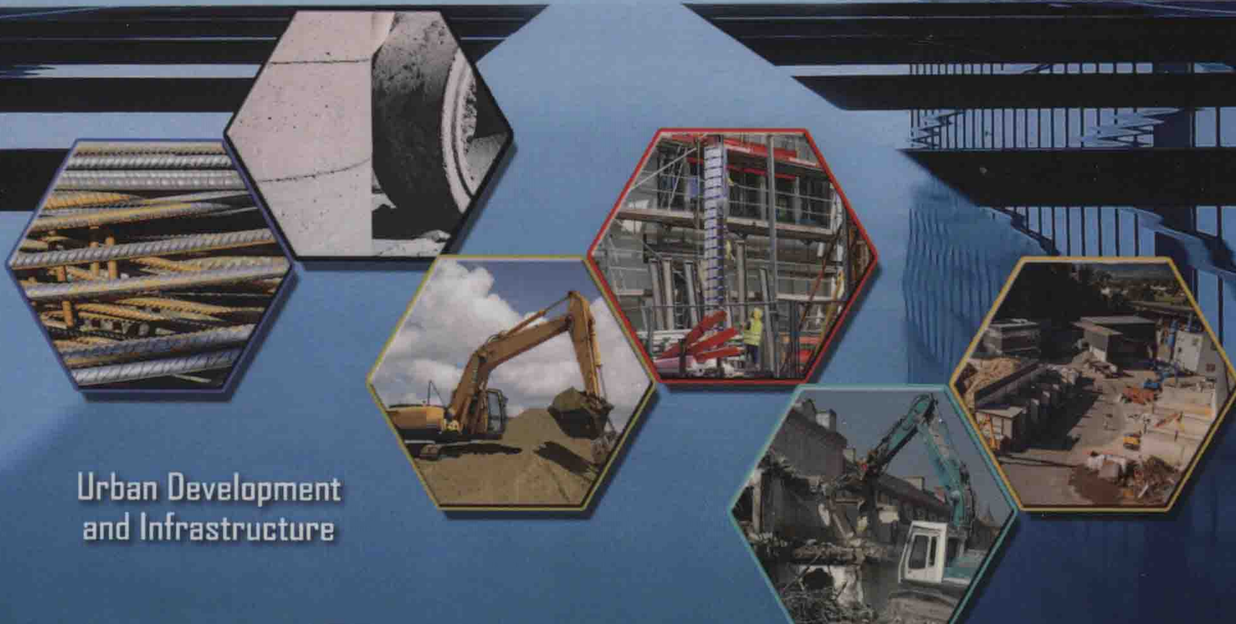
Analysis of the Life Cycle of a Built Environment



Urban Development and Infrastructure

Arturas Kaklauskas

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ANALYSIS OF THE LIFE CYCLE OF A BUILT ENVIRONMENT

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PREFACE

Various researches on the life cycle of a built environment and/or its composite parts at its micro-, meso- and macro-levels are under development globally. Such researches analyze energetic, technical, technological, economic, legal/regulatory, innovative and microclimatic aspects. However, they ignore the social, cultural, ethical, psychological, emotional, religious and ethnic aspects of a built environment's life cycle. This monograph contains detailed revisions of the research along with theoretical and practical tasks for analyzing the life cycle of a built environment and includes presentations of distinctive examples. The concept of a modern life cycle of a built environment as a model is under discussion. The theoretical and practical analyses presented in this monograph verify that intelligent decision support systems allow different stakeholders to achieve improved work quality results and productivity. Realistically most of the life cycle of a built environment will have both positive and negative features. The mission is to arrive at an equilibrium of pros and cons to optimize the life cycle of a built environment by a system of qualitative and quantitative criteria. Integration of intelligent decision support systems in the life cycle of a built environment is undoubtedly one step in the right direction.

The readers targeted for this monograph include researchers, MSc and PhD civil engineering students and parties involved with construction management and real estate development. Additionally the book could be useful for other scholars along with MSc and PhD students of economics and management and other areas of expertise.

