# Environment – Driven Change Management in AEC Firms

*A. Dalla Valle*, Politecnico di Milano, D-ABC, anna.dalla@polimi.it

## ABSTRACT

*The growing awareness of sustainability goals and environmental issues pushes even more the ongoing process of transformation and increasingly complexity of building sector, bringing out new pressure and more radical changing, involving all the firms' inner resources. The change management process has been disruptive to the extent that while until a short time ago environmental targets were seen as constraints, today they are even more considered as a way to improve performance and increase competitiveness. The result is that nowadays more or less every design firms claim to be environmentally friendly to take advantage for their business.*

*In this context, the research project aims to understand and depict how Architecture, Engineering and Construction (AEC) firms are equipping and reorganizing themselves in order to address and meet environmental issues. In particular, the effort is to identify all the tangible and intangible resources invested by design companies to achieve environmental goals and their role in decision-making process. In this direction, the attention is focused on the relationships and the information's flow among i) the team of actors and experts involved in the design process; ii) the set of tools and assets adopted; iii) and the collection of data required both by experts and tools to work and design. The mapping of design process is fulfilled conducting, in relation to the phase of the project, two different models of interviews within AEC firms: the submission of a questionnaire survey and the examination of case studies. Moreover, consistently with current trends that lead to consider artefacts as small part of a larger networks, systems and environment, life cycle approach is taken during the entire work, to take a broadening of perspective and to avoid shifting problems from one stage to another.*

*Analysing and deepening current practice, the challenge is to develop a framework able to orient and streamline the design process in line with environmental targets and life cycle perspective. The goal is achieved combining the theoretical level, represented by Life Cycle Thinking (LCT) and Life Cycle Assessment (LCA), and the practical level, represented by AEC firms. Life cycle approach is therefore matched and implemented in design process, according to the different phases of the process and identifying the actors engaged and tools used. To face the complexity of the system and to handle the large amount of data, Building Information Modeling (BIM) is identified as the most suitable tool to embed the proposed framework. The application of the framework allows to enforce life cycle perspective in AEC practice starting from the early stage of the project and to truly orient decision-making process in line with environmental targets.*

### Keywords

Environmental issues; AEC firm; change management; design process; competences; tools; information's flow; decision-making; optimization; Life Cycle Thinking (LCT); Life Cycle Assessment (LCA); Building Information Modelling (BIM).

## INTRODUCTION

All over the world, the awareness of sustainability and environmental issues is raised over time to the extent that, after creating a heated debate in the academic community and obtaining consensus among politicians and practitioners, they become part of many agenda and standards. In particular, the first of January 2016 represents a turning point since the 17 Sustainable Development Goals (SDGs) of the 2030 Agenda for Sustainable Development, previously adopted in September 2015, officially came into force. Indeed, over the next fifteen years, the 193 world leaders committed their respective countries to achieve the shared goals with the connected targets, mobilizing efforts not only to tackle climate change, but also to end all forms of poverty and fight inequalities, ensuring that no one is left behind. For this purpose, it is required a joined action at local, national and international level through a strong commitment of governments but also involving and empowering the private sector, the society and all individuals.

In this context, Life Cycle Thinking (LCT) becomes a crucial prerequisite to gain at different scale a global and holistic view of the ongoing processes and to help actors to think and operate in a sustainable perspective. Indeed, thinking in terms of life cycle allows to deal with problems avoiding to approach reality in a reductionist way, since too restrictive and obsolete to comply with the prescribed SDGs. Two are the key factors of LCT in promoting sustainable and innovative models, lifestyles and business. First, the chance to consider and evaluate in advance the possible reverberation that and action can have over time at environmental, economic and social level. Secondly, the chance to avoid shifting problems and so their transposition from one side to another, concerning not only the time frame but also the geographical location. All these factors are pivotal in sustainability, especially if it is expected to reach it at global scale as required by Agenda 2030.

Focusing on environmental issues, Life Cycle Assessment (LCA) methodology is currently the most well-established scientific method to assess the environmental impacts of products, processes and services throughout their entire life cycle. In particular, its application is decisive for achieving the following goals: number 12 “Responsible consumption and production” and, since different impact indicators fall into other goals, the number 3 “Good-health and well-being”, 6 “Clean water and sanitation”, 13 “Climate action”, 14 “Life below water” and 15 “Life on land”. This method is adopted in a more or less systematic way in the most various fields, on one hand, to monitor resources and environmental impacts and, on the other, to optimize processes. Despite LCA still have some critical aspects not yet solved, such as the methodology itself, data availability and comparability of results, it is important to foster its widespread dissemination in order to activate the virtuous mechanisms able to meet the environmental sustainability demanded by SDGs.

To this end, construction sector is certainly a strategic field of action to address sustainable and environmental goals as it is esteem as one of the most incisive and impacting sector at a global scale, due to the high consumption of soil, natural resources and energy and the high emission in air, water and ground. Just to give some numbers, from the environmental point of view, it consumes each year about 3 billion tons of raw materials to manufacture building products worldwide and it is responsible for 40% of solid waste derived from construction and demolition and for 25-40% of the total energy use at global level. Furthermore, it must not forget the economical point of view, since the construction industry collects total annual revenues of almost $10 trillion, accounting for about 5% of global GDP and employing more than 100 million people worldwide. In addition, with regards to social point of view, it is well known that construction continues to shape our daily life in unique ways, with a high impact on the health and well-being of its occupants (WEF, 2016).

The growing awareness of sustainability goals and environmental issues led many governments to provide regulations and requirements with the aim to control the impacts generated by building sector. In this way, environmental targets spread in design and construction firms, boosting the ongoing process of transformation and increasingly complexity of building industry and bringing out new pressure and more radical changing. The integration process has been disruptive to the point that while until a short time ago environmental targets were seen as constraints (just think about energy efficiency directive), today they are even more considered as a way to improve performance and increase competitiveness. The result is that nowadays more or less every design firms claim to be environmentally friendly to take advantage for their business.

Over time, several studies dealt with sustainability and environmental aspects in construction sector, on one hand, analysing advancement, key factors, weakness points, barriers and all the related topics to clarify the current state and, on the other, exploring new methodologies, framework, instruments and tools to support design tasks. The problem is that while we have a wide knowledge from the theoretical point of view, there is no literature about what happens in design practice. In this regard, many are yet the open questions to be solved, just to name a few: the environmental issues taken into consideration, the way of practice to address them, their role within the decision-making process, the kind of tools and software used for that purpose, the skills and competences involved in the process and the related information’s flow. Since this field remains until now fuzzy, the research project seeks to fill the gap with the aim to understand how AEC firms are equipping and reorganizing themselves in order to address and meet environmental issues.

The subject engaged are thus both Architecture and Engineering firms but also Construction companies, since they represent the key actors and practitioners responsible for the built environment development. Indeed, in a simplified and synthetic way, artefacts are essentially conceived and designed by architectural and engineering studios and they are physically realized and built by construction companies. Nevertheless, today the boundaries between AEC firms are blurred, since for several reasons they are even more characterized by an “hybrid” nature to interplay and collaborate in an integrated way. On account of this, the research deals with the whole AEC industry to identify shared strategies but also individual practice and decision-making process in relation to the type of company. In addition, with regards to firms’ dimensions, the attention is focused on big and medium-size firms, since they are strongly involved in the process of transformation, rather that small firms where inner changes are limited and less visible.

In this direction, the effort is to identify all the tangible and intangible resources invested by AEC firms to achieve environmental goals and their influence in the decision-making process. In particular, the attention is focused on the relationships and the information's flow among i) the team of actors and experts involved in the design process; ii) the set of tools and assets adopted; iii) and the collection of data required both by experts and tools to work and design. Moreover, consistently with current trends that lead to consider artefacts as small part of a larger networks, systems and environment, life cycle approach is taken during the entire work, to take a broadening of perspective and to avoid shifting problems from one stage to another.

The research project analyses current practice with the aim to orient and streamline the design process in line with environmental targets and life cycle perspective and thus to decrease, as demanded, the high impacts of building sector. To this end, the implementation of Life Cycle Thinking, as first, and then, in the next future, the application of Life Cycle Assessment within AEC practice are considered the key challenges to allow practitioners to make aware decisions, to gain long-term perspective, to optimize design process, to lead decision-making and to truly decrease construction impacts.

## STATE-OF-THE-ART

The research project involves a broad spectrum of topics of growing interest in the international panorama such as, just to mention a few, sustainability, life cycle, Life Cycle Assessment (LCA), Information and Communication Technology (ICT), Building Information Modelling (BIM) and change management. To face the complexity of the matter and the wide background available, the state-of-the-art is structured in three main sections: i) change management in AEC practice; ii) environmental issues and tools in AEC practice; and iii) AEC firms sustainable practice. For each section a comprehensive literature was developed based on two different type of sources: on one hand, through the Web of Science to identify the scientific and academic paper and, on the other, through the Web to locate other researches, documents, reports and supporting materials on the topics. Indeed, dealing with design practice, it is important to examine not only the publication of the academic community but also internet browser, since only here are visible all the assets developed by the same AEC firms.

In the first section, the keywords used in the starting literature review included "AEC change management" and "design building practice change management" for ISI search and "AEC firms change management" for Web search. In the second section, the keywords are "sustainable building design practice", "green BIM", "interoperability BIM LCA", "LCA software", "LCA software building", "Life Cycle design building practice" for ISI search and "sustainable design practice" and "tools sustainable building practice" for Web search. In the third section, the only source adopted is the Web and the keywords used are "AEC firm's name sustainable practice" (considering the name of the first ten AEC firms listed in ENR's ranking of 2015) and a randomly research. In relation to scientific publications, a cross-reference activity was carried out for the latest papers (considering the ones developed until 2014) to avoid losing documents, while were surfed the web checking the first twenty pages.

Given the topicality of the subject, the articles and papers collected refer mainly to the timespan between 2010 and 2017, with a strong concentration in recent years even though there are scattered references related to previous years. In this regard, it is possible to notice that the documents concerning change management are the most dated, since the topic in question emerged earlier than environmental issues that, on the contrary, are gaining more importance especially in recent years. Some of the top journals included in literature search were including, but not limited to: Automation in Construction, Building and Environment, Energy and Buildings, International Journal of Life Cycle Assessment, Journal of Cleaner Production and Renewable and Sustainable Energy Reviews. The documents and papers gathered during this process are then categorized according to specific sub-topics for each section.

The following paragraphs depict the three main sections of the state-of-the-art, explaining in a synthetic way the sub-clustering and the main findings to offer a quick overview of the phenomenon in progress (WP1 – cognitive phase at theoretical level).

### Change management in AEC practice

The first section, related to change management in AEC practice, is split in the listed four main sub-topics: "increasingly complexity", "tangible resources", "intangible resources" and "decision-making process".

Indeed, over the recent decades, building sector has expanded and become increasingly complex (Browning, 2016), as direct consequence of the globalization of the market (Bond and O'Byrne, 2014) and the demand of a wide range of requirement (Yu and Chan, n.d.), like the ones related to sustainable development and environmental issues (Štefaňák, 2011; Woods, n.d.). To face these pressures, construction field is changing step by step (Deamer and Bernstein, 2010; Renz et al., 2016; Weippert and Kajewski, 2004; Witthoeft et al., 2017), even if it is considered resistant to change (Davis, 2008; Smollan, 2011). The transformation process involves all the firms' inner resources (Chinowsky and Byrd, 2001): tangible resources, such as materials, buildings, plant, equipment, tools, money; and intangible resources, such as knowledge, organization and intelligence of people (Norsa, 2005; Sinopoli, 1997). Regarding tangible resources, it is important to stress the relevance of technology in AEC practice, with tools able to meet any design issues (Boddy et al., 2007; Fox, n.d.; Rezgui et al., 2011; Riese, 2012), and the so-called digital revolution of BIM (Autodesk, 2011b; Babič et al., 2010; BCG et al., 2016; Becerik-Gerber and Kensek, 2010; Harris, 2010; Reinhardt et al., 2013; Succar and Kassem, 2015). By contrast, intangible resources deal with the specialization of competences (Cerovšek et al., 2010; Hoffman and Lintern, 2006), knowledge and know-how (Mills et al., 2003), conceiving design process as an integrated practice where autonomous units of work turn into systems (Tiwari and Howard, 1994). In this context, a key ingredient is the ability of the companies to manage decision-making process and thus to achieve collaboration, cooperation and coordination (AberdeenGroup, 2007; Shen et al., 2010; Susman et al., 2006), handling at best information's flow and workflows (Carson and Baker, 2006; Sakhare et al., 2014). Due to the dynamic and fragmented nature of construction sector, the problem of data integration throughout the projects' life cycle still remains a challenge (Chinowsky and Carrillo, n.d.; Mokhtar et al., 1998; Rezgui et al., 2010).

## Environmental issues and tools in AEC practice

The second section, related to environmental issues in AEC practice, is a little more complex and articulated. It is split in four main sub-topics: "approaches life cycle", "drivers", "practice" and "tools", which are in turn divided according to other themes. The sub-topic "approaches life cycle" is divided in: "life cycle approaches", "Life Cycle Assessment" and "LCA case studies". The sub-topic "drivers" is divided in: "clients" and "environmental policies". And finally, the sub-topic "tools" is divided in: "environmental tools", "LCA building tools", "green BIM", "BIM – Rating Systems", "BIM – LCA".

