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DECISION-MAKING FOR ENHANCING BUILDING SUSTAINABILITY THROUGH LIFE CYCLE – A REVIEW

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Abstract: *Today, the society faces major challenges to act and react against the climate change by all possible means. As the building sector contributes significantly to energy consumption worldwide, it also presents many opportunities for integrating sustainability in both existing and new buildings. This paper presents a review on the main aspects concerning buildings sustainability focusing on a life cycle approach, which is seen as an efficient way to improve the environmental dimension of sustainability. The findings show that decisions in each life cycle phase affect the subsequent outcomes, with the design stage being the most important for implementing long term sustainable measures. Following, the present review outlines the process of decision-making in each stage and the current approaches for reducing the built environment impact on the planet. But the economic and social aspects could not be neglected as shown by the latest studies in the field.*

Keywords: *Sustainability, building sustainability, life cycle, decision-making.*

1. INTRODUCTION

Although the idea of sustainable development has been mentioned since the 1950s, the first mention of the term sustainability and sustainable development was in 1987 when the Brundtland Report of the Environment Commission (“Our Common Future”) was published [1]. The definition provided then is the most widespread, although there are more discussions to reach a unanimously accepted definition: “sustainable development is the one that meets the needs of the present without compromising the ability of future generations to satisfy theirs”[1]. So the basic of a system’s sustainability is the concept of survival or persistence [2], which extrapolated to the planet means supporting the continuity of life on Earth.

Subsequently, in 1992 the same concept was reiterated at the UN Conference held in Rio de Janeiro [3], highlighting also the economic factor besides the need for action to protect the environment. In the past two decades, the interest of international institutions increased, as shown by numerous annual meetings where interventions for the environment and progress of emerging and developing countries have been agreed such as Agenda 21 adopted in 1992 in Rio, the "Kyoto Protocol" negotiated in 1997 by 160 countries, the "Millennium Development Goals" adopted in 2000, or the "Sustainable Development Goals" adopted in 2015 [4]. Sustainability is not freewill anymore, it is a must as proved by 194 countries which adopted a binding global agreement that requires the reduction of greenhouse gas emissions (the Paris Agreement) within the United Nations Framework Convention on Climate Change (UNFCCC) in December 2015.

According to worrying statistics and specialty research [5, 6], the building sector is one of the largest energy consumers and producer of greenhouse gases at global level [7], so it requires a separate and thorough approach to counteract the impact on the environment and society as efficiently as possible. Considering that the construction sector represents more than 40% of the materials consumption and over 30% of total greenhouse gas emissions of the planet [8], building in a sustainable manner cannot be a choice anymore but a need. The positive side is that there is huge potential in both existing and new buildings to increase sustainability [9].

This paper aims to present the most important topics related to buildings sustainability with an extended view on decision-making processes through the life cycle of a building. The review is based on articles and books from the field summarizing the general subjects the studies are dealing with, such as approaches for buildings sustainability, life cycle assessment, energy efficiency in buildings and decision-making for buildings sustainability. Following this, the authors explore the latest trends in the field and where the research is heading to.

2. MAIN ASPECTS OF BUILDING SUSTAINABILITY PAPER

2.1 Building sustainability

The concept of sustainability in the field of construction refers to a multitude of interdependent aspects and principles, because a building is a complex system involving various stakeholders and environmental requirements, so when it comes to sustainability, all the components and stakeholders should be considered: climate, local resources, infrastructure, cultural needs, policies and regulations, costs, etc. requiring an integrated approach to energy, health and operational performance issues [10].

Although the notion of building sustainability is often used in the literature, there is no commonly agreed definition, yet it presents some common elements such as its temporal dimension, the protection of the environment and the human component. Beside the long-time perspective of the building which supports humans without affecting the environment, Berardi (2013) introduces even an additional aspect of regeneration [11]. A more concrete definition is given by Wang & Adeli (2014) who sustain the change in attitudes, paradigms, processes and delivery of a project [12].

It is therefore proven that this concept presents uncertainty and ambiguity and building sustainability cannot be defined in absolute terms [11, 6], but there are several similarities: it presents three areas (environmental, economic and social) and has two dimensions (temporal and spatial). Addressing sustainability principles should be done locally, contextually and long-term.

