herzog, T., Flagge, I., Herzog-Loibl, V., & Meseure, A. (2001). Thomas herzog: architektur+ technologie. *Prestel Publishing.*

Huberman, N., & Pearlmutter, D. (2008). A life-cycle energy analysis of building materials in the Negev desert. *Energy and Buildings*, *40*(5), 837–848.

Huovila, P. (2007). *Buildings and climate change: status, challenges and opportunities (UNEP/Earthprint)*. [Retrieved from http://www.unep.fr/shared/publications/pdf/DTIx0916xPA-BuildingsClimate.pdf.].

ISO I 14040 (2006): environmental management–life cycle assessment–principles and framework. London: British Standards Institution.

ISO I 14044 (2006): environmental management—life cycle assessment—requirements and guidelines. International Organization for Standardization.

Ip, K., & Miller, A. (2012). Life cycle greenhouse gas emissions of hemp–lime wall constructions in the UK. Resources. *Conservation and Recycling*, *69*, 1–9.

Jordan, D. C., & Kurtz, S. R. (2013). Photovoltaic degradation rates—an analytical review. *Progress in Photovoltaics: Research and Applications*, *21*(1), 12–29.

Leckner, M., & Zmeureanu, R. (2011). Life cycle cost and energy analysis of a Net Zero Energy House with solar combisystem. *Applied Energy*, *88*(1), 232–241.

Lehmann, U. (2011). *Analyse du cycle de vie du Green-Offices (Minor Thesis)*. Lausanne: Lausanne.

Lovins, A. B., Lovins, L. H., & Hawken, P. (1999). *A road map for natural capitalism.* [Retrieved from https://books.google.be/books?hl=nl&lr=&id=nO9MMxTtaeMC&oi=fnd&pg=PA250&dq=hawken+1999+building&ots=KxAPp6S_jv&sig=MCuDiXK06LHE-VJKrHGtBxiHBW4>https://books.google.be/books?hl=nl&lr=&id=nO9MMxTtaeMC&oi=fnd&pg=PA250&dq=hawken+1999+building&ots=KxAPp6S_jv&sig=MCuDiXK06LHE-VJKrHGtBxiHBW4].

Lyle, J. T. (1996). *Regenerative design for sustainable development*. John Wiley & Sons. https://books.google.be/books?hl=fr&lr=&id=qB3v3gYofSUC&oi=fnd&pg=PR9&dq=Lyle+(1996)+on+regenerative+design&ots=DbahlmbGgc&sig=6dZOtRXfnSI92EgEsOAcZ7ObxBI

Marszal, A. J., & Heiselberg, P. (2009). *Zero energy building (ZEB) definitions–A literature review*. Aalborg University-Department of Civil Engineering. https://gin.confex.com/gin/2009/webprogram/Manuscript/Paper2784/Zero%20Energy%20Building%20definitions.pdf?q=project-profile-riverdale-netzero-projectedmonton-alberta

McDonough, W., & Braungart, M. (2010). *Cradle to cradle: remaking the way we make things*. MacMillan. https://books.google.be/books?hl=fr&lr=&id=KFX5RprPGQ0C&oi=fnd&pg=PP1&dq=cradle+to&ots=iqElx-xfHk&sig=kHJuJFP9F8gC-kzDKQD1s1KkO_0

McHarg, I. L., & Mumford, L. (1969). *Design with nature*. New York: American Museum of Natural History. http://student.agsci.colostate.edu/rdfiscus/Design%20with%20Nature.pdf

Meadows, D. H., Meadows, D. L., Randers, J., & Behrens, W. W. (1972). *The limits to growth.New York, 102*. https://books.google.be/books?hl=nl&lr=&id=vb8_BAAAQBAJ&oi=fnd&pg=PA25&dq=The+Limits+to+Growth:+&ots=7povdGueyi&sig=T5HJMZPQe4s6rAzRioVd6MTYjkA

Mertins, D. (2007). *Where architecture meets biology: an interview with detlef mertins*. http://scholar.google.be/scholar_url?url=http%3A%2F%2Frepository.upenn.edu%2Farch_papers%2F7%2F&hl=fr&sa=T&ct=res&cd=2&ei=YRfnVNOgBqTd0wGKqoHoBg&scisig=AAGBfm2S9UgggVSmUI_cED2anqLFY-Ba-g&nossl=1&ws=1536 754

Olgyay, V. (1953). *Bioclimatic approach to architecture. BRAB conference report* (Vol. 5) Washington, DC: National Research Council.