Environmental issues are gaining even more attention in the construction field, fostered by the concept of sustainable development and circular economy (Accenture, 2014; Arup, 2016; Carra and Magdani, 2017; Ellen MacArthur Foundation, 2015, 2016) and becoming part of many international agenda and standards. In this context, many approaches and methodologies arose in order to promote new business models, while reducing dependence on primary materials and energy. One of the most affirmed purpose is that whole-system thinking is required to reduce environmental impacts within construction sector and drive both sustainability and innovation (Faludi, 2015), starting at small scale with building level (Annex31, 2004d) to end at large scale with supply chain (Antink et al., 2014). In this direction, LCA is considered as the most scientific method and it is growing of importance (Annex31, 2004b; Bayer et al., 2010; Zabalza Bribián et al, 2009), not only to meet customer demands for environmental friendly products/projects, but also to improve environmental processes and services and thus increase competitiveness (Cassidy, 2005; Khasreen et al., 2009; Ortiz et al., 2009). The main drivers are, on one hand, clients, which have a key role in creating and stimulating the right conditions for construction innovation, understanding and sharing the needs of both end-users and stakeholders (Häkkinen and Belloni, 2011; Hartmann et al., 2006; Kilinc et al., 2015); and, on the other, regulation, policies and planning in encouraging and facilitating facilities that meet high environmental standards (Fischer and Guy, 2009; Shaw and Ozaki, 2016). Due to sustainability and environmental targets, the shared belief is that probably in the next future every company will need to transform itself and change management to survive and succeed (Farmer, 2013; Hedstrom, 2015; Kaatz et al., 2006; Mendler et al., 2006; Pan and Ning, 2015), facing the several barriers that today occur in construction sector and sustainable practice (Robichaud and Anantatmula, 2011). This challenge is not only addressed by AEC firms but also by software corporations (Autodesk, 2015), describing through reports their efforts and progress in sustainability during the last years. In this way, the set of tools available on the market is even more broader, allowing AEC practice to potentially meet any design issues concerning environmental issues (Forsberg and von Malmborg, 2004; Haapio and Viitaniemi, 2008a; Reijnders and Van Roekel, 1999; Zhai and McNeill, 2014) but also LCA (Gantner et al., 2012; Han and Srebric, n.d.; Hitchcock et al., 2011; Lehtinen et al., 2011; Peuportier et al., 2005, n.d.). Moreover, given the potentialities of BIM (Autodesk, 2011a), it is possible to streamline the design process, exchanging data and models between different software and creating great opportunity to achieve sustainability targets (Azhar et al., 2008; BLP and Miller, 2011; Cidik et al., 2014; Koppinen and Morrin, n.d., Levring and Nielsen, 2011; Rajendran et al., 2012; Liu et al., 2015; Wong and Zhou, 2015; Zhang et al., 2013), Rating System certification (Azhar et al., 2011; Biswas et al, 2013; Jalaei and Jrade, 2015; Nguyen et al., 2010; Wu and Issa, 2015) and LCA analysis (Anton and Diaz, 2014; Basbagill et al., 2013; Kovacic, 2016; Lee et al., 2015).

## AEC firms sustainable practice

The third section collects AEC firms sustainable practice, without any sub-division in sub-topics.
AEC firms (AECOM, 2012, 2013, 2016; AMEC, 2014, 2015a, 2015b; ARCADIS, 2015; Arup, 2015, n.d.a, n.d.b; CH2M, 2015; Fluor, 2014; Foster&Partners, 2005; Jacobs, 2015; MottMacDonald, 2016; SOM, 2013a, 2013b, 2014; WorleyParsons, 2015; WSP-Parsons Brinckerhoff, 2014a, 2014b) as well as other institutions, organizations, associations, companies and corporations (BusinessRoundtable, 2015; McKinsey, 2014; RobecoSAM, 2015a, 2015b) disseminate several documents, reports and supporting materials concerning environmental issues and in general sustainability. The problem is that looking into AEC publications, more or less every big and medium-size company claim to be environmentally-friendly, not allowing to really understand by the documentations available how they work, act, design and process in practice.

## SoA in detail

In addition to the above reported overview, an in deep analysis was conducted in relation to the key issues of the research project.
With the aim to look into AEC firms' perspective, the state-of-the-art was examined pointing out the literature studies based on questionnaire surveys inputs from design and construction company and concerning the following topics: BIM, Green BIM, LCA.
Regarding BIM, some questionnaires spread with the aim of exploring the users and business value of BIM to provide an overview of the trends in action (McGraw Hill Construction, 2009, 2010) or focusing on its implementation in specific countries, for instance UK (Khosrowshahi and Arayici, 2012). Moreover, some others broaden the perspective examining the degree of adoption and impact of BIM in relation to Integrated Project Delivery (IPD), Integrated Design Process (IDP) and Building Energy Simulation (BES) (Becerik-Gerber and Kensek, 2010; Farias Stipo, 2015).
With regards to Green BIM, various surveys were developed to investigate the current state in which BIM operates and functions with respect to sustainable design practice as well as the potential of Green BIM in the future (Azhar and Brown, 2009; Bynum et al., 2013; McGraw Hill Construction, 2010).
Concerning LCA, some authors explored the point of view of building designers on BES and LCA but enclosed to US context (Han and Srebric, 2015) and some others deepened the status of LCA application and challenges limited to Nordic countries (Schlanbusch et al., 2016).
The attention was furthermore focused on the application of LCA methodology in construction sector, analyzing the LCA tools now available on the market and developed to support practitioners for their environmental choices. In fact, several authors identified the existing stand-alone LCA tools for buildings, presenting their main characteristics (Annex31, 2004; Bayer et al, 2010; Gantner et al, 2012; Han and Srebric, n.d.; Hitchcock et al., 2011; Lehtinen et al., 2011; Peuportier et al., 2005, n.d.; Quinones, 2011), while others analyzed the possible integration of LCA in BIM. Indeed, some authors report a critical review of BIM-based LCA method to buildings (Spiegelhalter, 2012; Anton and Diaz, 2014; Soust-Verdaguer et al., 2017) and some others present environmental assessment tools to provide fully integrated approach applying LCA directly in BIM (Tucker et al., 2003; Kulahcioglu et al., 2012). Some studies focus on the evaluation of buildings' carbon emissions and embodied energy in a BIM-driven design process (Li et al., 2012; Shadram et al., 2016) and some others restrict the field of application to commercial buildings (Means and Guggemos, 2015) or structural systems (Eleftheriadis et al., 2017). In addition, some case studies shown and explore the potentialities of BIM as supporting tool for LCA starting from the early stage of design decision-making process (Basbagill et al., 2013; Lee et al., 2015; Kovacic and Honic, 2016). Lastly, few case studies display models that link BIM and LCA with other functionalities such as energy analysis, lighting simulation and green building certification systems (Jalaei and Jrade, 2014), or Life Cycle Costing (Shin and Cho, 2015), or scheduling, costing and sustainability dimensions (Yung and Wang, 2014).
Finally, the search explored the developed LCA studies, finding in literature a lot of single LCA studies carried out at building level but also some literature reviews on collected LCA analysis (Buyle et al., 2013; Cabeza et al, 2014; Chastas et al., 2016; Soust-Verdaguer et al., 2016).

# METHODS FINDINGS AND ARGUMENT

With the aim to understand how environmental issues are addressed in AEC practice and their role within the decision-making process, during the entire work the adopted methodology combines the search conducted at theoretical level with the search conducted at practical level. In particular, the theoretical research is developed exploring and upgrading the studies and findings available in literature, while the practical research is developed conducting interviews to design and construction firms. In the last case, the working method elected is strictly related not only to the subject in question that requires itself a close investigation into AEC firms and their workability, but it also calls to mind the field of qualitative research methodologies: the ethnography approach. Indeed, as stated in literature (Pink et al., 2013), ethnography is now emerging as part of the set of techniques used to understand the construction industry, a sector considered extremely complex and influential but that despite this remains mostly unexplored and under-theorised. In this way, the research project embraces the ideas that construction ethnography, involving the main actors engaged in the process, can offer new routes to knowledge about and in the construction sector. Ethnography become thus the methodology adopted to deal with the practical search, applying two different models of interviews in relation to the level of detail to be achieved according to the phase of the project.

The following paragraphs shown the structure of the research project, briefly presenting the Work Packages (WP) and describing for each phase the associated specific targets and the results expected.

The cognitive phase at theoretical level (WP1), previously depicted, aims to define the state-of-the-art of the research project, identifying through the Web of Science the related scientific and academic paper and through the Web other researches, documents, reports and supporting materials on the topic. The outcome is the identification at theoretical level of current trends in the field of change management ongoing in AEC practice and specifically focusing on environmental issues.

The cognitive phase at practical level (WP2) aims to start gain insight on the AEC perspective in order to understand if the theoretical data are confirmed by real practice and to provide an overview of the transformation process and trends in environmental topics. To this end, the first model of interview is applied by means of the spread of a questionnaire survey. It involves a large target audience, focusing on general design practice and using indirect means of communication, such as mail or telephone interviews, structured with open-ended questions. The outcome is the identification at practical level of current trends within AEC practices, since design and construction firms are analysed as groups rather than as individuals.

The descriptive phase (WP3) aims to develop at conceptual level the supporting materials necessary to the following research's phases. The challenge is to match, integrate and interconnect life cycle approach (theoretical level) and design process (practical level). The outcome is a framework able to figure out LCA data and choices according to the different phases of the process, as well as the connected actors engaged and tools used. In this way, the research proposes a new way to orient the change management of design process in line with environmental targets and life cycle perspective.

The partnership phase (WP4) aims to establish agreements with some national and international AEC firms in order to encompass their practices in the analysis. This is a crucial point since from the companies' point of view the partnership can represents an effort but at the same time an opportunity for their workability. The call is turn to AEC firms considered environmentally friendly, selecting from their portfolio a case study, built with the accomplishment of high environmental targets and possible equipped with an LCA study. The outcome is a list of design and construction firms available to actively contribute to the research goals.

The analytic phase (WP5) aims to understand how AEC firms deal in practice with environmental issues and how environmental issues are integrated in the design process and the connected information's flow. To this end, the second model of interview is applied by means of a personal involvement within the joined practice. It involves punctual partnerships, focusing on specific environmental-friendly projects and using direct means of communication, such as face to face questions, not structured since they vary in relation to the firms' practice. The outcome is a mapping of AEC design process stressing environmental issues and their role in decision-making.

The synthetic phase (WP6) aims to get the meaning of the different AEC design processes examined and of the possible application of the suggested framework within their practice. The outcome is a validated framework able to orient and streamline the design process in line with environmental targets and life cycle perspective, optimizing the decision-making process and thus the connected tangible and intangible resources and maybe introducing new competences and new organizational models.

The following paragraphs look into the Work Packages of the research explaining, on one hand, the methods and the main findings of the WP addressed and still now underway (WP2 and WP3) and, on the other, the plan of action for the WP started but not yet concluded (WP4) and in the forthcoming agenda (WP5).

## Starting gain insight on AEC firms

From the first steps of the research, a questionnaire survey was conducted to start gain insight on AEC perspectives, analyzing current design practice in order to provide a general overview of the transformation process and determine trends in environmental topics (WP2 – cognitive phase at practical level).

The target audience was architectural and engineering firms but also construction companies established both at national and international level and restricted to big and medium-size firms. Indeed, as just mentioned, with regards to environmental issues the transformation process gets involved especially the big and medium-size firms rather than the small ones which are for this reason excluded from the study. In addition, since today a variety of design firms operate worldwide and that the sample population can affect significantly the outcome of the study, it was adopted an as unbiased as possible criterion for the selection. AEC firms were thus identified through published ranking, considering for the medium-size firms the Italian list named "Top 100 national design firms" developed by Edilizia e Territorio in 2013 (Edilizia e Territorio, 2013) and for the big-sized firms the "Top 150 global design firms" developed by ENR according to revenue for design services performed in 2015 (ENR, 2015). Right now, it is possible to point out that seven of the ten global AEC firms are tagged environmentally friendly by ENR, stressing the assumption that design business are taking advantage by the integration of environmental topics and goals. Participants were recruited through email invitations to the selected ranking lists and were later widen through the direct contacts gained during the study. Moreover, to meet as much as possible firms' demand, AEC companies can choose if reply independently to the survey, if set a phone/skype call or fix a meeting according to their preference and availability.

The questionnaire is structured with open-ended questions split in three main sections: i) general info; ii) structure and organization; and iii) environmental issues. The first section provides an overview of the firm interviewed, explaining the type, the network in relation to the number of offices, the size in relation to the number of employees, the competences required and the projects/tasks developed. The second section deals with the structure and the organization of the firms, depicting the operational units and the sub-specialized units, if necessary the support of external partners, the different ways to manage and tackle the design process, the potential use of BIM tools and the information's flow between the different actors involved. The third and last section is focused on environmental issues, pointing out the main drivers of such topics, the main goals addressed, the main experts engaged, the main environmental consultants if any and the use of Life Cycle Assessment as supporting tool in the decision-making process. Before the widespread dissemination of the survey, the questionnaire was validated inviting one national and one international company to respond in advance to the survey in order to understand if questions were clear and comprehensible form practitioners' point of view, testing and if required adjusting the queries.

The questionnaire survey was lunched on November 2015 and submitted to forty-six international and national AEC firms. Until now, despite the countless reminders, only nine firms completed the survey: four medium-size firms, involving Renzo Piano Building Workshop of Genova (ranked at the first place in Italy), Progetto CMR of Milano (eleventh place in Italy), PiuArch of Milano (sixteenth place in Italy) and Cucinella of Bologna (thirty-second place in Italy); and five big-size firms, including HDR of Chicago (ranked at the twenty-first place in the world), Arup of Berlino (twenty-fourth place in the world), HOK of Washington (seventy-eight place in the world), Foster and Partners of London and Skanska Finland and UK (not located in the raking). In this way, the survey response rate is 20% which is a little low but, given the diversity of firms, good enough to identify general current practice and trends. Among the survey respondents, the majority are architectural firms (45%) or integrated firms (33%), followed by engineering firms (11%) and construction companies (11%).

The survey was thus presented in the different AEC firms demanding for the responses the involvement of the environmental experts. Indeed, also the expertise, the background and the employment of the individuals engaged in the questionnaire going to strongly affect the outcome of the study. For this reason, it is important to underline that, in relation to firm's availability, in some case the informants are environmental experts while in others are workers of different hierarchical levels and positions. When possible, multiple participants were interviewed simultaneously to provide different point of views and improve the reliability of data. In this way, the wealth and the accuracy of the replies gained depends not only to the type and dimension of the firms but also to the willingness to participate which was not equal across the offices.

After the interview, for each firm the information gathered are summarized and schematized in a graphic way, as shown on Figure 1. At the base, it is specified the name of the company under study, followed by its location, the type of firm identifying with "A" architecture, "E" engineering and "C" construction, the position in the ranking explaining if at Italian level or in the world. Moreover, the base colour indicates whether the company belongs to big or medium-size firms. Afterwards, data are explained in eight columns: the first three columns provide "general info" related to the firm and the last five columns refer to "environmental issues". In this way, "general info" are grouped in "dimensions", "structure" and "experts"; while "environmental issues" in "drivers", "topics", "tools", "simulations" and "development". The column "dimensions" explains the number of country where is set the firm and the related number of offices and employees. The column "structure" explains the operational units, including administration, commercial and technical-operative areas, and if specified the tools used to share and manage the information's flow within the firm. The column "experts" explains the specific competences in-house, representing with the symbol if it is a single expert or a group, and eventually the external partners. With regards to "environmental issues", the column "drivers" explains the motivation items, such as regulations, clients or philosophy, that push in that direction the design practice. The column “topics” explains the environmental issues mostly considered, such as energy, water, pollution, health and wellness. The column “tools” explains the assets used by the firms during the design process, in particular simulation software, BIM, LCA study, environmental information and if it relies on external partners for some aspects. The column “simulations” explains the name of tools and software used by the firm to address environmental issues. Finally, the column “development” explains if these tools are available on the market or are homemade.