2.2 Particularities of building sustainability

Today, high-performance construction projects address three main aspects: (1) efficient buildings, (2) minimization of energy used for transport, and (3) climate change. In addition to these requirements, there are the secondary ones: the quality of the indoor environment, the protection of ecosystems and biodiversity, and the risks associated with building materials [13].

One of the main issues found in the literature is that the built environment (both residential and commercial buildings) loses a lot of energy due to the inefficiency of technologies [6]. Reduction of energy consumption in a building refers to all type of resources such as: electricity, gas, coal, wood, water, etc. and on the other hand, a considerable amount of energy is incorporated in the materials used, which brings into discussion the design stage: selection of the materials and transportation. The concerns of scientists are related to the impact of materials on the environment as a source of pollution and toxicity [14, 11], advocating that designing buildings should be done in accordance with nature [15] and respecting the environment [16].

For protecting nature it is essential to reduce the consumption of non-renewable resources (minerals, oil, gas, coal), but at the same time, to use renewable resources whose impact is minimal on the natural environment. Renewable resources that can be used in buildings include solar energy, hydraulic energy, wind energy, geothermal energy or biomass – as active energies, but passive applications of renewable energies can also be mentioned - natural lighting or use of wind [17]. Solar energy can be used for houses to heat water and space or to produce electricity. Additionally, solar collectors located on a large area of land together with an energy storage system could be connected to a local heating network [18]. Biomass accounts for about 13% of the world's primary energy sources and according to statistics more than 60% of the energy consumption in developing countries is provided by bioenergy [19]. Using geothermal energy can have various effects on sustainable development, not always positive, so it demands adequate and specialized management [20]. Further, recovering heat from a building is a source of energy. Heat exchangers and heat pumps can recover part of the heat used in the ventilation or the waste water. Among the first systems used in buildings were air-to-air heat exchangers installed in the ventilation systems, and more recently heat pumps used to reuse heat from evacuated air [18].

Concrete which is considered to have the largest share of the economic and social cost but also of the environmental impact, being the most widely used material in construction projects, could be partially replaced with recycled concrete aggregates [21], although their lower mechanical performance and durability compared to conventional concrete [22].

Although the research focus is on environmental protection, there are studies that also address human dimension elements within a building, such as buildings health, increasing welfare by improving the quality of the built environment or increasing awareness of sustainability [14, 11, 23]. The first standards emerged around the year 2000 and in 2006 ISO / TS21929-1:2006 (Building Construction - Building Sustainability) was the first ISO standard to address sustainability, although many already existing standards contained significant references, such as ISO 14000, Life Cycle Assessment ISO 14040 or International Standards on Service Life Planning - ISO 15686 series [24].

2.3 Other perspectives of building sustainability

The current challenge when building and designing a building is to increase the quality of life while reducing social, economic and environmental effects [25]. Quality of life in relation to construction refers to the provision of decent, inclusive and accessible living conditions, by reducing the factors that can affect human health, such as the following risks: allergens, mould, tobacco smoke, carbon monoxide, asbestos, radon, volatile organic compounds, excessive heat and coldness, agglomeration or the risk of being hit or dropped. These can cause human diseases such as asthma, lung cancer, injuries, poor mental health or mental disorders [26].

Furthermore, discussion about quality cannot be distinct from the occupants' requirements, which are usually: a comfortable interior, the provision of the necessary heating or cooling, the ventilation of the dwelling, the facilitation of maintenance and cleanliness, a suitable design to ensure the natural lighting, lack of moisture, building services (lighting, heating, ventilation, waste disposal, internet connection, etc.).

As it can be seen from the examples above, all sustainability principles are applicable throughout the life cycle, and moreover, they are in relation to each other, which leads to the idea of a holistic approach of building sustainability. Evaluating a building's lifecycle can provide important information because focusing on just one phase of the building's life may have a negative impact in later stages [27]. Concerns for environmental effects of buildings must exist at every stage of the life cycle, not just in the use phase, when energy consumption is higher. In addition to the energy used for operating, there is a certain amount of energy incorporated into building materials, which is defined as the sum of all the energy needed to manufacture a product [28]. According to Chang, Lee, & Chen (2014) the amount of built-in energy accounts for almost one-sixth of the energy savings that could have been achieved in 2007, predicting that it will represent a fifth in 2015 [29]. Other estimations claim that this energy is up to 20% of the total life cycle energy of the construction project [13]. There are also researchers which advocate for a low share of the built-in energy [30].