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INTRODUCTION

This monograph on the multiple criteria analysis of the life cycle of a built environment reflects the experiences of this author since 1992 (Zavadskas, Kaklauskas, Bejder 1992,[1] Zavadskas, Peldschus, Kaklauskas 1994[2]). The know-how of the author in conjunction with his colleagues and their up-to-date, scholarly results on analyzing the life cycle of a built environment are presented exhaustively aiming to inspire scientists for describing forthcoming research directions.

A thorough, built environment's life cycle includes a brief; design; raw material extraction, transport and processing; construction materials production and distribution; construction; use, repair and maintenance; demolition; and a disposal, reuse or recycling analysis. This is quite difficult to undertake, because a building and its environment comprise a complex system (in terms of technical, technological, economical, social, cultural, ecological and such aspects), where all sub-systems influence the total efficiency performance and where the interdependence between subsystems plays a significant role. Noticeable is that researchers from various countries engaged in analyzing the life cycle of a built environment and its stages did not consider the object of their researches the same as did the author analyzing this present investigation. The author of this monograph analyzes the life cycle of a built environment by including the stakeholders involved in its life cycle as well as in its micro-, meso- and macro-environments, those stakeholders who have a particular impact on making the integral whole. Various stakeholders, including clients, users, architects, designers, utilities engineers, economists, contractors, maintenance engineers, built environment material manufacturers, suppliers, contractors, financing institutions, local and state governments and state institutions, are involved in the life cycle of an energy-efficient built environment. These stakeholders are trying to satisfy their own needs and they affect its efficiency.

The term built environment refers to the human-made surroundings that provide the setting for human activity, ranging in scale from buildings and parks or green spaces to neighborhoods and cities that can often include their supporting infrastructures, such as water supply or energy networks. A built environment is a material, spatial and cultural product of human labor combining physical elements and energy in forms for living, working and

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[1] Zavadskas, E. K., Kaklauskas, A., Bejder, E. (1991). *Multiple criteria analysis of projects*. Aalborg University. Aalborg: Aalborg Universitetscenter, p. 93.

[2] Zavadskas, E. K., Peldschus, F., Kaklauskas, A. (1994). Multiple criteria evaluation of projects in construction. Vilnius: *Technika*, p. 226.

playing. Another definition is, "the human-made spaces in which people live, work and engage in recreation on a day-to-day basis" (Linked in). Many merely analyze the quantitative information involved in the life cycle process of a built environment involving energetic, technical, technological, economic, legal/regulatory, infrastructure, microclimatic and other aspects. However, their options under consideration require assessment, not only by quantitative factors but also by qualitative characteristics, such as social, cultural, ethical, psychological, emotional, religious, ethnic and other such features. Application of intelligent decision support systems may increase the efficiency of the life cycle process of a built environment. The publications reviewed with a citation index, the Web of Science Core Collection, have published the results of numerous scientific investigations for developing decision support systems that the author of this monograph developed in conjunction with his colleagues.

The development of a built environment is for satisfying the requirements of its residents. Human needs can be physiological or social and can be relevant to security, respect and self-expression. People want their built environment to be aesthetically attractive and to be in an accessible locale with a well-developed infrastructure, convenient access of communications and good roads. The dwelling under consideration should also be comparatively cheap and comfortable and have low maintenance costs as well as have walls with sound and thermal insulation. People are also interested in ecologically clean and almost noiseless environments, which offer sufficient options for relaxation, shopping, easy access to work or other destinations and good relationships with their neighbors.

Admittedly the most serious social problems of built environments, which include, e.g., unemployment, vandalism, lack of education or robberies, do not always relate to the direct physical structure of the housing. Such problems might be resolved by increasing investments into developing social and recreational centers, such as athletic clubs, physical fitness gyms and family entertainment centers. Resolution might also relate to the infrastructure, having a good neighborhood and providing better education for its young people. There are related legal issues regarding an investment, purchase and sale of a property and the registration of the property. The legal system of a country aims to reflect its existing social, economic, political and technical situations along the lines of market economy requirements. An assessment of the life cycle of a built environment can take into account many quantitative and qualitative criteria, including economic, legal/regulatory, technical, technological, organizational, managerial, quality of life, thermic, indoor quality, social, cultural, political, ethical, psychological and other aspects.