Pajchrowski, G., Noskowiak, A., Lewandowska, A., & Strykowski, W. (2014). Materials composition or energy characteristic–What is more important in environmental life cycle of buildings? *Building and Environment*, *72*, 15–27.

Petersdorff, C., Boermans, T., & Harnisch, J. (2006). Mitigation of CO2 emissions from the EU-15 building stock. beyond the EU directive on the energy performance of buildings (9 pp). *Environmental Science and Pollution Research*, *13*(5), 350–358.

Phinikarides, A., Kindyni, N., Makrides, G., & Georghiou, G. E. (2014). Review of photovoltaic degradation rate methodologies. *Renewable and Sustainable Energy Reviews*, *40*, 143–152.

Pless, S., & Torcellini, P. (2012). *Controlling capital costs in high performance office buildings: a review of best practices for overcoming cost barriers. Preprint. NREL CP-5500-55264*. Golden, CO: National Renewable Energy Laboratory [http://www.ashburnerfrancis.com/SiteAssets/news/Controlling%20Capital%20Costs%20in%20High%20Performance%20Office%20Buildings%20A%20Review%20of%20Best%20Practices%20for%20Overcoming%20Cost%20Barriers.pdf]. Http://www.Nrel.gov/docs/fy12osti/55264.Pdf

Porteous, C. (2013). *The new eco-architecture: alternatives from the modern movement*. Taylor & Francis. https://books.google.be/books?hl=fr&lr=&id=UcBSAQAAQBAJ&oi=fnd&pg=PP1&dq=Neutra+(1929)+on+regionalism+architecture&ots=tDiedDhd2z&sig=XmedlZ1HSIDZtLl3AiEJukJfXsc

Prétot, S., Collet, F., & Garnier, C. (2014). Life cycle assessment of a hemp concrete wall: impact of thickness and coating. *Building and Environment*, *72*, 223–231.

Protocol, K. (1997). *United Nations framework convention on climate change*. Kyoto: Kyoto Protocol. http://www.globaldialoguefoundation.org/files/ENV.2009-jun.unframeworkconventionclimate.pdf

Sartori, I., Napolitano, A., & Voss, K. (2012). Net zero energy buildings: a consistent definition framework. *Energy and Buildings*, *48*, 220–232.

Serrano, C., & Martin, H. (2009). Global securitized real estate benchmarks and performance. *Journal of Real Estate Portfolio Management*, *15*(1), 1–19.

Spiegel, R., & Meadows, D. (2010). *Green building materials: a guide to product selection and specification*. John Wiley & Sons. https://books.google.be/books?hl=nl&lr=&id=VFg3iSOBPVYC&oi=fnd&pg=PT5&dq=materials+building+recycling+colorado&ots=8bzGLYJ56V&sig=hRsXwYQL5CuotlxiMHLORI8EhwI

Spoerri, A., Lang, D. J., Binder, C. R., & Scholz, R. W. (2009). Expert-based scenarios for strategic waste and resource management planning—C&D waste recycling in the Canton of Zurich, Switzerland.Resources. *Conservation and Recycling*, *53*(10), 592–600.

Stevenson, A. (2012). *One planet, how many people? a review of earth's carrying capacity*. Switzerland: UNEP. http://www.unep.org/pdf/UNEP_GEAS_June_2012.pdf

Stewart, F. (1974). Technology and employment in LDCs. *World Development*, *2*(3), 17–46.

