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Comparison of eco-effectiveness and eco-efficiency based criteria for the construction of single-family homes

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Abstract. The built environment faces diverse sustainability challenges concerning the ecological, the economic and the sociocultural dimension. However, common construction practices mainly focus on the reduction of environmental impacts, especially the energy consumption in the usage phase. Despite their long tradition of implementation, these eco-efficiency based strategies can only be regarded as a useful and groundwork lying step and opportunity to reduce the ecological impact in the short-term, but are insufficient for addressing the need for fundamental redesign of buildings in the long-term. In contrast, the cradle to cradle concept offers a model for fundamental redesign of buildings allowing positive interaction with the ecosystem based on the eco-effectiveness approach. The paper will analyse and compare eco-efficiency and eco-effectiveness based criteria for the construction of single-family homes with the help of guidelines and assessment methods for buildings and materials. The analysis serves the aim of identifying learnings from the long-term experience in the field of eco-efficiency and benefitting from it for the future implementation of eco-effectiveness based strategies. Single-family homes are chosen as typology as they represent the most popular housing type in Germany, but show numerous disadvantages regarding the ecological, economic and socio-cultural dimension compared to other forms of housing. Representing the smallest but worst typology from a sustainability point of view, they offer an ideal starting point. In a next step, the results can be transferred and expanded to other typologies.

Keywords: eco-effectiveness, cradle to cradle, eco-efficiency, positive footprint, single-family homes, Germany

1. Introduction

1.1. Eco-efficiency approach

The built environment currently faces diverse sustainability challenges ranging from ecological problems like the depletion of finite resources and the pollution of the environment to economic problems like high life cycle costs and low utilization flexibility to sociocultural problems like low indoor air quality and user comfort. Currently, the mentioned challenges related to buildings are mainly addressed by means of the eco-efficiency concept. Originally described as "being reached by the delivery of competitively priced goods and services that satisfy human needs and bring quality of life, while progressively reducing environmental impacts and resource intensity throughout the life cycle, to a level at least in line with the earth's carrying capacity" by the World Business Council for Sustainable Development in 1992 [1], many different definitions for the term eco-efficiency have emerged since then. Braungart et al. (2007) state that within the variety of definitions, all notions of eco-efficiency have the aim of getting more from less and the assumption of linear cradle to grave flow of materials in common. In the material and resource context this means to generate "more product or service value with less waste, less resource use or less toxicity" [2]. In the energy context, eco-efficiency means generating more performance, service, goods or energy output from less energy input following the definition of energy efficiency as "ratio of output of performance, service, goods or energy, to input of energy" [3].

1.2. Eco-effectiveness approach

In contrast to the described eco-efficiency approach, the eco-effectiveness model aims for fundamentally optimized and beneficial buildings in order to generate a supportive relationship with ecological systems and economic growth. Instead of reducing the cradle-to-grave flow of materials, the eco-effectiveness approach promotes cradle-to-cradle "metabolisms" which allow maintaining or increasing the quality and productivity of materials through many cycles of use rather than aiming at reducing waste [2]. The cradle-to-cradle concept represents a design strategy to implement the approach of eco-effectiveness. It is based on the three principles of "everything is a nutrient for something else", "use current solar income" and "celebrate diversity" and aims at generating a positive footprint instead of reducing the negative footprint. The first principle "waste equals food" aims at transferring closed ecologic metabolisms to the industrial production of goods by the means of the biological and the technical metabolism. The second principle "Use current solar income" refers to the current energy generation which still mainly relies on the incineration of fossil fuels. In order to completely close the cycle described within the principle "everything is a nutrient for something else", is it essential to generate energy from renewable sources instead of wasting fossil fuels irretrievably. The third principle "Celebrate diversity" follows the complexity and diversity of natural ecological systems. While products and systems designed by mankind are often characterized by standardization and simplification since the industrial revolution, nature provides diverse solutions and can serve as a model for production to meet the needs of diverse starting conditions [4].