This monograph consists of five chapters.

The design and realization of a high-quality project requires efficiency maintenance from its brief stage to the end of its life of service. Planning and executing this entire process should include consideration of the participating, interested parties and their goals as well as the micro-, meso- and macro-environments. These purposes constitute the reason this author developed an original Model for a complex analysis of the life cycle of a built environment. It emphasizes the building life cycle assessment to enable users and parties involved in the project to analyze a built environment's life cycle themselves. Furthermore these participating parties are also able to see a built environment's micro-, meso- and macro-environments as one integrated entity.

Chapter 1, "The life cycle of a built environment and its analysis," presents aspects on the life cycle of a building, phases of its Life Cycle Assessment (LCA), integration of the

LCA in the green building rating system, stakeholders involved in various stages of the life cycle of a built environment and a criteria system for systematically describing the life cycle of a built environment with a vision for Lithuania. It also discusses quality of life relevant to the building life cycle and its constituent parts, criticism regarding an LCA and future incentives for developing an LCA.

Chapter 2 contains the description of the LCA databases and tools of a building. It also analyses LCA databases, life cycle assessment software and databases, the multi variant design and analysis of a building's life cycle and selection of the most efficient options. It describes the vision of the information and communication technology (ICT) in the life cycle of a built environment. The researches on building LCA databases and tools aimed at increasing efficiency, which are in progress worldwide, may be classified in various ways. Such classifications can include investigations aiming at resolutions of the actual problems of a particular stage of a building's LCA, handling some certain problem throughout a building's LCA and aiming to increase overall efficiency of a building's LCA. Others can also be investigations aiming at increasing the efficiency of a building's LCA or some particular phase of it by applying recent achievements of ITC (intelligent decision support systems, virtual and augmented reality and such). This chapter also presents examples of some building LCA databases and tools.

Chapter 3 "DSSs, IDSSs and their Review" presents a brief analysis of the decision-making alternatives, information, data, intelligent database management system, intelligent database, equipment subsystem, model base management system, intelligent model base and user interface. Many intelligent decision support systems only process and submit quantitative information for decision-making involving energetic, technical, technological, economic, legal/regulatory, infrastructure, microclimatic and such aspects. Options under consideration also require qualitative evaluations on, e.g., social, cultural, ethical, psychological, emotional, religious, ethnic and other characteristics, not only on the quantitative aspects. Thus application of intelligent decision support systems may increase the efficiency of decision support systems. Developments of many intelligent decision support systems for analyzing the life cycle of a built environment and its constituent parts have taken place worldwide. Short descriptions of some Web-based intelligent decision support systems are provided.

Chapter 4 "Applications of IDSSs and the IoT for Various Life Cycle Stages of a Built Environment and their Assessments" presents a brief analysis of the use of intelligent decision support systems (IDSSs) and the Internet of Things (IoT) in the life cycle of a building and its assessment. This chapter analyses recommender, advisory and expert systems and their integration into various stages of the life cycle of a building and its assessment; data mining research; data analytics in various stages of the life cycle of a building; IDSS for the life cycle of a building and its assessment as well as applications of the IoT for various stages of the life cycle of a building. Text and data analytics, text, data and process mining, expert and advisory systems, neural networks, intelligent software agents, natural language processing, voice recognition, speech understanding, language translation, robotics and sensory systems, computer vision, fuzzy logic, rough sets, case based reasoning and genetic algorithms become important components in designing IDSSs. The IoT has many potential applications at various stages of the life cycle of a built environment. For example, Libelium has released the document titled "Top 50 Internet of Things Applications."