Thompson, S., Johnston, C. J., & Thurlow, M. L. (2002). *Universal design applied to large scale assessments*. National Center on Educational Outcomes Synthesis Report. https://osepideasthatwork.org/Toolkit/pdf/Universal_Design_LSA.pdf

Thormark, C. (2002). A low energy building in a life cycle—its embodied energy, energy need for operation and recycling potential. *Building and Environment*, *37*(4), 429–435.

Thormark, C. (2006). The effect of material choice on the total energy need and recycling potential of a building. *Building and Environment*, *41*(8), 1019–1026.

Torcellini, P., Pless, S., Lobato, C., & Hootman, T. (2010). Main street net-zero energy buildings: the zero energy method in concept and practice. In *In ASME 2010 4th international conference on energy sustainability* (pp. 1009–1017). http://proceedings.asmedigitalcollection.asme.org/proceeding.aspx?articleid=1607404

Turner, C., Frankel, M., & Council, U. G. B. (2008). *Energy performance of LEED for new construction buildings*. Vancouver, WA: New Buildings Institute. https://wiki.umn.edu/pub/PA5721_Building_Policy/WebHome/LEEDENERGYSTAR_STUDY.pdf

US DOE, (2012). National Renewable Energy Laboratory, Electronics Lifecycle Management Case Study Golden, Colorado http://www.epa.gov/sites/production/files/documents/lifecycle.pdf.

Uechi, N. (2009). Evolving transcendentalism: thoreauvian simplicity in frank lloyd wright's taliesin and contemporary ecological architecture. *The Concord Saunterer*, 73–98.

Uihlein, M. S. (2014). Ove Arup's total design, integrated project delivery, and the role of the engineer. *Architectural Science Review*, 1–12 [ahead-of-print].

Vaidya, P., Greden, L., Eijadi, D., McDougall, T., & Cole, R. (2009). Integrated cost-estimation methodology to support high-performance building design. *Energy Efficiency*, *2*(1), 69–85.

Van der Lugt, P. (2008). *Design interventions for stimulating bamboo commercialization-Dutch Design meets bamboo as a replicable model*. Delft University of Technology: TU Delft. http://repository.tudelft.nl/view/ir/uuid:6ee4497f-9a2c-4d40-ba89-d869e2d75435/%3C/A%3E%20%20%20%20%20%20%20%20%20%20%20%20%20%20Hardcopies%20available%20via%20%3CA%20HREF=

Van der Ryn, S., & Calthorpe, P. (1991). *Sustainable communities*. http://scholar.google.be/scholar_url?url=http%3A%2F%2Ftrid.trb.org%2Fview.aspx%3Fid%3D421478&hl=fr&sa=T&ct=res&cd=1&ei=LD3nVL69DIqc0AHy9IEg&scisig=AAGBfm2VsQ3mlJRdnFLjfpJUftvPqmvdmA&nossl=1&ws=1536722

Villecco, M. (1977). Energy conscious design in schools of architecture. *Journal of Architectural Education*, *30*(3), 6–10.

Vogtländer, J. G. (2010). *A practical guide to LCA for students, designers and business managers: cradle-to-grave and cradle-to-cradle*. VSSD.

Waldron, D., Cayuela, A., & Miller, D., (2013). Regenerative neighbourhoods–Scaling up from net positive buildings. In Conference Proceedings, Stream (Vol. 5, pp. 80–93). Retrieved from http://norcalapa.org/wp-content/uploads/2014/12/Waldron-et-al-Regenerative-Neighbourhoods-SB13.pdf.

Waugh, A., Wells, M., & Lindegar, M. (2010). Tall timber buildings: application of solid timber constructions in multi-Storey buildings. *International convention of society of wood science and technology and united nations economic commission for europe*, http://www.swst.org/meetings/AM10/pdfs/SD-5%20waugh%20paper.pdf

Werner, F., & Richter, K. (2007). Wooden building products in comparative LCA. *The International Journal of Life Cycle Assessment*, *12*(7), 470–479.

Wolpensinger, H., & nachhaltiges Bauen, F. (2016). *Ökobilanz: punkten mit dem plusenergiebaustoff holz.* [Retrieved from http://www.forum-holzbau.ch/pdf/ihf09_Wolpensinger.pdf]