However, the environmental aspect is the main topic the literature dealt with, but there are voices opposing this approach, claiming the need for a holistic approach, extended to all dimensions, so that interrelationships are taken into account. The social benefits of sustainable design are related to improvements in the quality of life, health, and well-being and can be realized at different levels – buildings, the community, and society in general [31]. Despite of this promoted equality between the environmental, economic and social matters, in practice is not a real balance, as represented in below figure [32]:

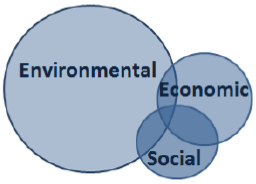

Figure 1: Actual sustainability dimensions (after [32])

Additionally, the authors consider that sustainability cannot be promoted without taking into account the quality principles, based on the new paradigm promoted by El-Mikawi [33] – see figure 2. Quality of a construction project should be achieved by delivering outcomes timely, costly and in a safe manner, taking into consideration at the same time the environmental impact and the socio-economic benefit [33]. Moreover, the main aspect to be considered is the value for the customer: by satisfying his needs. With regard to sustainability, the positive impact on the environment is brought into discussion which indirectly leads to benefits for the society, considering at the same time the constraints of the stakeholders (beneficiaries, occupants, constructors, etc.).

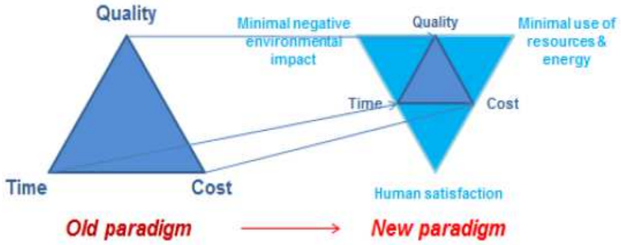

Figure 2: New sustainability's paradigm (after [33]

3. OTHER PERSPECTIVES OF BUILDING SUSTAINABILITY

3.1 Life cycle phases in buildings

Life Cycle Approach is an "objective process for assessing the environmental impact associated with a production process or activity and for evaluating and implementing opportunities for environmental improvements" [34]. The need for such an approach comes precisely from the fact that a building affects the environment particularly throughout its lifetime. In each phase of their life cycle, building systems interact with other systems, forming an open cycle. Development relationships and interactions are dynamic, and in some cases they can become even competitive as in case of a green building which usually requires an increase of direct costs [10]. So, for reaching acceptable solutions for all stakeholders, it is desirable to analyze all influence factors during the lifetime of a building, as well as the requirements that occur.

In this paper the five-step life cycle is considered relevant: design, construction, operation, renovation and demolition or deconstruction. The design phase deals with solutions for technical, economic, ecological and social optimizations, which impact the entire performance of the building in the future [35], whilst the construction phase means the actual implementation of them. The operation phase refers to the period when the building is in use by its occupants, including services like heating, electricity or water services but not material replacement [36]. The renovation offers great opportunities to improve the energy performance of buildings and to bring other social benefits [37, 38]. The last phase refers to the decommissioning of the building, the disposal / recycling / reuse of building components and their transportation [36].

With respect to the impact on the life cycle the division is made into four categories [12]: initial effect (construction of the building and production of materials); energy used during construction; effects of renovation; end-of-life effects of the building, i.e. the environmental impact after the end of the building's life cycle (residual impact) [12].

3.2 Life cycle phases in buildings

The life cycle assessment (LCA) is a methodology used for evaluation of the environmental impact of a product throughout its entire life cycle - from cradle to grave [39] and has been used successfully in the building sector since 1990 [40]. By using the life cycle assessment (LCA) in buildings development, sustainability could be enhanced from design to disposal [14]. This instrument can be applied for the full life cycle or just for building materials or for some components. The evaluation of the embodied energy of the materials gains even more importance due to regulations imposing reduction of energy consumption during operation phase [41].