Chapter 5 "Web-based Intelligent Decision Support Systems Developed by this Author with his Colleagues" contains descriptions of a few web-based intelligent decision support systems developed by this author with his colleagues. These are Decision support system for analyzing the market value of real estate, pollution and health effects; Cooperative integrated web-based negotiation and decision support system for real estate; Virtual and augmented realities along with intelligent systems and Advisory, negotiation and intelligent decision support system for leadership analysis. This author in joint with his colleagues based their work on the following major principles and methods while developing the Web-based intelligent decision support systems:

- Complex analysis method. The use of a complex analysis makes it possible to carry out economic, technical, qualitative, technological, environmental, managerial and other kinds of optimizations throughout the life cycle of a built environment.
- Functional analysis method. The expenditures associated with project functions are usually determined by considering the benefits of a function along with the cost of its realization.
- Cost-benefit ratio optimization principle. The efforts are for gaining maximum benefits (economic, qualitative, environmental and social, legal and others) at minimum expenses for a built environment's life cycle, i.e., to optimize the cost-benefit ratio.
- Interrelation of various sciences principle. Only applications of the achievements of various sciences, such as management, economics, law, engineering, technology, ethics, aesthetics, psychology and/or others, could successfully solve the cost-benefit ratio problem.
- Multi-variant design and multiple criteria analysis methods. These methods allow considering the quantitative and qualitative factors as well as cutting the price of a project and better satisfying the needs of all interested parties.
- Close interrelation between project's efficiency and interested parties with their aims principle.

This monograph should prove of significant interest to academics, students and practitioners in the area of built environments, artificial intelligence and decision support systems. It might also be useful for other researchers, practicing engineers and managers as well as MSc and PhD students of economics, management and other areas of expertise. Various stakeholders (clients, users, facilities and property managers, architects, designers, utilities engineers, economists, contractors, maintenance engineers, built environment material manufacturers, suppliers, contractors, financing institutions and governmental institutions at local and state levels) are involved in the life cycle of a built environment. They affect the efficiency of the entire life cycle while trying to satisfy their needs.

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CONTENTS

Chapter 1

LIFE CYCLE OF A BUILT ENVIRONMENT AND ITS ANALYSIS

ABSTRACT

Chapter 1, "The life cycle of a built environment and its analysis," presents aspects on the life cycle of a building, phases of its life cycle assessment (LCA), integration of the LCA in the green building rating system, stakeholders involved in various stages of the life cycle of a built environment and a criteria system for systematically describing the life cycle of a built environment with a vision for Lithuania. It also discusses quality of life relevant to the building life cycle and its constituent parts, criticism regarding an LCA and future incentives for developing an LCA.

1.1. THE LIFE CYCLE OF A BUILDING

The research object is a building's life cycle, the interested parties striving to attain their goals and the micro-, meso- and macro-environments making an integral whole. A comprehensive research into the above object required the development of new methods of project multiple criteria analysis enabling the user thoroughly to assess its economic, technical, qualitative (i.e., architectural, aesthetic, comfortability, etc.), technological, social, legislative, infrastructural and other aspects. The diversity of the factors under assessment should correspond to the various ways of presenting the data needed for decision-making.

Every product or process goes through various phases or stages in its life. Each stage is composed of a number of activities. For industrial products, the broad definitions of these stages can be material acquisition, manufacturing, use and maintenance and end-of-life. In case of buildings, these stages are more fully delineated (per Bayer 2010) as:

- Material Manufacturing. This stage includes removal of raw material from the earth, transportation of these materials to the manufacturing location, manufacture of finished or intermediate materials, building product fabrication, and packaging and distribution of building products.
- Construction. This phase accounts for activities relating to actual construction of a building project. Typically, the following activities are included in this stage: transportation of materials and products to the project site, use of power tools and

equipment during construction of the building, on-site fabrication, and energy used for site work. Permanent impacts to the building site also fall into this stage, though these impacts are fully considered in current LCA methods.