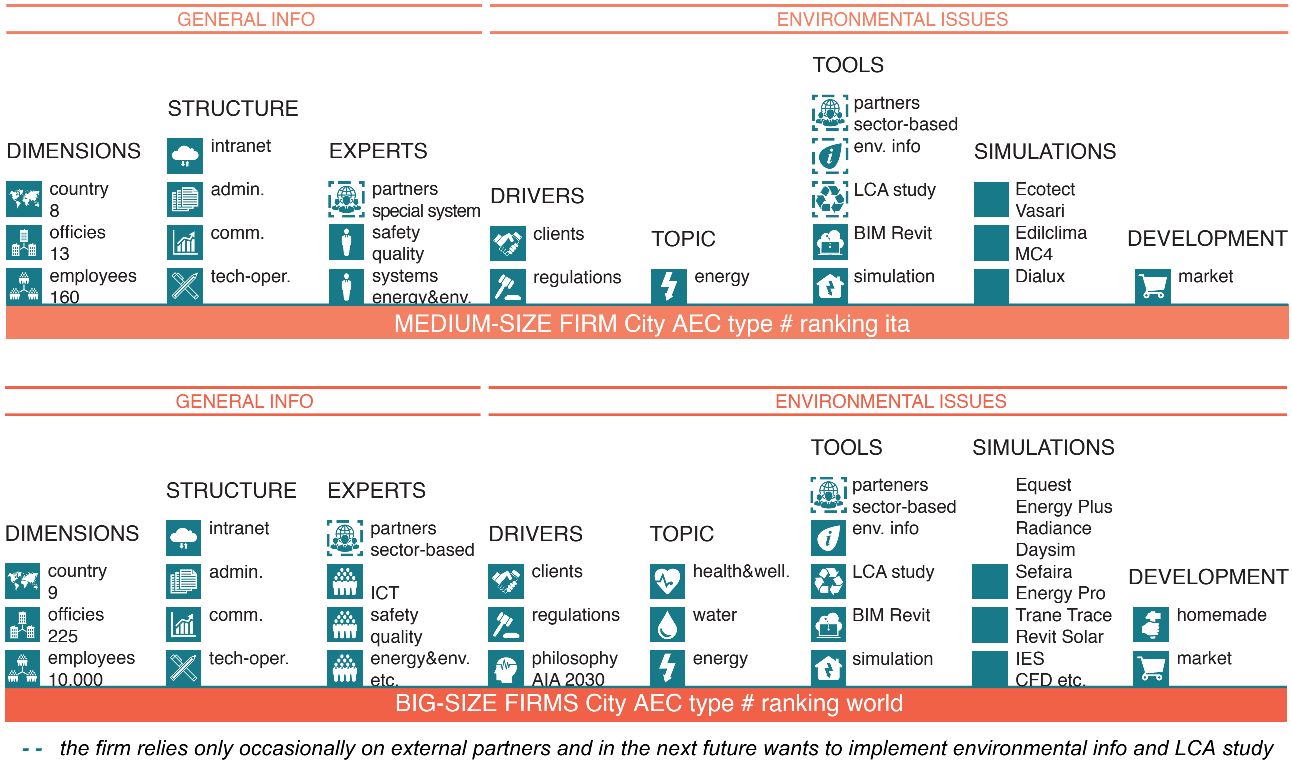


*Figure 1. AEC firms surveyed – examples of individual analysis*

In a second time, the AEC firms interviewed are analysed as groups rather than as individuals to identify current practice and determine trends, as shown in Figure 2. Therefore, all design practice are gathered together in relation to their dimension, creating two synthetic graphs: one for the medium-size firms and one for the big-size firms. Despite the previous graphs developed at individual level, the cumulative graphs picked out only the most significant indicators, respectively “structure”, “experts”, “topics” and “tools”, with the aim to briefly illustrate the difference inherent design firms according to their size. Here the focus is on the technical-operational area that it is in turn divided in sub-specialized units to meet the emerging issues, such as energy and environment, systems, quality, safety and ICT, just to mention a few. Every unit is made up of individual experts within medium-size firms, while is built of specific teams within big-size firms. Of course, not all the specialized units with the related experts and specialists are embedded in all the analysed design structures, but their existence shows the growing interest to the performed issues and their strengthening over time to the point to require their establishment within the firm. When for economic and/or organizational reasons not all the required different skills are present internally, AEC firms rely on external partners to meet the specific design requirements. For medium-size firms this happens quite often, especially if they deal only with architecture or engineering, but also for the integrated practice. Nevertheless, even big-size firms, although they embedded all the expertise in house and they are technically able to handle all the aspects of the project, sometimes they prefer to be supported by external strategic partners that know local requirements and have better skills in certain area to enhance the project. Environmental issues are generally addressed by AEC firms and are stressed in different manner within the design process. Here the mindset of the client and the type of project play a key role in fostering the greenness that, as shown by questionnaire’s feedback, have focused on energy and water for the past 5 years and on health and wellness starting from 2016 and beyond. Big-size firms usually comply with all the aspects related to environmental and human impacts, while medium-size firms mainly deal with energy issues, since it is the subject that raises more interest in clients and customers. Concerning the tools used, all the AEC firms interviewed claim to be BIM-oriented in order to facilitate the exchange of design data but also to make verifications with other software, including simulation plug-ins as well as stand-alone modelling software. Indeed, nowadays, every design company is accustomed to make simulations to analyze the performance of the project, choosing from a wide range of tools able to meet every design demand from energy and lighting simulation to impact assessment and so on. In this case, while generally medium-size firms used the tools available on the market, big-size firms developed some of them in-house to customized their equipment to specific needs. On the contrary, the minority of the firms interviewed, involving notably the big-size firms, use to attach in the BIM model the environmental information of the products, including external LCA database rather than personal data. Concerning LCA analysis, 44% of the firms interviewed are used to develop LCA studies of the projects/services, involving specifically the big-size firms in all the type: architectural, engineering and construction companies. They adopt the LCA tools available on the market (for instance SimaPro for construction company and Tally in implementation within integrated practice) and the connected environmental database embedded. Typically, LCA is performed starting with the technological components accountable for the large impacts, such as concrete, steel and façade, and then working down to the smaller installation items. By contrast, the resulting 56% of company, engaging in particular the medium-size firms, do not perform LCA analysis essentially because it is not required by clients and regulations. Nevertheless, sometimes they estimate the environmental impacts of the projects (expressed in $tCO_2e/y$), considering only the in-use phase and so the energy consumption. However, all the companies surveyed are aware that LCA becomes part of many Green Building Rating Systems and so that they probably should implement it within practice, if they do not want to rely on external consultants focused on life cycle services.

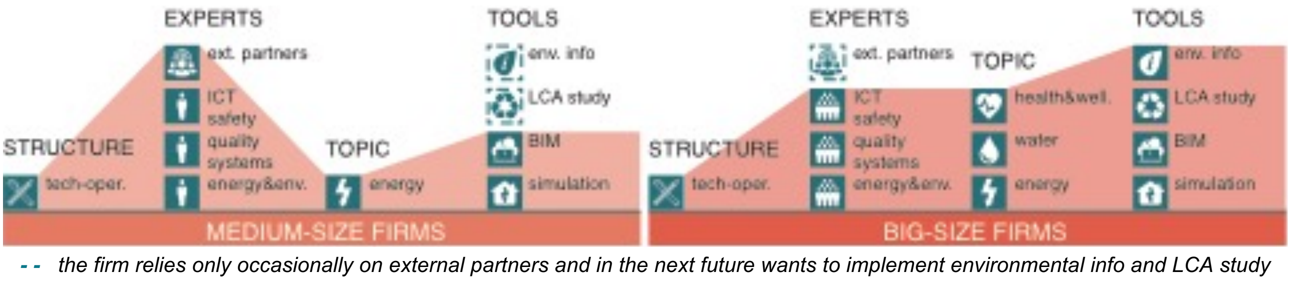


*Figure 2. AEC firms surveyed – collective analysis*

The critical aspect of this type of interview is that the reliability of data and the amount of information achieved are difficult to handle for many reasons. First of all due to the variety of practice in question that can be really different each other, making the process of generalization in some parts very hard. Furthermore, since the sample population is not large enough, it is possible to make considerations and determine trends only in relation to firms' dimensions, flatten the peculiarity of the different type of firms. With regards to the participation of AEC firms, probably it is discouraged by the open-ended questions that if, on one hand, were opted with the intention to affect as little as possible the answers, on the other, the fulfilment of the questionnaire requires a lot of time and effort by the respondents. Moreover, the outcomes depend on the role of the people interviewed and from their competence in design process and especially in environmental issues. Finally, given the specificity of some questions, the answers gathered risk to be project-based, strictly related to one virtuous case with the connected project's location, type, dimensions and clients.

## Life Cycle approach in design process

In order to stress a life cycle perspective during the research project and the examination of AEC practice, a background activity has been developed and is still ongoing with the aim to orient and streamline the design process in line with environmental targets. The effort is to combine, on one hand, the theory of the scientific community and, on the other, the practice of design and construction firms (WP3 – descriptive phase).

As stated, due to the high impacts generated on the environment and the strong international pressure of Sustainable Development Goals to be met by 2030, it is extremely compelling to appropriately change the attitude and way of practice of building sector. In fact, to comply with the shared environmental targets, it is crucial to dive and orient in the right direction construction sector and the related built environment, to achieve great results in a limited time span. The required environmental-oriented change represents a big challenge for the construction sector, demanding an even more robust transformation process in a sector still now considered resistant to change. Moreover, the change management should embrace all the actors responsible for the built environment, starting from the mindset to end with practical actions and operations. In this context, two are the shared strategy that need to be applied. Firstly, the implementation of Life Cycle

Thinking to change the way of thinking within the construction sector. Secondly, the application of LCA method to evaluate, change and control the way of acting within design and construction practice.

However, to activate the type of mechanisms able to meet environmental sustainability, it is not enough to identify the helpful methodologies, such as LCT and LCA, but it is necessary to understand what are the actors involved and how the methods can be integrated within the process. To this end, AEC firms, including both architectural and engineering studios as well as construction companies, represents the key actors responsible for the built environment. In fact, constrained, on one hand, by regulations and standards and, on the other, by clients and users' requirements, they take most of the decisions that will condition the building environment during the entire life cycle. Nevertheless, despite the wide range of LCA tools and software available on the market to help designers and practitioners in assessing environmental impacts and orienting design choices, LCA analysis is not common in design and construction practice. Moreover, when performed, it is mostly considered as a tool to demonstrate to the clients the green-ness of the proposed solution, rather than as a tool to compare alternatives and to support decision-making.

In this context, the research project seeks to combine the theoretical level, represented by LCT and LCA, and the practical level, represented by AEC firms. For this purpose, a conceptual framework was developed to match and implement life cycle approach in design process, trying to figure out how it can be employed according to the different phases of the process. The goal is to enforce life cycle perspective in AEC practice starting from the early stages of the project and to truly orient decision-making process in line with environmental targets.

The basic matrix of the framework, shown in Figure 3, is established, on one hand (in the horizontal axis), by the different stages of LCA and, on the other (in the vertical axis), by the different phases of design process. LCA methodology and the connected stages and environmental information are analyzed according to the European Standard "Assessment of environmental performance of buildings" (EN 15978:2012) and Product Category Rules "Buildings" (PCR UN CPC 531:2014). In this way, the identification of LCA stages follows the typically classification prescribed by the standards: product stage (A1-A3), construction stage (A4-A5), use stage (B1-B7), end of life stage (C1-C4), benefits and loads beyond the system boundary (D). Instead, design process phases are pointed out with reference to the documents and reports produced by the United Nations Environmental Programme "Greening the building supply chain" (UNEP, 2014), by the American Institute of Architects "The architect's handbook of professional practice" (AIA, 2014) and by the Royal Institute of British Architects "Plan of Work" (RIBA, 2013). In this case, due to the different partitioning provided by the institutions, the terminology was harmonized splitting the design process in five main phases: concept phase, design phase, construction phases, in use phase and end of life phase. Note that despite the similarity of the terms, the stage of LCA method do not correspond to those of design process. Indeed, for example, the design phase has to take into consideration all LCA stages, while the in use phase should consider the LCA use stage but also the product stage with regards to the maintenance and operational activities. To this end and in agreement with the proposed framework, Figure 3 shows the LCA stages that can be addressed in relation to each phase of the design process. The configuration of the matrix is not valid in absolute terms but may change based on the way of practice, depending in particular on how deeply life cycle perspective is integrated in the design process in object.

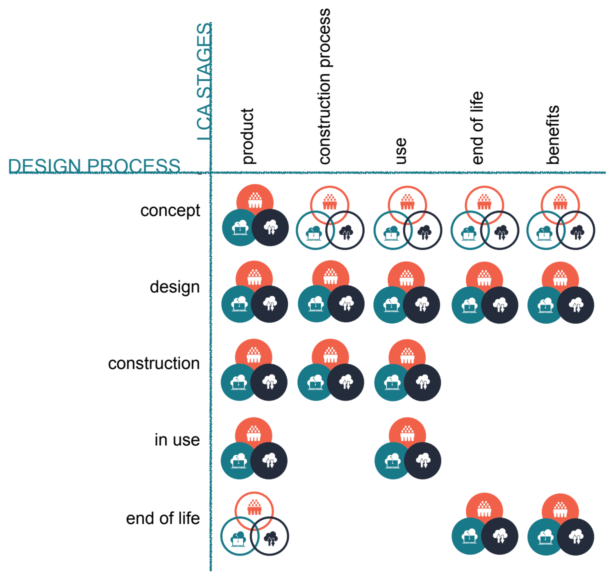


*Figure 3. Matrix and application of the conceptual framework*

Specifically, the framework is developed to interrelate design process with LCA pointing out for each phase of the process: i) the information required to develop an LCA study; ii) the actors engaged to gather that type of information; and iii) the related tools and sources used to take data. To face the complexity of the system and to handle the large amount of data, LCA standards were taken as starting points, gathering first of all the complete list of information required to perform the inventory phase of an LCA study. Hereafter, for each information is explained: i) the design process stage that can deal with that type of data; ii) the actors who can collect the information; and iii) the sources and tools where information can be taken. In this way, as shown in Figure 4, the framework becomes more manageable, being organized in a flow chart that show in order: on the left side, the list of data taken from LCA standards and, on the right side, the additional part where the information required are explained also with the relative units, specifying the design stage, the actors and the source and tools concerning quantitative and environmental data. Indeed, it is important to underline that in a LCA study the inventory phase represents the most demanding phase of the analysis, given the large amount of information required split up in two distinct type: quantitative data and environmental data. For instance, the amount of concrete kilograms located in the building (quantitative data) is associated with the corresponding emission in air, with the raw materials extracted, and so on (environmental data), representing the elementary flows in inputs and in outputs between the technosphere and the ecosphere. The consistency and the variety of this type of information significantly affect the level of completeness of the study and their quality affects the reliability and accuracy of the results.