The LCA methodology comprises four steps: the goal and scope definition; the inventory analysis; the impact assessment, and the interpretation, as described by the International Standard of series ISO 14040 [39]. Based on the goal, the spatial and temporal limitations of the LCA process should be established. The timeframe selected could have a significant impact on the results, taking into consideration the total energy consumption resulted during the use phase [42]. The inventory analysis implies collection of data about inputs and outputs of energy and materials [14] and it can be calculated from the bills of materials [43]. The next step is the evaluation of the potential environmental impacts and the last one the interpretation. In the final stage findings and major issues are determined in order to formulate conclusions and recommendations [39]. Although a lot of the environmental aspects of a building cannot be measured [44], LCA remains an efficient and popular method for evaluation. There is a high interest in assessing the energy during the life cycle [45]. Some studies try to evaluate the impact of energy on building by applying versions of LCA: life cycle cost (LCC) [46, 47, 48, 49], life cycle energy analysis (LCEA) [50, 51, 52, 53] or various LCA approaches [54, 55, 56, 57, 58, 59]. Due to the many differences in the approach of the lifecycle analysis methodologies, it is difficult to compare buildings, especially because there are major differences between climatic zones or socioeconomic contexts [60, 30]. An analysis of the assessment methods on the life cycle of buildings, resulted from the need to distinguish elements that significantly affect the environment, concluded that ISO 14040 guidelines are the basis for the assessment methods, but the multitude of methods limits fair comparisons between the results of different research, so that there is a need for standardization of lifecycle assessment methodologies [42]. Considering the life cycle in the energy certification process is a way to promote high energy efficiency solutions in buildings and innovations in the construction sector [61].

Concluding, LCA is a mean to improve the construction processes, to mitigate the environmental impact and to increase the quality of human lives. LCA can provide a good level of quality and sustainability [44].

4. DECISION-MAKING PROCESS FOR ENHANCING BUILDING SUSTAINABILITY

In a decision-making process within a construction project, collaboration between stakeholders is crucial for a successful sustainable building, as decision-makers have to agree on numerous options available for materials, components, locations, building systems, etc. [62]. Reaching out to a common denominator between all parties can very often lead to a compromise.

The professionals have a range of tools and methods at disposal for assessing options to facilitate and streamline decision-making during the construction project, during the operational life of the building and in the deconstruction phase. Multicriterial decision-making methods can help field professionals (architects, engineers, builders) structure the decision process [62]. Multi-criterion decision-making methods can be optimization methods [63, 64], value-based methods (eg, AHP) [65, 66], assessment and classification methods, or choice-by-benefit method. In the literature are numerous examples where multi-criteria methods are used in decision-making: comparative value analysis to demonstrate the impact of energy incorporated in building materials [67]; a model for assessing the environmental impact of building envelope based on LCA sustainability indicators in order to assist designers in choosing materials [68]; a lifecycle analysis method that integrates AHP technique for choosing the optimal flooring system in terms of sustainability [69].

4.1 Decision-making in the design phase

The design phase implies the most important decision-making process with impact on the long term building's sustainability, with two sub-processes: the design and the material selection [70]. The design of a building is a collaborative, interdisciplinary process, where decisions are made by all interested parties: architects, engineers, contractors, beneficiaries [71], and even the building users (occupants) [12]. The current approach should be an integrated one where designers work together with architects to meet the requirements of a sustainable building, often confused with the criteria for green buildings. Architects need support tools to effectively analyze the energy consumption of the building in order to overcome their possible limitation with regard to technical knowledge. At present, there are many energy simulation tools in buildings, the America's Department of Energy mentioning a number of 417 [72]. But although their purpose is to help industry professionals assess the energy consumption of buildings by providing accurate information, less than a third of architects use them [72].

As a major source of energy consumption in buildings, heating and air conditioning systems draw interest of researchers. Kovacic and Zoller (2015) performed a comparative analysis of three decision support tools in the early design phase (9 Indicator 16 - LCC provided by DGNB / BNB, ABK LEKOS software and LEGEP software), starting from integration of a cost-cycle analysis (LCC) [35]. BIM (Building Information Modelling) is very popular and efficient in design of green buildings [73], but also recognized as valuable for the construction, facility and operations management phases [74]. Further, researchers developed BIM based multi-objective decision support tool, like for selecting processes, systems, techniques and materials (PSTM) combinations during design [75]. Liu, Meng and Tam (2015) present a method of optimizing design based on BIM (Building Information Modeling) and apply an optimization algorithm between LCC (Life Cycle Cost Analysis) and LCCE (Life Cycle Carbon Emissions Analysis), thus a middle path between economic and environmental requirements [76]. The decision to one tool or another is subjective and must be addressed based on the objectives of the project.