- Use and Maintenance. This stage refers to building operation, which includes energy consumption, water use, and environmental waste generation. It also takes into account the repair and replacement of building assemblies and systems. The transport and equipment use for repair and replacement is also considered in this stage.
- End of Life. This includes energy consumed and environmental waste produced due to building demolition and disposal of materials to landfills. The transport of waste building material is also included in this stage. Recycling and reuse activities related to demolition waste can also be included in this stage, depending on the availability of data (The return of significant high-value materials to the inventory through recycling can even be considered as a "negative impact").

Life cycle analysis examines the environmental impacts of a product by considering the major stages of a product's life, which are (Williams 2009):

- Raw material acquisition, which includes material harvesting and transportation to manufacturing sites
- Processing, which involves materials processing and transportation to production sites
- Manufacturing, which includes product manufacture and assembly, packaging, and transportation to final distribution
- Product life, which includes energy and emissions during normal product life, required maintenance and product reuse (refurbishing, material reuse) and
- Waste management/end of life, which includes recycling, landfills, liquid waste, gas emissions, etc.

Many studies on the building life cycle and its constituent parts have been performed worldwide. Brief overviews of some of them appear below.

Islam et al. (2015) describe life cycle assessment (LCA) and life cycle cost (LCC) analysis for typical Australian houses. It reports how different roofing (i.e., roof and ceiling) and floor designs affect the life cycle environmental impacts and cost (LCEI & LCC) over the various life stages of buildings (i.e., construction, operation, maintenance and final disposal). A case study house, called Base House, was modified with 8 alternative roofing and 4 floor designs to generate 12 variant houses. Specifically, one variable either from roofing or from floor was varied at a time while keeping wall and other components as in the Base House. The four life cycle environmental impacts were greenhouse gas (GHG) emission, cumulative energy demand (CED), water use, and solid waste generation, evaluated by LCA approach. The LCC was estimated based on life cycle costing approach. The results of LCEI & LCC of each house were evaluated on a whole of life cycle basis. A number of trades-off on the houses modified with roofing and floor designs were identified based on LCEI & LCC results. For the houses modified with roofing and floor designs, the high star skillion flat roofing and mixed floor houses were the attractive trades-off (Islam et al. 2015).

Traditionally, building rating systems focused on, among others, energy used during operational stage. Recently, there is a strong push by these rating systems to include the life cycle energy use of buildings, particularly using Life Cycle Assessment (LCA), by offering credits that can be used to achieve higher certification levels. As LCA-based tools are evolving to meet this growing demand, it is important to include methods that also quantify the impact of energy being used by ecosystems that indirectly contribute to building life cycle energy use. Using a case-study building, Srinivasan et al. (2014) research provides an up-to-date comparison of energy-based indicators in tools for building assessment, including those that report both conventional life cycle energy and those that also include a wider systems boundary that captures energy use even further upstream. This research applies two existing LCA tools, namely, an economic input–output based model, Economic Input–Output LCA, and a process-based model, ATHENA® Impact Estimator, to estimate life cycle energy use in an example building. In order to extend the assessment to address energy use further upstream, this research also tests the Ecologically based LCA tool and an application of the emergy methodology. All of these tools are applied to the full service life of the building, i.e., all stages, namely, raw material formation, product, construction, use, and end-of-life; and their results are compared. Besides contrasting the use of energy-based indicators in building life cycle tools, this research uncovered major challenges that confront stakeholders in evaluating a built environments using LCA and similar approaches (Srinivasan et al. 2014).

Building construction consumes large amount of energy and material. Despite that, not much effort has been directed to examine the environmental impact of the construction phase, and this is particularly relevant to Hong Kong where the demand for building construction is ever increasing. In this study, a life cycle assessment (LCA) model namely the Environmental Model of Construction (EMoC) is developed to help decision-makers assess the environmental performance of building construction projects in Hong Kong from cradle to end of construction. The model provides comprehensive analyses of 18 environmental impact categories at the midpoint and endpoint levels. By inputting project specific data to EMoC, it can generate results of over two-hundred detailed processes. A public rental housing (PRH) project is fed into EMoC to examine the environmental performance of this type of projects. The results indicate that material is the major contributor to environmental impacts of the upstream stages of public housing construction. The carbon emissions of the studied project amount to 637 kg carbon dioxide equivalent per square meter of the gross floor area. Sensitivity analysis reveals that the environmental pollution can be significantly reduced by adopting a higher proportion of precast concrete components. The model should help support decision-makers identifying pragmatic solutions to reduce the environmental burden of a building project at the design, procurement and construction stages (Dong, Ng 2015).