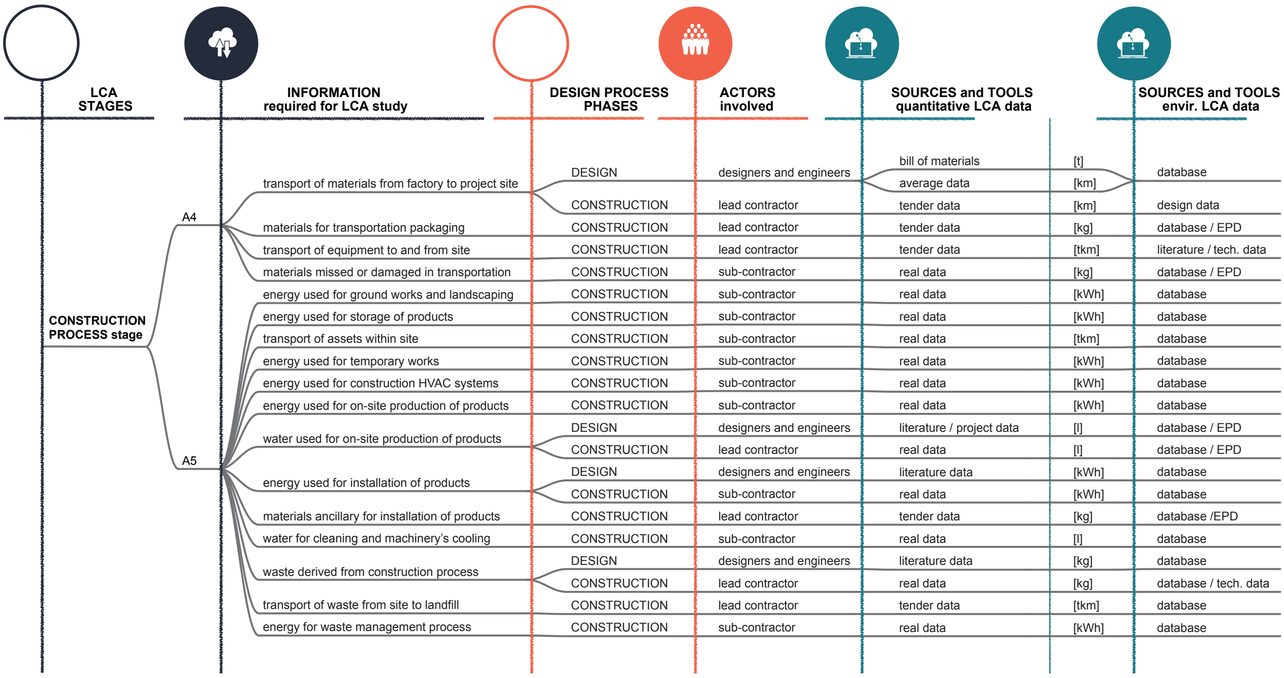


*Figure 4. Framework depicted by LCA stages – focus on construction process stage*

Obviously, although built starting from LCA stages, the framework can be reversed by explicating it in relation to the design process phases. In this way, the designers and practitioners' comprehension is facilitated and encouraged by the supporting tool developed with the aim to help them to design and operate in a life cycle perspective. Indeed, for each phase of the design process are pointed out: the LCA stages that can be taken into consideration; the related LCA steps (sub-stages); i) the LCA information that can be gathered; ii) the actors who can collect that data; iii) the sources where quantitative information can be found and their relative units of measurement. Contrary to the previous case, here only the quantitative data are taken into account since they represent the type of information directly demanded by AEC firms to develop an LCA study and therefore to bear in mind during the design process. Environmental information are thus not reported, since they not depend to design practice, but they can be attributed to database and/or EPD (when available) as well as literature data or direct measurements, in relation to the phase of process and the type of information in object. Given the amount and complexity of data required to develop an LCA study, Figure 5 displays a limited part of the conceptual framework enclosed to the only design phase of the process.

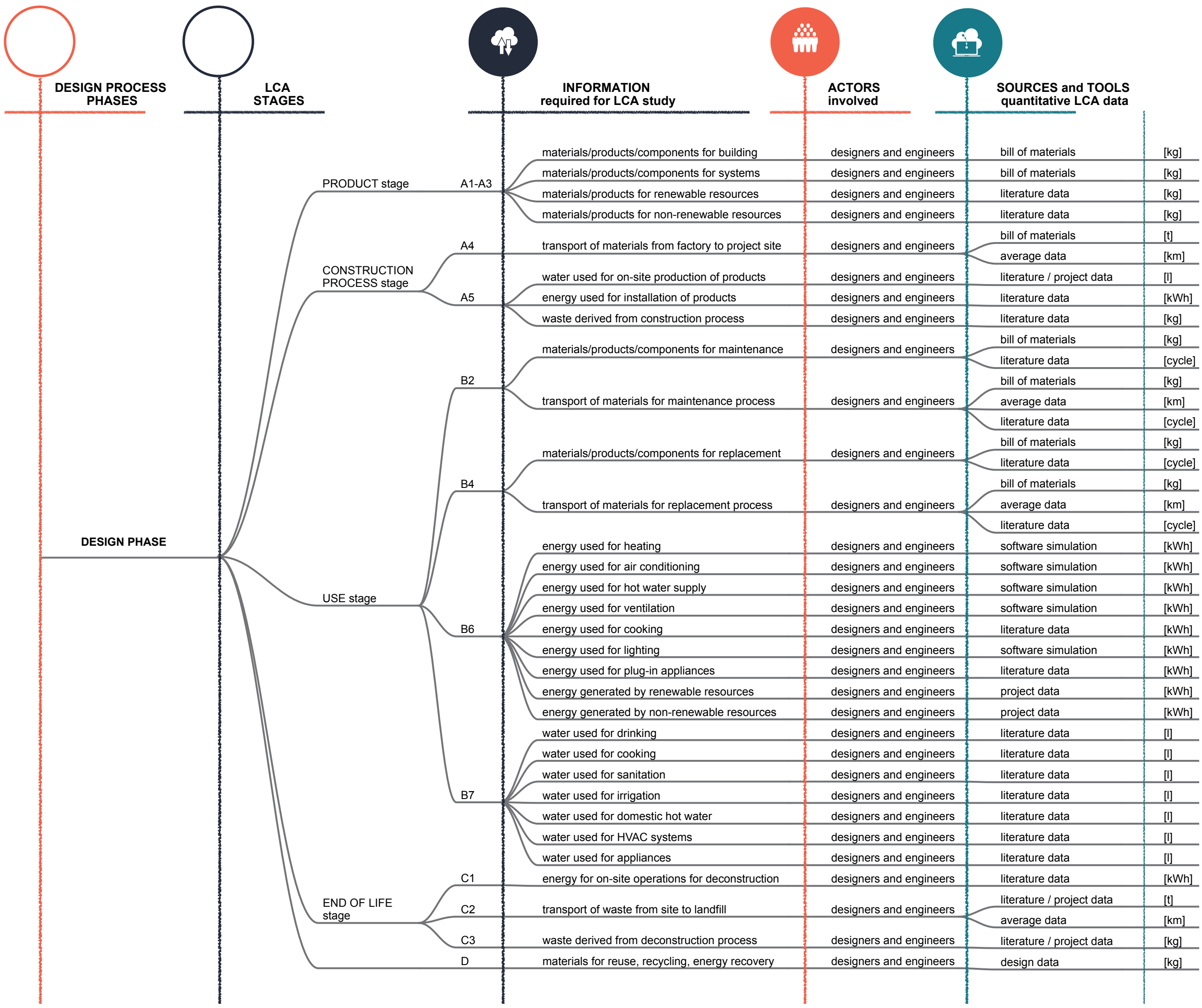


*Figure 5. Framework depicted by design process phases – focus on design phase*

In this way, the framework allows to join the large amount of LCA information with the different phases of design process, setting out in addition the related actors involved and references used. The first key factor of the framework is that quantitative and thus environmental data are collected in relation to the phase of the design process. The second key factor is that they are gradually defined, specified and detailed in conjunction with the process, becoming even more accurate, reliable and corresponding to reality. The third key factor is that LCA information are gathered in every phase of the design process by different actors, empowering therefore designers, contractors and facility managers for the choices and operations taken in their own expertise area. Indeed, these factors are crucial to achieve the following goals: turn LCA into a real supporting tool within the decision-making process of AEC practice and activate the type of mechanisms able to start the process of improvement and optimization of the construction sector in line with life cycle perspective and environmental targets. In addition, it is important to underline that this conceptual framework is developed on the basis of LCA methodology (environmental impacts) but can be easily improved with Life Cycle Costing – LCC methodology (economic impacts) and with greater difficulty with Social Life Cycle Assessment – S-LCA methodology (social impacts).

## Life Cycle approach in design process within a BIM-oriented environment

As stated in the last paragraph, the implementation of the life cycle approach in the design process represents one of the challenges of the next years, due to the large contribution of the construction sector to the achievement of the shared sustainable and environmental goals. Undoubtedly, this requires a complex and demanding course of action, emphasized in particular by two factors: the increasingly fragmentation that characterizes the construction field and the fact that the built environment constitutes an unicum strongly influenced by the context. In this perspective, it is important to not reduce the complexity of the construction system assimilating it to standardized industrial products and processes, but rather to consider each system with the related design process in its individuality taking into account the own peculiarities of the case in object.

With this aim and consistently with the trends currently underway in AEC practice, Building Information Modeling (BIM) is identified as the most suitable tool to face the hard task established by the suggested conceptual framework. The same denomination of BIM allows to make clear its potentialities in relation to the requirements previously set by matching LCA and design process. Indeed, the term "Building" concerns the physical characteristics of the model and stresses its capability to virtually recreate the facility considering the project-based tangible features. The term "Information" concerns the intangible characteristics of the model and stresses its capability to organize the set of facility's data in a meaningful and actionable manner. Lastly, the term "Modelling" concerns the act of shaping, forming, presenting and scoping the facility and stresses its capability to enable multiple stakeholders to collaboratively design, construct and operate the facility. The resulting BIM model is therefore conceived as a database that embedded, display and calculates graphical/tangible and non-graphical/intangible information, linking each other and forming a reliable basis for decisions potentially during the project life cycle. In this way, BIM is perfectly able to fit the proposed conceptual framework and thus to embrace the wide range of information required to develop an LCA study as well as the plurality of actors involved in the process.

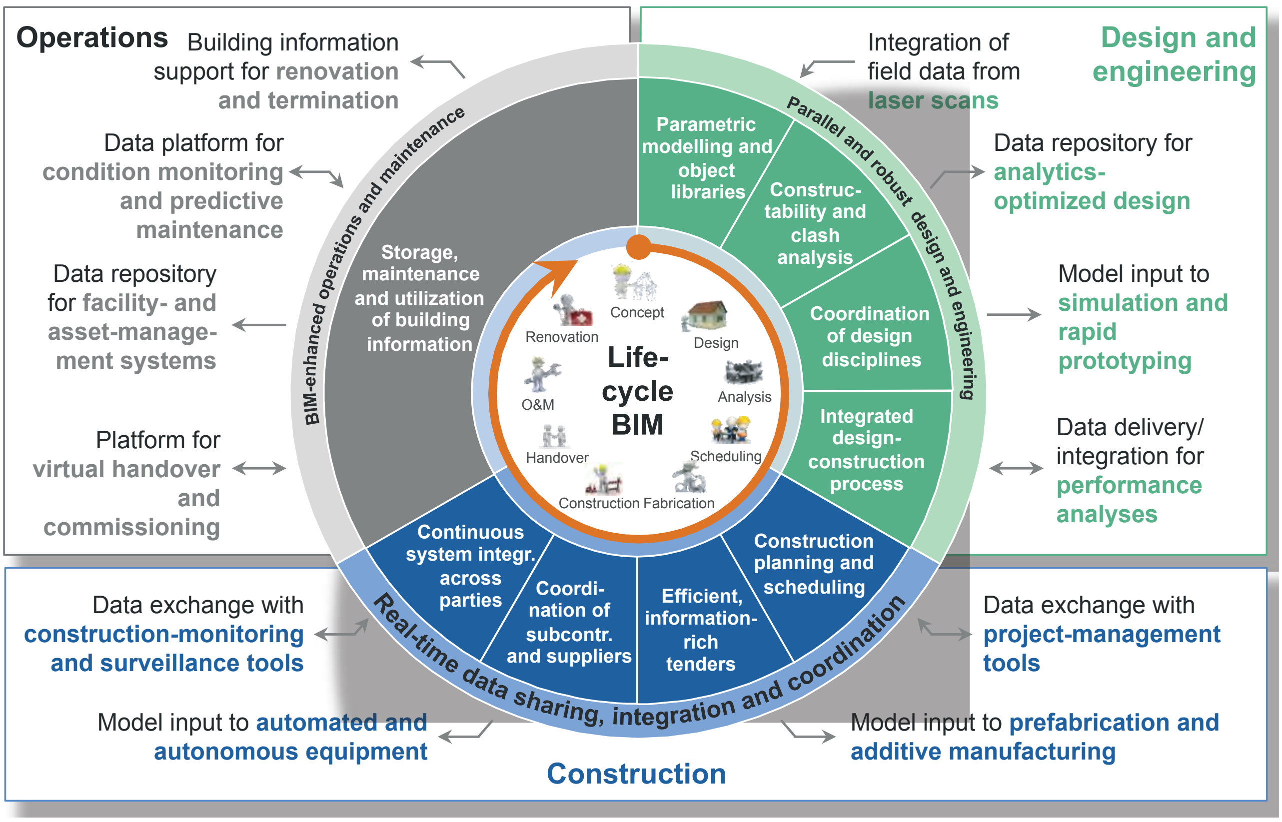


*Figure 6. Application of BIM along the value chain*
*(source: The Boston Consulting Group, in Shaping the future of construction, WEF, 2016)*

The integration of the suggested framework within BIM allows not only to shift from the theoretical to the practical level but also to create a well-framed and organized set of data of the facility during the whole life cycle. To this end, the first step is the implementation of the LCA information in BIM, enriching the set of information just embedded in the model and connecting when possible the data with the relative physical objects. Note that for the moment the LCA information in subject concern only quantitative information, keeping out the environmental information since their values do not depend on AEC practice and are mainly attributed to external database or EPD. The second step is the clustering of LCA information in relation to the phase of the design process, including a wider range of data with the advancement of the process. The third step is the arrangement for each LCA information of the additional linked data such as the actors responsible for the data insertion and the source where data are gathered. This stage acquires a key role within AEC practice since the sources used are expected to be even more specific and detailed, in order to provide information gradually more accurate and reliable in conjunction with the development of the design process. Moreover, also the actors involved are expected to be various in relation to the phase of the process, in order to empower designers, engineers, contractors and facility managers to make responsible decisions and operations in their own expertise area. These factors become crucial if the final goal is to orient and streamline the AEC design process in line with environmental target and life cycle perspective.