Sustainable design means also the right choice of building materials [67, 77, 78]. A method to include the potential for recycling (a long term approach) besides the embodied energy in the material selection is described by Saghafi and Teshnizi (2011) [79]. Designers have to decide which materials to be used for construction, trying to minimize their impact on the environment, which is quantified by the built-in energy.

4.2 Decision-making in the construction phase

In the construction phase, the decision-making process is more limited and is rather transposed into project management which seeks to implement the design specifications [70]. One key role for the success of the project is the knowledge transfer from the researchers, designers, architects to the practitioners (constructors) [80].

The constructors are also in charge of purchase and installation of design solutions, therefore assessing the available options and taking a decision [81]. The selection criteria are the following: aesthetics, availability, compatibility (with other products), compliance with legislation, cost, durability, buildability, environmental impact, health and safety, replacement and recyclability or other product and manufacturer associated risks [81].

4.3 Decision-making in the operation phase

In the operational phase, it is decided if the building should be restored, renovated or extended [82] or simply about replacement of some components as part of maintenance task. This is usually based on monitoring and evaluations. A sustainability assessment should imply examination of the environmental, social, and economic impact on the building's local community, the region, and the planet for which there are tools available [83]. Some examples of global sustainability assessment rating systems are LEED (Leadership in Energy and Environmental Design), BREEAM (Building Research Establishment Environmental Assessment Method), ABGR (Australian Building Greenhouse Rating), HKBEAM (Hong Kong Building Environmental Assessment Method), Chinese Three Star, SBAT (South African Sustainable Building Assessment Tool), G-SEED (Green Standard for Energy and Environmental Design in Korea), a.o. [84, 85].

Also in this stage, BIM [86] and LCA [87] are valuable tools to be used for collecting data and monitor the energy consumption in buildings, as starting point for future decisions. Beside the existing professional tools, the internet offers access to some ICT tools which can be easily used also by non-professionals. Most of the key decision-makers in this phase are not experts (building owners, developers, users, property managers) but people who could reach the best compromise between sustainability and costs at a small scale [83].

4.4 Decision-making in the renovation phase

Building renovation is a good opportunity to streamline energy consumption in a building [88, 89], as well as to implement measures on all three dimensions of sustainability: for efficient resource use [90], for improving the indoor environment [91, 92] or for reducing operating and maintenance costs [93], which in the end can result in improvement of occupant's health and productivity [94].

In the refurbishment phase, an organized process is also necessary, taking into account all the existing options and the multiple objectives that come in: improving energy efficiency, indoor comfort, air conditioning, natural lighting etc. In order to initiate a refurbishment process, an exhaustive investigation of all possible solutions is required and the efficiency level depends on: costs, annual energy savings after renovation, time of investment recovery, impact of materials used on human health, aesthetics, maintainability, functionality, comfort, sound insulation and durability [95]. Renovation implies several decision levels: functional requirements, energy performance, cost optimization, reducing environmental impact and increasing occupant welfare [96].

To address simultaneously all these constraints, researchers in the field have tried to develop multi-criteria decision-making models and instruments. Chantrelle et al. (2011) proposes a tool for optimizing refurbishment operations, with emphasis on building envelope, heating and cooling systems and control strategies [96], while others focus on comfort level and occupants' behavior [97, 98]. Decision based on information from life cycle assessment is also common [99, 100]. Other authors deal with the decisional aspects of refurbishment from a more complex qualitative and quantitative perspective in which stakeholder requirements are integrated into a design team's analysis process and then confronted with the results of computerized optimization [101]. The KPI (Key Performance Indicators) method is one of the most commonly used and most cost-effective tool for measuring the sustainability level of a construction project [102].

4.5 Decision-making in the deconstruction phase

The options for sustainable dismantling are significantly depending on the early design solutions [103, 104], the main issue being the fact that the buildings in the past were seen as permanent [105].

Appropriate decisions should take into considerations the costs and the possible environmental effects of the old materials – for example old windows could be less effective than new ones [105]. Recycling is the most sustainable way, providing benefits in terms of costs, energy, emissions and extraction [106], like producing concrete aggregate from recycled elements or demolition waste [107, 108], but once again the decision should be taken individually for each case [21]. Tingley and Davison (2012) presented a LCA-based tool (Sakura) which can be used to compare different end of life options like reuse, recycling or landfill for the buildings components at component level and at whole building level [109]. This assesses also the environmental impact on the other life cycle stages. Other author proposes a methodology of comparing four different scenarios for the end of life phase of buildings, applying a life cycle energy analysis [110].