The existing assessment tools for the life cycle carbon dioxide ($LCCO_2$) have certain limitations in that users have to directly enter quantities of materials after the construction document phase and they are likely to find it difficult to formulate an optimal strategy to reduce CO_2 emissions. Therefore Global Environmental Model/Management-21P (GEM-21P) was developed for establishing a responsive and accurate system for suggesting methods for high energy efficiency in the planning phase. The objective of this study is to identify the requisites for an $LCCO_2$ assessment program that is based on the technical elements of GEM-21P and that can be used in the schematic design phase. The life cycle of a building is divided into four stages: material production, construction, operation and dismantlement/disposal. Further, the technical elements of GEM-21P are examined for assessing CO_2 emissions in each of the stages (Baek et al. 2013). On the basis of the examination results, Baek et al. (2013) specify the requisites for a system that can assess, in the planning phase, the CO_2 emitted from a building during its entire life.

The construction industry plays an important role in economic and social development, yet it is also a primary source of carbon emissions. Accordingly, owing to global climate change, energy conservation and carbon reduction have become critical issues in the construction industry. However, to date, no established theory has been proposed for the life-cycle carbon assessment of typical buildings in China. To address this, the present study proposes a detailed carbon emission inventory for buildings and divides the life-cycle of a typical building into three stages based on material and energy flow: the materialization stage, the operation stage, and the disposal stage. Additionally, an analytical framework and evaluation indices are established and the proposed methodology is applied to three case studies. The results demonstrate that residential and office buildings with a reinforced concrete block masonry structure could reduce carbon emissions by 38–112 $kgCO_2/m^2$ compared with either a reinforced concrete structure or a brick–concrete structure. Although the operation stage appears to contribute approximately 82–86% of the total emissions, the materialization stage is also of considerable importance in alleviating the present environmental pressure. Furthermore, possible measures to control carbon during the materialization stage are proposed and evaluated, including optimization design of building structures based on carbon emissions and the selection of insulation materials. Accordingly, this study provides a standard method for life-cycle carbon assessment of buildings, which will be critical for future low-carbon development (Zhang, Wang 2015).

In the framework of the European research project SB_Steel, a new life cycle methodology was developed aiming at the evaluation of life cycle impacts of buildings in the early stages of design. The proposed approach includes the estimation of the energy needs of the building during the operation stage. The early stages of design have the higher influence on the life cycle performance of the building; however, in these stages the availability of design data is often limited. Moreover, the estimation of energy needs is usually based on a performed-based approach, requiring a full definition of the building design. In the proposed methodology both problems are addressed by the macro-component approach, which provides a range of pre-defined construction solutions for the main components of a building, integrating life cycle embodied data. The approach enables a simplified estimation of the life cycle environmental performance of a building based on limited design data and provides aid for decision making in relation to the use of different materials and construction solutions aiming to lower life cycle impacts and lower energy consumption. The proposed approach is illustrated by a case-study, in which a residential building is assessed in the early stages. Finally, based in complete data, an advanced analysis of the building is performed in order to discuss the limitations of the developed approach (Gervásio et al. 2014).

The generation of a significant amount of emissions from the building construction process has led the promotion of controlling emissions as an important strategy for implementing sustainable development principles in a built environment. The emissions incurred during various stages include carbon dioxide, methane, nitrous oxide, sulphur dioxide, carbon monoxide, nitrogen oxide, non methane volatile organic compounds and particulate matter. This research conducts the life cycle assessment of the air emissions by using a particular case to examine emissions during construction stage. This study examines the emissions sources in each of the six stages and presents an inventory analysis method to