By joining LCA approach and BIM environment by means of the proposed framework, BIM turn out to be not only as a shared platform of exchange among the different practitioners and stakeholders and as a life cycle information database of the facility, but also as a feasible supporting tool to reduce the environmental impacts of the AEC value chain and so of the whole construction sector. In fact, regardless the environmental data and the methodology employed to develop a possible LCA study, if the project's LCA quantitative information are lowered in value with the progressive advancement of the design process, necessarily also the relative impacts of the facility will decrease on the environment. Moreover, in this way, since BIM is already widespread within AEC practice (although at different levels), it would become a reliable basis for decisions during the facility life cycle from the inception onward. If in the next future the suggested framework will become an integral part of the AEC practice, significant reverberations would be visible at the different scale. Firstly, the adoption of Life Cycle Thinking in the built environment with the resulting change of mind of all the actor engaged in the design process. Secondly, the implementation of the LCA method as an effective decision supporting tool in design process and therefore the enhancement of the following LCA studies with remarkable improvements both for the completeness and the reliability of the information considered. Thirdly, the activation in the construction sector of the type of mechanisms able to start the process of improvement and optimization in line with life cycle perspective and environmental targets, as demanded worldwide by Sustainable Development Goals.

Furthermore, besides the benefits that such application entails for the design process and, in general, for the environment, it should not neglect the added value for owners and clients. Indeed, from early design to even the decommissioning phase, all stakeholders contribute information to and extract information from the shared model, providing a lifelong view of the facility. In this way life cycle BIM allows a continuous built-up of know-how, enabling, on one hand, a seamless flow of information across process phases and stakeholders and, on the other, a life cycle database strategical also for owners and clients to have full control of the facility and thus a more efficient asset management.

However, in this perspective, it is important to not underestimate the following main barriers. First of all, the fact that the framework implementation presumes the BIM equipment at least of all the AEC firms involved. Nowadays the uptake and maturity of BIM vary considerably from country to country and from company to company, according to their size and position in the value chain. Indeed, for some big companies it is already part of current practice and business, but most small companies have little or none experience about it. The second barrier is the need of a "wide and open" BIM, which integrates the entire value chain and it is characterized by full interoperability of software and open access to it. While the technical challenges are likely to be overcome in the next future, it might result more difficult to change in an increasingly disruptive way the existing processes and to enhance collaboration, including data sharing. Lastly, the fact that digital technologies will realize their full potential only if they are widely adopted and regulated by norms and standards. This task is crucial to create a fertile environment for the digitalization of the construction sector and, in any given country, it is demanded to the government, as regulator and incubator as well as often a key project owner.

Since BIM and LCA are available methodologies and the construction sector is just involved in the process of transformation and change management, the need is to seize the opportunity, orient the process development in the right direction and know how to exploit the most of it.

## Deepening methodologies and tools in LCA and BIM environment

At this point, the framework has been disclosed and developed with the aim to understand how to orient and streamline the design process in line with environmental targets and life cycle perspective. After arguing it, before from the theoretical/conceptual point of view and then from the practical/applicative point of view, the focus turns back to the initial subject of the research: AEC firms. The purpose is to try to indicatively verify the practicability and feasibility of the suggested framework, analyzing the current practice in relation to the main issues in question.

From the analysis of the questionnaire surveys available in literature, regardless of the target audience, the perspective of AEC firms seems clear. BIM adoption is on the rise essentially because fosters collaborations among many disciplines and stakeholders typically regarded as individual building tasks, with visible results in saving time and money as well as improved quality and more efficient buildings. In addition, the utilization of BIM as a catalyst for sustainable design and construction practice is growing within AEC sector. Indeed, Green BIM turns out to be strategic for the following performance analysis: building orientation, building massing, energy modeling, daylight analysis, water harvesting, sustainable materials, HVAC design, green building certification, cost estimating and so on. However, since most of these green activities rely on external performance analyses software, despite the wide range of tools today available, software-interoperability remains one of the greatest challenges for the success of BIM and Green BIM in practice. Note that interoperability concerns not only the technological level, as generally conceived, but involves four broad layers of complex systems: technological, data, human and institutional. The technological layer is the hardware and code that allow the connection of different software and thus the exchange and share of data through an explicit and agreed-upon interface. The data layer is the ability of interconnected software to understand each other and process what is being transmitted, representing a prerequisite for making the technological layer useful and effective. The human layer is the ability of humans to understand and act on the data that is exchanged and shared. The institutional layer is the ability of societal systems to well engage and handle interoperability, for instance from the legal point of view in relation to responsibility roles.

Regarding LCA, the questionnaire surveys available concerns specific contexts but can probably be generalized to all the practice that use LCA. Interviews indicate that the main drivers for doing LCA are building owners/clients, followed by designers, codes and LEED requirements. Moreover, they emphasized that building LCA is time-consuming and expensive, with huge difficulties in finding and collecting data and with problems in the comparability and transparency of LCA results. They outlined the need to find new efficient ways of performing LCA in the early design stages through easy-to-use tools and database, the need for a better understanding of the relative significance of the different factors and building part and the need to refine and harmonize the existing building LCA tools and databases.

Nowadays, copious LCA software are available on the market to encourage LCA application within AEC practice and enable practitioners to make aware choices in terms of environmental impacts. Given the complexity of the construction sector and its close relationship with the surrounding context, buildings LCA tools generally refer to national context, both for the compliance with regulations and for the database embedded, even if some of them take a wider perspective. Just to mention a few, LCA tools developed for general purpose and spread worldwide are SimaPro and GaBi, while the ones developed specifically for building sector are: Ecosoft in Austria, Elodie in France, Legep in Germany, Ecoeffect in Sweden, Impact in United Kingdom, Lisa in Australia, Athena in Canada, Bees in USA. Each tool possesses its own characteristics which affect the spread of the methods in practice and the completeness of the resulting LCA study. The main features to take into consideration are: the context of reference, that is meaningful to understand the purpose and the possible dissemination; the cost, that shows the level of accessibility and diffusion of the tool; the degree of analysis, that allows, if provided, to perform different level of analysis in relation to the phase of the project; the database adopted, that strictly influence the accuracy of the study, based for instance on their updating according to Environmental Product Declarations; the output environmental indicators, that influence the results interpretation; further potentialities, such as the inclusion of the technical systems, the evaluation of cost and the interoperability with CAD and BIM tools (Dalla Valle et al., 2016). However, the problem is that to offer accessible and comprehensible tools to a wider audience, they tend to simply LCA methodology and the set of information required, providing only in rare cases different level of detail. The result is that they are generally used for finished projects, when all construction materials are defined, and only in sporadic cases as supporting tools to compares alternatives and orient decision-making process. To fill this gap and given the potentialities of BIM, some producers work up on LCA software interoperable with BIM tools, such as Tally and IES IMPACT Compliant Suite, employed at international level, and Elodie, adopted in France.

Certainly, the implementation of LCA in BIM provides several advantages for AEC practice, as shown below. The chance to achieve a holistic overview of the project including environmental criteria starting from the early stages. The accomplishment to enable better decision-making by providing feedback from the beginning on the environmental impact of building design choice. The solution to the redundant, manual and time-consuming tasks, typical for the standard processing of LCA. The guidance to material and dimensioning decisions that mostly determine the facility’s environmental impact. Lastly, a general optimization of LCA processes and life cycle management. Nevertheless, most of the studies available in literature perform LCA with the support of BIM but relying for the assessment on external LCA software (for instance SimaPro, LCADesign, Athena EcoCalculator and Athena Impact Estimator), recalling the problems of data- and model-exchange. Indeed, actually BIM turns out to be useful basically for: i) the automatic quantification of materials and components, profitable for all material-based LCA information; ii) the development of energy performance simulations, profitable for the use phase analysis; and iii) the quickly comparisons between different design alternatives. Still a long way it is required to make LCA implementation in BIM really effective for AEC practice and decision-making process.

LCA method is not yet common in design and construction practice and, when adopted, the environmental analysis performed by firms are not available for all. For this reason, to understand how LCA studies are generally worked out, the literature studies are the only reference point. Nonetheless, it is important to underline that, in literature studies, LCA is performed ex-post by researchers only for research purposes without affecting the project decision-making process and so not representing properly the current state. Anyway, the review of the LCA studies allows to verify the completeness and the quality of the considered LCA information and, therefore, to understand how to improve the data retrieval and the information flow management of future evaluations, also concerning the framework previously proposed. Based on selected studies, quantitative LCA information were identified for each life cycle stage, pointing out the types and the quality of data considered, starting from the most virtuous cases. The quality of data was established in relation to the reference sources used to gather the information (e.g. high level if personally monitored and gradually lower level if calculated from technical project documentation or deduced by statistical and literature data). Instead, the types of data refer to the information taken into account in the inventory phase and, comparing them with the complete list of information required to perform an LCA study, the data currently excluded were highlighted, suggesting possible areas of improvement (Dalla Valle et al., 2017). From the analysis of literature LCA studies, it emerges that in all studies some life cycle stages are omitted as well as some of the required information. Moreover, depending on the cases, the process of quantitative data collection occurs by means of the following sources, explained in order of data appropriateness in relation to the peculiarity and objectivity of the evaluation. Measurements, based on direct survey activities carried out on-site. Questionnaires, based on interviews to suppliers, contractors and/or entrepreneurs. Project documents, based on technical drawings, reports and other supporting materials of the facility in question. Statistical data, based on statistical analysis performed at municipal, regional, national or international level. Hypothesis, based on personal assumptions without any reference to reliefs and literature. Indeed, lack of data is still now considered as key issue in the development of LCA evaluations.

## Mapping environmental issues in AEC practice

The next phase in the works concerns the second type of interview that, given the multitude of variables on the line in design practice, focused on real case studies with a personal engagement in certain AEC firms in order to map ex-post the design process of the specific projects, stressing environmental issues and their role in decision-making (WP4 e WP5 – partnership and analytic phases).

The prerequisite of this step is the involvement of punctual partnerships with some worldwide AEC firms, establishing agreements to spent few months of the PhD activity in their office and to encompass their practice in the study. This phase is pivotal for the research project, representing from the companies' point of view an effort but at the same time an opportunity for their workability. For this purpose, it is important to have the chance to engage a representative number of firms, different in type and practice, to be able to take a wider perspective as possible. The strategy adopted for the selection endorses the AEC firms already in touch thanks to the questionnaire survey. Moreover, to take advantage of the period abroad two foreign cities (e.g. London and New York) were selected as strategic for building design, given the concentration of firms and then ideally the possibility to analyze simultaneously different practice. Since the feedbacks received were limited and without concrete proposal, the boundary is now expanded to other AEC firms, especially seeking the ones at the forefront of environmental issues or anyway considered environmentally friendly. Two different ways are pointed out for the selection: i) the identification of the projects certified by Green Building Rating Systems, such as LEED, DGNB, BREEAM, to involve the companies responsible for their design; ii) the dissemination of LCA tools in AEC practice, to understand the users of the software solutions available on the market, such as Ecosoft, Elodie, Legep and Impact. Specifically, the countries in object turn out to be: Switzerland, Austria, France, Germany and United Kingdom. The involvement of the partnerships aims to pinpoint the case studies of the research project. Indeed, a case study is picked out from the portfolio of each company selected, choosing a settled and possible built project considered environmentally friendly and possibly equipped with and LCA study. The decision to opt for concluded projects and not to ongoing decision-making process is due to time restriction and to the intent of deepen a higher number of projects, recreating thus ex post the design process instead of supervise it when underway.

The identification of different case studies aims to understand how deeply environmental issues are considered and faced by AEC practice, since at first glance more or less every design firms claim to be environmental friendly to take advantage for their business. To achieve this goal, the effort is to map the design process of a growing number of projects, based on the partnerships feedbacks received from the companies, trying to involve as much as possible type of firms and ways of practice, and focusing on environmental issues. Note that environmental issues are here conceived as the five core environmentally aspects: material, energy, water, waste and carbon as well as the interrelationships between the facilities and the surrounding environment. Analyzing and mapping the design process, the focus of the research is to point out all the resources invested by the companies to achieve environmental targets and to understand how they influence the decision-making process. In particular, three entities are taken into consideration: i) the team of humans, including all the actors and experts involved in the design process; ii) the set of tools and the assets, including all the physical items, computer and software necessary to design; and iii) the collection of data, including all the information required both by experts and tools to work and design.