5. DISCUSSIONS AND RESEARCH TRENDS IN BUILDING SUSTAINABILITY

The building sector presents great opportunities to address environmental aspects, as well to improve humans' health and wellbeing. Quality for people refers to the chance of enjoying healthy and fulfilling lives. The ecological dimension of building sustainability is a major concern for scientists and industry professionals, but the social and cultural aspects cannot be neglected in a comprehensive approach to sustainability. Lately, there is a more increased interest in the social dimension: health of the building and of the indoor environment [111, 23, 112], the occupants' comfort [113], the behavior of the occupants in relation to the building systems [114, 115], the perception of the occupants regarding the performance of the building [116, 117], education of the population in a spirit of sustainability and ethical aspects in the sustainable approach of buildings [189, 119]. These main topics are not treated independently, because there are relations between them, e.g. occupants' comfort is closely related to the health of the building [23] or the comfort felt by the occupants is a factor contributing to shaping their perception of building performance [116]. Moreover, people's perception of the performance of a green building is heavily influenced by their degree of education related to the operation of building systems [115]. So, the occupants' behavior for energy saving has a central place in the approach for the sustainability of buildings, which lead to a critical topic today: the education for sustainability (ESD). People should learn how to respect the nature, how to behave without affecting the surrounding and how to use modern technologies within nature's limits. The latest technologies can bring substantial improvements to reduce energy consumption and increase occupants' comfort. One solution is the development of green buildings which are defined and classified by certification programs. The construction of a green building generally requires higher costs than a conventional building, but in order to obtain the most efficient solutions, an analysis of all the factors involved during the lifecycle has to be made, and an appropriate method for this purpose is LCA [10].

The concept of intelligent building is a recent emerging technology that is often confused with building automation. An intelligent building is basically a structure that uses automated processes for lighting, heating and electronic devices controlled by a smart device but which should be self-programmed to perform certain tasks depending on the occupants' behavior and the environment [120]. With the new requests of the population to improve living conditions, Internet of Things (IoT) has become increasingly demanded and needed in buildings [121]. Intelligent buildings that make use of the Internet of things involve family security, medical facilities, family data processing, family entertainment and business facilities [121]. As there is a need for connectivity between people, organizations, companies and electronic devices to get real-time responses and control, the IoT things is exactly the one that could offer these facilities, enabling the home objects to be monitored and controlled over the network [122].

In conclusion, energy-efficient buildings can bring major benefits to the owners, to the environment, but also to the society in general. Reducing energy, water and waste costs brings in addition economic gains.

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PROCESUL DECIZIONAL PENTRU ÎMBUNĂTĂŢIREA SUSTENABILITĂŢII CONSTRUCŢIILOR PE DURATA CICLULUI DE VIAŢĂ – STADIU ACTUAL

Rezumat: Astăzi, societatea se confruntă cu provocări majore de a acţiona şi de a reacţiona la schimbăril climatice prin toate mijloacele posibile. Întrucât sectorul construcţiilor contribuie în mod semnificativ la consumul de energie la nivel mondial, acesta prezintă, de asemenea, multe oportunităţi de integrare a durabilităţii atât în clădirile existente, cât şi în cele noi. Această lucrare prezintă o rezumat asupra principalelor aspecte privind sustenabilitatea clădirilor, orientându-se pe o abordare bazată pe ciclul de viaţă, care este văzută ca o metodă eficientă pentru îmbunătăţirea dimensiunii de mediu a sustenabilităţii. Rezultatele arată că deciziile în fiecare fază a ciclului de viaţă afectează ieşirile din proces ulterioare, etapa de proiectare fiind cea mai importantă pentru punerea în aplicare a unor măsuri durabile pe termen lung. În continuare, această lucrare prezintă procesul de luare a deciziilor în fiecare etapă şi abordările actuale pentru reducerea impactului mediului construit asupra planetei. Dar, aspectele economice şi sociale nu pot fi neglijate, după cum arată cele mai recente studii din domeniu.

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