Moreover, since there is no pre-determined relationship between the resources of a firm and its capabilities, the mission is to figure out how they are linked together and the related information flow within the decision-making process. Indeed, the types, amounts and qualities of the exploited resources, both tangible and intangible, have certainly an important bearing on the workability of the firm, since they place technical and organizational constraints, but a key ingredient is the aptitude of the team to achieve cooperation and coordination in order to handle the flow of information. This kind of synergy is essential in design practice, even more if we consider sustainable design. In fact, contrary to other sector where different issues are managed in a more or less autonomous way by team or specific experts, environmental issues involve all the actors engaged with significant reverberation in the decision-making process. Particular attention therefore is directed to the design phases in which sustainable targets are set and in which environmental experts and, eventually, outsourcing partners are involved within the process also in relation to firm's size. In addition, skills and competences with the related tools and software will be matched, on one hand, with design requirements (input) and, on the other, to final performance (outputs). In this context, starting from the early stage of the project, collaboration, coordination and communication play a key role in making sure that firm resources turn first into "capabilities" (minimum ability) and later into "maturity" (quality achieved by good practice).

Furthermore, in line with current tendencies that lead to consider artefacts as small part of a larger networks, systems and environment (just to think "Industry 4.0" and "Internet of things" trends), the life cycle approach is stressed as an ongoing and future challenge for AEC firms, to take a broadening of perspective and to avoid shifting problems from one life cycle stage to another. To this end, during the selection of case studies, the priority is given to the projects equipped with an LCA study, identifying the background of the related experts, the type of information addressed and the data sourcing. When LCA is applied to the project, the goal is to improve, by means of the proposed framework, its forcefulness and usefulness in the design process, while when it is not developed, the goal is to try to figure out how it could be implemented within the design process and what are the information already available for the tasks. Indeed, LCA method allows AEC firms to make aware decisions, gain long-term perspectives and define the most effective and efficient way to meet environmental requirement and decrease environmental impacts.

After the case studies experiences, the mappings fulfilled for every firm in partnership aims to depict the design process of the project in question, taking a life cycle perspective and focusing on environmental issues and their role in the decision-making process. For this purpose, this type of interview adopts direct means of communications, such as face to face questions to the actors involved, as well as a close examination of the set of documents related to the case study, provided by the same AEC firm but also by external partners.

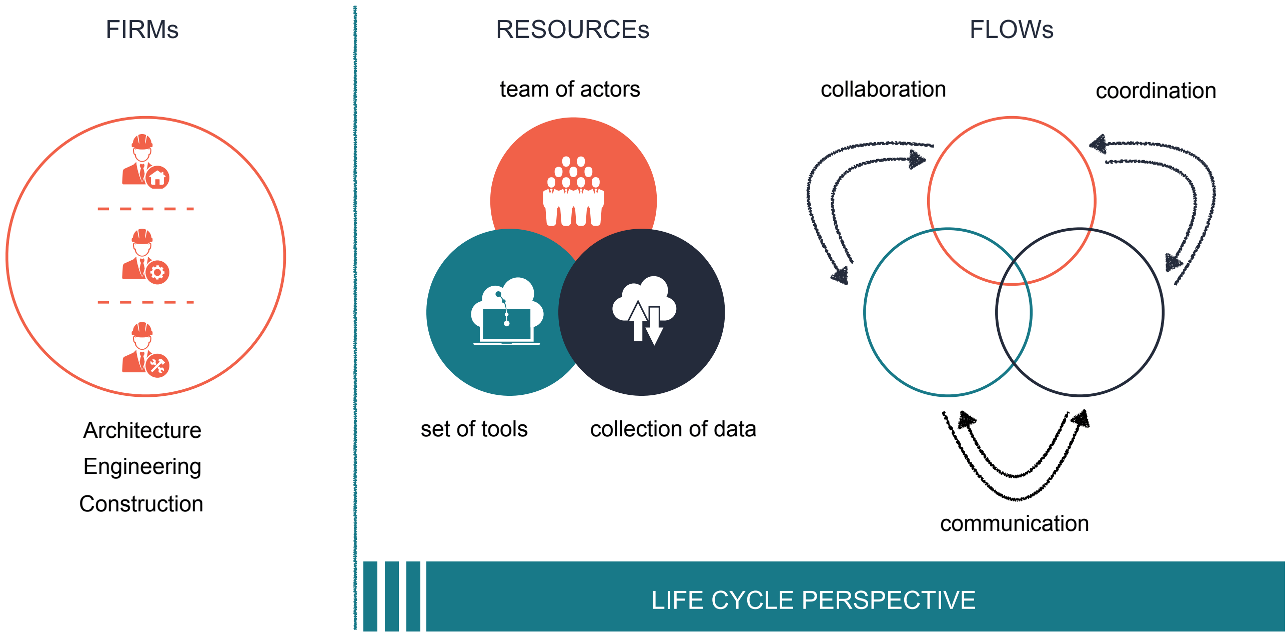


*Figure 7. Key subjects of the research project*

# CONCLUSION

The research project is turned to examine the increasingly complexity of AEC firms with the aim to understand and depict how they are organizing and equipping themselves in order to meet environmental issues. The effort is to bridge the gap between theory and practice. Indeed, on one hand, we widely know how sustainability and environmental topics are tackled at theoretical level within the scientific community. But, on the other hand, we mostly unknown how green topics are faced in practice within design and construction firms. The challenge is thus to analyze current practice in order to orient and streamline the design process in line with environmental target and life cycle perspective.

To start dealing with the complexity of the matter, the state-of-the-art was developed exploring three main subjects: change management, environmental issues and AEC firms. Thereafter, since the subject in question requires a close investigation into design firms and their workability, ethnography was elected as working method, in compliance with the emerging tendency that consider it as part of the set of techniques used to understand the construction sector. In this way, the research project conducts interviews within AEC firms by means of two different models, in relation to the level of detail to be achieved according to the phase of the project. The first model (currently underway) concerns a questionnaire survey and starts gain insight on AEC perspective. It aims to provide an overview of the transformation process and to determine trends in environmental topics. It involves a large target audience, focusing on general design practice and using indirect means of communication, such as mail or telephone interviews, structured with open-ended questions. By contrast, the second model (actually on the agenda) focuses on real case studies and demands a personal involvement in specific AEC firms. It aims to map ex-post the projects' design process and the connected information's flow, stressing environmental issues and their role in decision-making. It involves punctual partnerships, focusing on specific environmental-friendly projects and using direct means of communication, such as face to face questions, not structured since they vary in relation to the firms' practice.

Moreover, since the goal is to stress the life cycle perspective during the research project and the examination of AEC practice, a background activity has been developed and it is still ongoing with the aim to orient and streamline the design process in line with environmental targets and life cycle approach. To this end, a conceptual framework was proposed in order to match LCA with AEC practice and implement it according to the different phase of design process. The basic matrix of the framework is established, on one hand, by the different stages of LCA method and, on the other, by the different phase of the design process. The framework points out for each phase of the process: i) the information required to develop and LCA study; ii) the actors engaged to gather that type of information; and iii) the related tools and sources used to take data. It can also be reversed by explicating it in relation to the LCA stages and the related quantitative information required to perform the inventory phase. In this way, it allows to join the large amount of LCA information with the different phases of design process, setting out in addition the related actors involved and references used. The first key factor of the framework is that quantitative and thus environmental data are collected in relation to the phase of the design process. The second key factor is that they are gradually defined, specified and detailed in conjunction with the process, becoming even more accurate, reliable and corresponding to reality. The third key factor is that LCA information are gathered in every phase of the design process by different actors, empowering therefore designers, contractors and facility managers for the choices and operations taken in their own expertise area. All these factors are crucial to turn LCA into a real supporting tool within the decision-making process of AEC practice and to activate the type of mechanisms able to start the process of improvement and optimization of the construction sector in line with environmental targets and life cycle perspective.

To shift the suggested framework from the theoretical to the practical level, consistently with the trends currently underway in AEC practice, BIM is identified as the most suitable tool. Indeed, it is perfectly able to face the hard task proposed and thus to embrace the wide range of information required to develop an LCA study as well as the plurality of actors involved in the process. The integration of the framework within BIM allows to create a well-framed and organized set of data of the facility during the whole life cycle, with visible benefits to project management. In fact, by joining LCA approach and BIM environment, BIM turns out to be not only a shared platform of exchange among the different practitioners and stakeholders and as a life cycle information database of the facility, but also as a feasible supporting tool to reduce the environmental impacts of the AEC value chain and so of the whole construction sector. Of course, in this perspective, many barriers have yet to be overcome and solved.

After arguing the framework before from the theoretical/conceptual point of view and then from the practical/applicative point of view, the focus turns back to the initial subject of the research: AEC firms, with the aim to verify the feasibility of the suggested framework. For this purpose, the state-of-the-art was deepened pointing out the literature studies based on questionnaire surveys submitted to AEC firms in relation to the main topics in question: BIM, Green BIM, LCA. Hereafter, LCA tools now available on the market were identified and examined, even if their application in AEC practice and during the decision-making process is until now unknown. The attention was then focused on the research studies available in literature in relation to the following issues: the models and methods that allow the integration of LCA in BIM and the review of LCA studies to verify the completeness and the quality of the considered LCA information.

The identification and the examination of the AEC case studies will become the turning point of the research project, starting to answer the several issues still pending about design and construction practice. In this context, it is important to stress that during the entire work and especially in the case studies analysis, life cycle perspective is adopted in order to examine in depth, by means of the proposed framework, which aspects of the project life cycle are taken into account in practice and in which phase of the process. For this reason, during the selection of case studies priority is given to the projects considered environmentally-friendly and possibly equipped with LCA, to explore their role in the decision-making process. Otherwise, if the projects selection is based only on environmental performance, life cycle approach is anyway adopted during the examination and the mapping of the processes. Indeed, throughout the case studies, the effort is to validate the suggested framework, identifying where the quantitative information required to perform an LCA study can be gathered at the present state and which are the responsible actors. In addition, the collection of all data and information will be organized in a systematic way in order to be able to compare the different AEC practice, examining and proving the applicability of the framework in relation to the type of firms and projects.

Consistently with the trends currently underway, in the next future sustainability and environmental goals, on one side, and BIM and collaborative and shared working environment, on the other, will represent the driving factors of AEC firms. Challenge of the research project is thus to combine the two parts in order to establish the best course of action for the construction sector. To this end, a framework is developed, matching theoretical and practical level, to integrate life cycle approach within design process in a BIM-oriented environment. The proposed framework will be confirmed and validated through its application on the selected case studies and will be then disseminate in AEC practice to orient and streamline, as expected, the design process in line with environmental goals and life cycle perspectives.

Many are the stakeholders that might profit of the main research project's outcomes: the mapping of AEC practice and the development of the framework. As first, the AEC firms directly involved in the study, because they have the chance to observe and examine in a critical way their workability and to optimize and streamline their design process. AEC firms in general, because they can be aware of some reference practice models, gathering some improvement strategies and actions. The construction industry, followed by all the companies that provide design service and tools, because looking over case studies analysis and the framework application they can discover points of weakness or strength, in order to develop new and innovative instruments, methods and services. Regulators and legislators, because throughout the overview of AEC firms they can be mindful of the impact that policies, regulations and standards have in practice in order to manage and adjust laws also with regards to environment. Clients and users, because they have the chance to become informed about current and future trends of practice environmental-oriented to strongly drive construction sector and sustainable buildings. The academic community, because becoming aware of AEC practice can understand how adjusting training needs, in order to provide future architects and engineers capable to reason and meet environmental issues in line with the life cycle perspective.

## REFERENCES

Note that this is not the full bibliography of the research project (attached to the report), but just the list of the fundamental references used in the document.

AIA, & Hayes, R. L. (2014). *The Architect's Handbook of Professional Practice*. (TheAmericanInstituteofArchitects, Ed.) (Fifteenth). Wiley. http://doi.org/10.1017/CBO9781107415324.004

Annex31. (2004). *Directory of tools: A Survey of LCA Tools, Assessment Frameworks, Rating Systems, Technical Guidelines, Catalogues, Checklists and Certificates*. *Energy-Related Environmental Impact of building*.

Anton, L. A., & Diaz, J. (2014). Integration of life cycle assessment in a BIM environment. *Procedia Engineering*, *85*, 26–32. http://doi.org/10.1016/j.proeng.2014.10.525

Azhar, S., & Brown, J. (2009). BIM for Sustainability Analyses. *International Journal of Construction Education and Research*, *5*, 276–292. http://doi.org/10.1080/15578770903355657

Basbagill, J., Flager, F., Lepech, M., & Fischer, M. (2013). Application of life-cycle assessment to early stage building design for reduced embodied environmental impacts. *Building and Environment*, *60*, 81–92. http://doi.org/10.1016/j.buildenv.2012.11.009

Bayer, C., Gamble, M., Gentry, R., & Joshi, S. (2010). *AIA Guide to Building Life Cycle Assessment in Practice*. Retrieved from http://www.aia.org/aiaucmp/groups/aia/documents/pdf/aiab082942.pdf

Becerik-Gerber, B., & Kensek, K. (2010). Building information modeling in architecture, engineering, and construction: Emerging research directions and trends. *Journal of Professional Issues in Engineering Education and Practice*, *136*(3), 139–147. Retrieved from http://ascelibrary.org/doi/10.1061/(ASCE)EI.1943-5541.0000023

Buyle, M., Braet, J., & Audenaert, A. (2013). Life cycle assessment in the construction sector: A review. *Renewable and Sustainable Energy Reviews*, *26*, 379–388. http://doi.org/10.1016/j.rser.2013.05.001

Bynum, P., Issa, R. R. A., & Olbina, S. (2013). Building Information Modeling in Support of Sustainable Design and Construction. *Journal of Construction Engineering and Management*, *139*(1), 24–34. http://doi.org/10.1061/(ASCE)CO.1943-7862.0000560.

Cabeza, L. F., Rincon, L., Vilarino, V., Pérez, G., & Castell, A. (2014). Life cycle assessment (LCA) and life cycle energy analysis (LCEA) of buildings and the building sector: A review. *Renewable and Sustainable Energy Reviews*, *29*, 394–416. http://doi.org/10.1016/j.rser.2013.08.037

Chastas, P., Theodosiou, T., & Bikas, D. (2016). Embodied energy in residential buildings-towards the nearly zero energy building: A literature review. *Building and Environment*, *105*, 267–282. http://doi.org/10.1016/j.buildenv.2016.05.040

Dalla Valle, A., Lavagna, M., Campioli, A. (2016). Strumenti LCA di supporto al settore delle costruzioni, *Atti di Convegno del X Congresso della Rete Italiana LCA*, ENEA. Retrieved from: http://www.enea.it/it/pubblicazioni/pdf9volumi/atti9rete9lca92016.pdf

Dalla Valle, A., Lavagna, M., Campioli, A. (2017). LCA, raccolta dati di inventario e fasi del ciclo di vita degli edifici, *Atti di Convegno del XI Congresso della Rete Italiana LCA*, ENEA. Soon available.

Edilizia&Territorio. (2014). *Top 100 national design firms*.

Eleftheriadis, S., Mumovic, D., & Greening, P. (2017). Life cycle energy efficiency in building structures: A review of current developments and future outlooks based on BIM capabilities. *Renewable and Sustainable Energy Reviews*, *67*, 811–825. http://doi.org/10.1016/j.rser.2016.09.028

EN (2014). EN 15804:2012 *Sustainability of construction works - Environmental product declarations - Core rules for the product category of construction products.*

ENR. (2015). *The Top 225 International Design Firms: Ups and Downs in the Global Market*.

Farias Stipo, F. J. (2015). A Standard Design Process for Sustainable Design. *Procedia Computer Science*, *52*, 746–753. http://doi.org/10.1016/j.procs.2015.05.121

Gantner, J., Saunders, T., & Lasvaux, S. (2012). *EeBguide - Requirements for building LCA tool designer*. *EeBGuide, Operational guidance for Life Cycle Assessment studies of the Energy Efficient Buildings Initiative*.

Han, G., & Srebric, J. (2015). Comparison of survey and numerical sensitivity analysis results to assess the role of life cycle analyses from building designers' perspectives. *Energy and Buildings*, *108*, 463–469. http://doi.org/10.1016/j.enbuild.2015.09.017

Han, G., & Srebric, J. (n.d.). *Life-Cycle Assessment Tools for Building Analysis*. *The Pennsylvania Housing Research Center*. Retrieved from http://www.engr.psu.edu/phrc/Publications/RB0511-Life-cycle assessment tools for bldg analysis .pdf

Hitchcock, D., Schenk, R., & Gordy, T. (2011). *Directory of Sustainability Life Cycle Assessment Tools*. *International Society of Sustainability Professionals*. Retrieved from https://www.sustainabilityprofessionals.org/system/files/ISSP_Life_Cycle_Assessment_Tools_Directory.pdf

Jalaei, F., & Jrade, A. (2014). An automated BIM model to conceptually design, analyze, simulate and assess sustainable building projects. *Journal of Construction Engineering*, 1–21. http://doi.org/10.1155/2014/672896

Khosrowshahi, F., & Arayici, Y. (2012). Roadmap for implementation of BIM in the UK construction industry. *Engineering, Construction and Architectural Management*, *19*(6), 610–635. http://doi.org/10.1108/09699981211277531

Kovacic, I., & Honic, M. (2016). BIM-supported Life Cycle Analysis: a case study. In *WBC16 Understanding impacts and functioning of different solutions* (pp. 190–201).

Kulahcioglu, T., Dang, J., & Toklu, C. (2012). A 3D analyzer for BIM-enabled Life Cycle Assessment of the whole process of construction. *HVAC&R Research*, *18*(1–2), 283–293. http://doi.org/10.1080/10789669.2012.634264

Lee, S., Tae, S., Roh, S., & Kim, T. (2015). Green Template for Life Cycle Assessment of buildings based on Building Information Modeling: focus on embodied environmental impact. *Sustainability*, *7*, 16498–16512. http://doi.org/10.3390/su71215830

Lehtinen, H., Saarentaus, A., Rouhiainen, J., Pitts, M., & Azapagic, A. (2011). *A Review of LCA Methods and Tools and their Suitability for SMEs*.

Li, B., Fu, F. F., Zhong, H., & Luo, H. B. (2012). Research on the computational model for carbon emissions in building construction stage based on BIM. *Structural Survey*, *30*(5), 411–425. http://doi.org/10.1108/S1479-3563(2012)000012B007

McGraw Hill Construction. (2009). *The business value of BIM. Getting Building Information Modeling to the Bottom Line*. Retrieved from http://bim.construction.com/research/pdfs/2009_BIM_SmartMarket_Report.pdf

McGraw Hill Construction. (2010). *Green BIM, How BIM is Contributing to Green Design and Construction*. *SmartMarket Report*. Retrieved from http://construction.com/market_research/FreeReport/GreenBIM/MHC_GreenBIM_SmartMarket_Report_2010.pdf

McGraw Hill Construction. (2010). *The Business Value of BIM in Europe. Getting Building Information Modeling to the Bottom Line in the United Kingdom, France and Germany*. Retrieved from http://images.autodesk.com/adsk/files/business_value_of_bim_in_europe_smr_final.pdf

Means, P., & Guggemos, A. (2015). Framework for Life Cycle Assessment (LCA) based environmental decision making during the conceptual design phase for commercial buildings. *Procedia Engineering*, *118*, 802–812. http://doi.org/10.1016/j.proeng.2015.08.517

PCR. (2014). PCR UN CPC 531:2014 *Buildings.*

Peuportier, B., & Putzeys, K. (2005). *PRESCO - Inter-Comparison and Benchmarking of LCA-Based Environmental Assessemnt and Design Tools*.

Peuportier, B., Scarpellini, S., Glaumann, M., Malmqvist, T., Krigsvol, G., Wetzel, C., … Stoykova, E. (n.d.). *ENSLIC_BUILDING: State of the art report and Collection of published material*.

Pink, S., Tutt, D., & Dainty, A. (2013). *Ethnographic Research in the Construction Industry*. Routledge, New York.

Quinones, M. C. (2011). *Decision Support System for Building Construction Product Selection Using Life-Cycle Management (LCM)*. Georgia Institute of Technology.

RIBA. (2013). *RIBA plan of work 2013*.

Schlanbusch, R. D., Fufa, S. M., Häkkinen, T., Vares, S., Birgisdottir, H., & Ylmén, P. (2016). Experiences with LCA in the Nordic Building Industry – Challenges, Needs and Solutions. *Energy Procedia*, *96*, 82–93. http://doi.org/10.1016/j.egypro.2016.09.106

Shadram, F., Johansson, T. D., Lu, W., Schade, J., & Olofsson, T. (2016). An integrated BIM-based framework for minimizing embodied energy during building design. *Energy and Buildings*, *128*, 592–604. http://doi.org/10.1016/j.enbuild.2016.07.007

Shin, Y., & Cho, K. (2015). BIM application to select appropriate design alternative with consideration of LCA and LCCA. *Mathematical Problems in Engineering*, 1–15. http://doi.org/10.1155/2015/281640

Soust-Verdaguer, B., Llatas, C., & García-Martínez, A. (2016). Simplification in life cycle assessment of single-family houses: A review of recent developments. *Building and Environment*, *103*, 215–227. http://doi.org/10.1016/j.buildenv.2016.04.014

Soust-Verdaguer, B., Llatas, C., & García-Martínez, A. (2017). Critical review of BIM-based LCA method to buildings. *Energy and Buildings*, *136*, 110–120. http://doi.org/10.1016/j.enbuild.2016.12.009

Spiegelhalter, T. (2012). Achieving the Net-Zero-Energy-Buildings “2020 and 2030 Targets” With the Support of Parametric 3-D/4-D BIM Design Tools. *Journal of Green Building*, *7*(2), 74–86. http://doi.org/10.3992/jgb.7.2.74

Tucker, S., Ambrose, M., Johnston, D., Newton, P., Seo, S., & Jones, D. (2003). LCADesign: An integrated approach to automatic eco-efficiency assessment of commercial buildings. In *CIB W078 conference* (pp. 1–11). Auckland, New Zeland.

UNEP, Antink, R., Garrigan, C., Bonetti, M., & Westaway, R. (2014). *Greening the Building Supply Chain*. Retrieved from http://www.unep.org/sbci/pdfs/greening_the_supply_chain_report.pdf

World Economic Forum. (2016). *Shaping the future of construction. A breaktrough in the mindset and technology.*

Yung, P., & Wang, X. (2014). A 6D CAD model for the automatic assessment of building sustainability. *International Journal of Advanced Robotic Systems*, *11*(131), 1–10. http://doi.org/10.5772/58446

## References of the STATE-OF-THE-ART overview

AberdeenGroup. (2007). *Engineering Change Management 2.0: Better Business Decisions from Intelligent Change Management*.

Accenture. (2014). *Circular Advantage: Innovative business models and technologies to create value in a world without limits to growth*. Retrieved from http://www.accenture.com/SiteCollectionDocuments/PDF/Accenture-Circular-Advantage-Innovative-Business-Models-Technologies-Value-Growth.pdf

AECOM, & Tang, T. (2012). *Sustainable Buildings: Smart, Green and People-Friendly*. Retrieved from http://www.aecom.com/deployedfiles/Internet/Capabilities/Architecture/_Events/AECOM_Sustainable Buildings_by Thomas Tang2.pdf

AECOM. (2013). *Sustainability Report: Managing complexity, building better lives*. Retrieved from http://www.aecom.com/about-aecom/sustainability/

AECOM. (2016). *Sustainability Report: The things we value*.

AMEC. (2014). *Sustainability Performance Report 2014 Resilient World*.

AMEC. (2015). *Sustainability: Materiality*.

AMEC. (2015). *Sustainability: Our approach to sustainability*.

Annex31. (2004). *Energy-Related Environmental Impact of Buildings: Environmental Framework*. Retrieved from http://www.iisbe.org/annex31/pdf/B_environmental.pdf

Annex31. (2004). *Energy-Related Environmental Impact of Buildings: Life Cycle Assessment*.

Antink, R., Garrigan, C., Bonetti, M., & Westaway, R. (2014). *Greening the Building Supply Chain*. Retrieved from http://www.unep.org/sbci/pdfs/greening_the_supply_chain_report.pdf

Anton, L. A., & Diaz, J. (2014). Integration of life cycle assessment in a BIM environment. *Procedia Engineering*, *85*, 26–32. http://doi.org/10.1016/j.proeng.2014.10.525

ARCADIS. (2015). *Sustainability Report: Improving quality of life*.

Arup. (2015). SPeAR - Sustainable Project Appraisal Routine. Retrieved from http://www.arup.com/Projects/SPeAR.aspx

Arup. (2016). *The Circular Economy in the Built Environment*.

Arup. (n.d.). *Life Cycle Assessment (LCA) and Life Cycle Cost (LCC) Tool*.

Arup. (n.d.). *Sustainability in Practice*.

Autodesk. (2011). *Building Information Modelling for Sustainable Design: Conceptual building performance analysis overview*.

Autodesk. (2011). *Realizing the Benefits of BIM*.

Autodesk. (2015). *Sustainability in action: from epic challenges to integrated solutions*.

Azhar, S., Brown, J., & Farooqui, R. (2008). *BIM-based Sustainability Analysis: An Evaluation of Building Performance Analysis Software*.

Azhar, S., Carlton, W. A., Olsen, D., & Ahmad, I. (2011). Building information modeling for sustainable design and LEED rating analysis. *Automation in Construction*, *20*, 217–224. http://doi.org/10.1016/j.autcon.2010.09.019

Babič, N. C., Podbreznik, P., & Rebolj, D. (2010). Integrating resource production and construction using BIM. *Automation in Construction*, *19*, 539–543. http://doi.org/10.1016/j.autcon.2009.11.005

Basbagill, J., Flager, F., Lepech, M., & Fischer, M. (2013). Application of life-cycle assessment to early stage building design for reduced embodied environmental impacts. *Building and Environment*, *60*, 81–92. http://doi.org/10.1016/j.buildenv.2012.11.009

Bayer, C., Gamble, M., Gentry, R., & Joshi, S. (2010). *AIA Guide to Building Life Cycle Assessment in Practice*. Retrieved from http://www.aia.org/aiaucmp/groups/aia/documents/pdf/aiab082942.pdf

BCG, Gerbert, P., Castagnino, S., Rothballer, C., Renz, A., & Filitz, R. (2016). *Digital in Engineering and Construction: The transformative Power of Building Information Modeling*.

Becerik-Gerber, B., & Kensek, K. (2010). Building information modeling in architecture, engineering, and construction: Emerging research directions and trends. *Journal of Professional Issues in Engineering Education and Practice*, *136*(3), 139–147. Retrieved from http://ascelibrary.org/doi/10.1061/(ASCE)EI.1943-5541.0000023

Biswas, T., Wang, T.-H., & Krishnamurti, R. (2013). From design to pre-certification using Building Information Modeling. *Journal of Green Building*, *8*(1), 151–176. http://doi.org/10.3992/jgb.8.1.151

BLP, & Miller, T. (2011). *Low Carbon Design & Decision Tool*.

Boddy, S., Rezgui, Y., Cooper, G., & Wetherill, M. (2007). Computer integrated construction: A review and proposals for future direction. *Advances in Engineering Software*, *38*, 677–687. http://doi.org/10.1016/j.advengsoft.2006.10.007

Bond, C., & O'Byrne, D. J. (2014). Challenges and conceptions of globalization: An investigation into models of global change and their relationship with business practice. *Cross Cultural Management*, *21*(1), 23–38.

Browning, T. R. (2015). Design Structure Matrix Extensions and Innovations: A Survey and New Opportunities. In *IEEE International Engineering Management Conference* (pp. 1–25). http://doi.org/10.1109/TEM.2015.2491283

BusinessRoundtable. (2015). *Create - Grow - Sustain: Leading by example*.

Carra, G., & Magdani, N. (2017). *Circular Business Models for the Built Environment*. Retrieved from http://www.duurzaam-ondernemen.nl/circular-business-models-for-the-built-environment-research-report-by-arup-bam/

Carson, T., & Baker, D. L. (2006). *The AEC Workflow*.

Cassidy, R. (2005). *Life Cycle Assessment and Sustainability*. *Building Design & Construction*.

Cerovšek, T., Zupančič, T., & Kilar, V. (2010). Framework for model-based competency management for design in physical and virtual worlds. *Journal of Information Technology in Construction*, *15*, 1–22. Retrieved from http://itcon.org/data/works/att/2010_1.content.06545.pdf

CH2M. (2015). *Sustainability and Corporate Citizenship Report*. Retrieved from http://sccr.ch2m.com/?_ga=1.42506789.1257332098.1447433785#.VkYcnOLEPfY

Chinowsky, P. S., & Byrd, M. A. (2001). Strategic management in design firms. *Journal of Professional Issues in Engineering Education and Practice*, *127*(1), 32–40.

Chinowsky, P. S., & Carrillo, P. M. (n.d.). *A strategic argument for knowledge management*.

Cidik, M. S., Boyd, D., Thurairajah, N., & Hill, S. (2014). BIM and Conceptual Design Sustainability Analysis: An Information Categorization Framework. In *50th ASC Annual International Conference Proceedings* (pp. 1–8).

Davis, K. A. (2008). Assessing individuals' resistance prior to it implementation in AEC industry. In *CIB W78 International Conference in Information Technology in Construction* (pp. 1–10). Santiago, Chile.

Deamer, P., & Bernstein, P. (2010). *Building (in) the Future: Recasting Labour in Architecture*. New York: Priceton Architectural Press.

Ellen MacArthur Foundation. (2015). *Growth within: a circular economy vision for a competitive Europe*.

Ellen MacArthur Foundation. (2016). *Intelligent assets: unlocking the Circular Economy potential*. Retrieved from http://www.ellenmacarthurfoundation.org/assets/downloads/publications/EllenMacArthurFoundation_Intelligent_Assets_080216.pdf

Faludi, J. (2015). A Sustainable Design Method Acting as an Innovation Tool. *Smart Innovation, Systems and Technologies*, *35*, 201–212. http://doi.org/10.1007/978-81-322-2229-3

Farmer, G. (2013). Re-contextualising design: three ways of practising sustainable architecture. *Architectural Research Quarterly*, *17*(2), 106–119. http://doi.org/http://dx.doi.org/10.1017/S1359135513000468

Fischer, J., & Guy, S. (2009). Re-interpreting Regulations: Architects as Intermediaries for Low-carbon Buildings. *Urban Studies*, *46*(12), 2577–2594. http://doi.org/10.1177/0042098009344228

Fluor. (2014). *Building Sustainable Solutions*.

Forsberg, A., & von Malmborg, F. (2004). Tools for environmental assessment of the built environment. *Building and Environment*, *39*, 223–228. http://doi.org/10.1016/j.buildenv.2003.09.004

Foster&Partners. (2005). *Sustainability Design Guide*.

Fox, R. N. (n.d.). *Engineering, Procurement and Construction (EPC) Projects: Opportunities for Improvements through automation*.

Gantner, J., Saunders, T., & Lasvaux, S. (2012). *EeBguide - Requirements for building LCA tool designer*. *EeBGuide, Operational guidance for Life Cycle Assessment studies of the Energy Efficient Buildings Initiative*.

Haapio, A., & Viitaniemi, P. (2008). A critical review of building environmental assessment tools. *Environmental Impact Assessment Review*, *28*, 469–482. http://doi.org/10.1016/j.eiar.2008.01.002

Häkkinen, T., & Belloni, K. (2011). Barriers and drivers for sustainable building. *Building Research & Information*, *39*(3), 239–255. http://doi.org/10.1007/s13398-014-0173-7.2

Han, G., & Srebric, J. (n.d.). *Life-Cycle Assessment Tools for Building Analysis*. *The Pennsylvania Housing Research Center*. Retrieved from http://www.engr.psu.edu/phrc/Publications/RB0511-Life-cycle assessment tools for bldg analysis .pdf

Harris, J. (2010). *Integration of BIM and Business Strategy*. McCormick School of Engineering and Applied Science. Retrieved from http://www.wbdg.org/pdfs/integratebim_harris.pdf

Hartmann, A., Dewulf, G., & Reymen, I. (2006). *Understanding the innovation adoption process of construction clients*. *Industry and technology diffusion*.

Hedstrom, G. S. (2015). Navigating the Sustainability Transformation. In D. Notes (Ed.), *The Conference Board, Trusted Insights for Business Worldwide* (pp. 1–16).

Hitchcock, D., Schenk, R., & Gordy, T. (2011). *Directory of Sustainability Life Cycle Assessment Tools*. *International Society of Sustainability Professionals*. Retrieved from https://www.sustainabilityprofessionals.org/system/files/ISSP_Life_Cycle_Assessment_Tools_Directory .pdf

Hoffman, R., & Lintern, G. (2006). Eliciting and Representing the Knowledge of Experts. In K. A. Ericsson, N. Charness, P. Feltovich, & R. Hoffman (Eds.), *Cambridge handbook of expertise and expert performance* (pp. 203–222). New York: Cambridge University Press. http://doi.org/10.1017/CBO9780511816796.012

Jacobs. (2015). *Sustainability Report*.

Jalaei, F., & Jrade, A. (2015). Integrating building information modeling (BIM) and LEED system at the conceptual design stage of sustainable buildings. *Sustainable Cities and Society*, *18*, 95–107. http://doi.org/10.1016/j.scs.2015.06.007

Kaatz, E., Root, D. S., Bowen, P. A., & Hill, R. C. (2006). Advancing key outcomes of sustainability building assessment. *Building Research & Information*, *34*(4), 308–320. http://doi.org/10.1080/09613210600724608

Khasreen, M. M., Banfill, P. F. G., & Menzies, G. F. (2009). Life-cycle assessment and the environmental impact of buildings: A review. *Sustainability*, *1*, 674–701. http://doi.org/10.3390/su1030674

Kilinc, N., Basak, G., & Yitmen, I. (2015). The changing role of the client in driving innovation for design-build projects: stakeholders ' perspective. *Procedia Economics and Finance*, *21*, 279–287. http://doi.org/10.1016/S2212-5671(15)00178-1

Koppinen, T., & Morrin, N. (n.d.). *Green BIM Innovation at Skanska*.

Kovacic, I. (2016). BIM for Life Cycle Assessment - A Case Study: Redensification. In *WBC16 Understanding impacts and functioning of different solutions* (pp. 1–16).

Lee, S., Tae, S., Roh, S., & Kim, T. (2015). Green Template for Life Cycle Assessment of Buildings Based on Building Information Modeling: Focus on Embodied Environmental Impact. *Sustainability*, *7*, 16498–16512. http://doi.org/10.3390/su71215830

Lehtinen, H., Saarentaus, A., Rouhiainen, J., Pitts, M., & Azapagic, A. (2011). *A Review of LCA Methods and Tools and their Suitability for SMEs*.

Levring, A., & Nielsen, D. (2011). *Schematic Strategies and Workflows for Sustainable Design Development*.

Liu, S., Meng, X., & Tam, C. (2015). Building information modeling based building design optimization for sustainability. *Energy and Buildings*, *105*, 139–153. http://doi.org/10.1016/j.enbuild.2015.06.037

McKinsey. (2014). *Sustainability's strategic worth: global survey results*. Retrieved from http://www.mckinsey.com/business-functions/sustainability-and-resource-productivity/our-insights/sustainabilitys-strategic-worth-mckinsey-global-survey-results\nhttp://goo.gl/4JVBMQ

Mendler, S., Odell, W., & Lazarus, M. A. (2006). *The HOK guidebook to sustainable design*. New Jersey: Wiley.

Mills, J., Platts, K., & Bourne, M. (2003). Competence and resource architectures. *International Journal of Operations & Production Management*, *23*(9), 977–994. http://doi.org/10.1108/01443570310491738

Mokhtar, A., Bédard, C., & Fazio, P. (1998). Information model for managing design changes in a collaborative environment. *Journal of Computing in Civil Engineering*, *12*(2), 82–92. http://doi.org/10.1061/(ASCE)0887-3801(1998)12:2(82)

MottMacDonald. (2016). Mott MacDonald launches the first carbon calculator for BIM design.

Nguyen, T. H., Shehab, T., & Gao, Z. (2010). Evaluating Sustainability of Architectural Designs Using Building Information Modeling. *The Open Construction and Building Technology Journal*, *4*, 1–8. http://doi.org/10.2174/1874836801004010001

Norsa, A. (2005). *La gestione del costruire: Tra progetto, processo e contratto*. Milano: FrancoAngeli.

Ortiz, O., Castells, F., & Sonnemann, G. (2009). Sustainability in the construction industry: A review of recent developments based on LCA. *Construction and Building Materials*, *23*, 28–39. http://doi.org/10.1016/j.conbuildmat.2007.11.012

Pan, W., & Ning, Y. (2015). The dialectics of sustainable building. *Habitat International*, *48*, 55–64. http://doi.org/10.1016/j.habitatint.2015.03.004

Peuportier, B., & Putzeys, K. (2005). *PRESCO - Inter-Comparison and Benchmarking of LCA-Based Environmental Assessemnt and Design Tools*.

Peuportier, B., Scarpellini, S., Glaumann, M., Malmqvist, T., Krigsvol, G., Wetzel, C., … Stoykova, E. (n.d.). *ENSLIC_BUILDING: State of the art report and Collection of published material*.

Rajendran, P., Wee, S. T., & Chen, G. K. (2012). Application of BIM for managing sustainable construction. In *International Conference of Technology Management, Business and Entrepreneurship* (pp. 305–310). Melaka, Malaysia. Retrieved from http://eprints.uthm.edu.my/3451/

Reijnders, L., & Van Roekel, A. (1999). Comprehensiveness and adequacy of tools for the environmental improvement of buildings. *Journal of Cleaner Production*, *7*, 221–225. http://doi.org/10.1016/S0959-6526(99)00080-3

Reinhardt, J., Bedrick, J., Ikerd, W., Merrifield, D., Vandezande, J., Cichonski, W., … Russell, D. (2013). *Level of Development Specification: for Building Information Models*. *BIM Forum*. Retrieved from http://bimforum.org/wp-content/uploads/2013/08/2013-LOD-Specification.pdf

Renz, A., Solas, M. Z., WEF, & BCG. (2016). *Shaping the Future of Construction. A Breakthrough in Mindset and Technology*.

Rezgui, Y., Boddy, S., Wetherill, M., & Cooper, G. (2011). Past, present and future of information and knowledge sharing in the construction industry: Towards semantic service-based e-construction? *CAD Computer Aided Design*, *43*, 502–515. http://doi.org/10.1016/j.cad.2009.06.005

Rezgui, Y., Hopfe, C. J., & Vorakulpipat, C. (2010). Generations of knowledge management in the architecture, engineering and construction industry: An evolutionary perspective. *Advanced Engineering Informatics*, *24*, 219–228. http://doi.org/10.1016/j.aei.2009.12.001

Riese, M. (2012). Technology-augmented changes in the design and delivery of the built environment. *Communications in Computer and Information Science*, *242*, 49–69. http://doi.org/10.1007/978-3-642-29758-8_4

RobecoSAM. (2015). *Measuring Intangibles: RobecoSAM's corporate sustainability assessment methodology*.

RobecoSAM. (2015). *The sustainability yearbook 2015*.

Robichaud, L. B., & Anantatmula, V. S. (2011). Greening project management practices for sustainable construction. *Journal of Management in Engineering*, *27*(1), 48–57.

Sakhare, K. N., Dabade, B. M., & Kadu, A. (2014). PLM: Change management Process with custom workflow template. *International Journal of Innovative Research in Science, Engineering and Technology*, *3*(3), 2677–2680.

Shaw, I., & Ozaki, R. (2016). Emergent Practices of an Environmental Standard. *Science, Technology & Human Values*, *41*(2), 219–242. http://doi.org/10.1177/0162243915589765

Shen, W., Hao, Q., Mak, H., Neelamkavil, J., Xie, H., Dickinson, J., … Xue, H. (2010). Systems integration and collaboration in architecture, engineering, construction, and facilities management: A review. *Advanced Engineering Informatics*, *24*, 196–207. http://doi.org/10.1016/j.aei.2009.09.001

Sinopoli, N. (1997). *La tecnologia invisibile*. Milano: Franco Angeli Editore.

Smollan, R. K. (2011). The multi-dimensional nature of resistance to change. *Journal of Management & Organization*, *17*, 828–849. http://doi.org/10.5172/jmo.2011.828

SOM. (2013). New tool measures emissions from Buildings.

SOM. (2013). *Timber Tower Research Project*.

SOM. (2014). *Sustainable engineering*.

Štefaňák, P. (2011). Sustainability as a Tool for Increasing Competitiveness. *Studia Commercialia Bratislavensia*, *4*(15), 469–476. http://doi.org/10.2478/v10151-011-0010-3

Succar, B., & Kassem, M. (2015). Macro-BIM adoption: Conceptual structures. *Automation in Construction*, *57*, 64–79. http://doi.org/10.1016/j.autcon.2015.04.018

Susman, G., Jansen, K., Judd, M., Steven, B., & Stites, J. (2006). *Innovation and Change Management in Small and Medium-Sized Manufacturing Companies*.

Tiwari, S., & Howard, H. C. (1994). Distributed AEC Databases for Collaborative Design. *Engineering with Computers*, *10*, 140–154.

Weippert, A., & Kajewski, S. L. (2004). *AEC industry culture: A need for change*. *CIB World Building Congress 2004: Building for the Future*. Retrieved from http://eprints.qut.edu.au/4052/1/4052.pdf

Witthoeft, S., Kosta, I., WEF, & BCG. (2017). *Shaping the Future of Construction. Inspiring innovators redefine the industry*.

Wong, J. K. W., & Zhou, J. (2015). Enhancing environmental sustainability over building life cycles through green BIM: A review. *Automation in Construction*, *57*, 156–165. http://doi.org/10.1016/j.autcon.2015.06.003

WorleyParsons. (2015). *Annual Report 2015*.

WSP-Parsons Brinckerhoff. (2014). IRIS for sustainability.

WSP-Parsons Brinckerhoff. (2014). *Sustainability Report*. Retrieved from http://www.ball.com/sustainability/

Wu, W., & Issa, R. R. A. (2015). BIM Execution Planning in Green Building Projects: LEED as a Use Case. *Journal of Management in Engineering*, *31*(1), 1–18. http://doi.org/10.1061/(ASCE)ME.1943-5479.0000314.

Yu, A. T. W., & Chan, E. H. W. (n.d.). *Requirements Management in the Architecture, Engineering and Construction (AEC) Industry: The Way Forward*. *Construction*.

Zabalza Bribián, I., Aranda Usón, A., & Scarpellini, S. (2009). Life cycle assessment in buildings: State-of-the-art and simplified LCA methodology as a complement for building certification. *Building and Environment*, *44*, 2510–2520. http://doi.org/10.1016/j.buildenv.2009.05.001

Zhai, Z. J., & McNeill, J. S. (2014). Roles of building simulation tools in sustainable building design. *Building Simulation*, *7*, 107–109. http://doi.org/10.1007/s12273-013-0169-9

Zhang, P., Ma, X., & Zhong, J. (2013). The BIM in green architectural design software investigation. In *2013 Third International Conference on Instrumentation and Measurement, Computer, Communication and Control* (pp. 830–833). http://doi.org/10.1109/IMCCC.2013.185