1.3. Comparison of eco-efficiency and eco-effectiveness based criteria for single-family homes

While the eco-effectiveness approach is still a relatively new concept that has been picking up pace during the last years, the eco-efficiency approach has been embedded in the German legislation on resources and energy in the built environment for a long time and is concretised in the Energy Saving Regulations 2014 and the Resource-Efficiency Programme II. However, eco-efficiency strategies can only be regarded as a useful and groundwork lying step and opportunity to reduce the ecological impact in the short-term, but are insufficient for addressing the need for fundamental redesign of buildings in the long-term [2]. Contrary, the eco-effectiveness approach offers the opportunity to develop concepts for beneficial buildings and convert weaknesses into positive potential. For this reason, the paper will analyse and compare eco-effectiveness and eco-efficiency based criteria for the construction of single-family homes with the help of guidelines and assessment methods. This serves the aim of identifying learnings from the long-term experience in the field of eco-efficiency and to benefit from them for the future implementation of the eco-effectiveness approach. Single-family homes are chosen as object of reflection as they represent the most popular housing type in Germany, but also the worst case from a sustainability point of view. In 2016, Germany's residential building stock amounted to 18,8 million, whereof 83 percent (15,7 million buildings) were single- and two-family houses [5]. Furthermore, forecasts predict that 230.000 further dwelling units will be needed annually till 2030, whereof the largest part with 128.000 will be attributed to single- and two-family houses [6]. Nevertheless, the building typology of single-family houses shows many disadvantages regarding ecological, economic and social aspects compared to other types of housing. Examples are their low compactness leading to a high energy demand for conditioning and a high need for building materials as well as above average construction and maintenance costs. Further problems include the massive increase of settlement and transport area which leads to ecological problems like surface sealing, destruction of soil functions and soil erosion as well as social problems like the segregation of social classes encouraging the development of underprivileged districts in cities. Representing the smallest but worst typology from a sustainability point of view, single-family homes offer an ideal starting point. As many of the examined criteria also apply to other typologies, the results can be transferred and expanded to bigger buildings in a next step.

2. Methodology

2.1. Criteria for the selection of literature

To compare the eco-effectiveness and the eco-efficiency based criteria for single-family homes, literature from both fields was analysed. The literature for comparison was chosen based on relevance. Literature with lists of criteria for designing and constructing single family-homes was preferred over indirect textual descriptions. For this reason, assessment systems and guidelines for the construction of single-family homes were in the scope of the analysis. Due to page limitations, the scope of the paper is on content-related criteria and criteria concerning their implementation are not taken into account.

2.2. Literature in the field of eco-effectiveness

In the field of eco-effectiveness, the literature research showed that there are currently no assessment systems for buildings, but several guidelines available. Most of the guidelines for cradle to cradle inspired buildings do not target specific building typologies, but buildings in general. Only one specific manual for single-family homes was found in the report of the research project on the development and evaluation of a cradle to cradle inspired plus energy house by Salfner et al. (2017). The research project analyses the implementation of the cradle to cradle principles in the NexusHouse, an entry for the Solar Decathlon student competition by the Technical University of Munich and the University of Texas at Austin and contains planning parameters for designing cradle to cradle inspired single-family homes [7]. Additionally, the manual "Cradle to Cradle Criteria for the built environment" by Mulhall et al. (2010) which does not focus on a specific building typology was taken into consideration. Based on the three cradle to cradle criteria, the document summarizes the guiding principles for the built environment [8]. In addition, the cradle to cradle product certification was considered in the comparison since there are no assessment systems for buildings available and the majority of certified products originates from to the building sector [9].

2.3. Literature in the field of eco-efficiency

The literature research showed that several assessment systems for small residential buildings which are based on the eco-efficiency approach are available in Germany. Three of them – BNK V1.0, NaWoh V3.1 and the DGNB system variant for small residential buildings V2013.2 – are audited and recognized by the Federal Ministry of the Interior, Building and Community [10] [11] [12]. While the Sustainability Evaluation System for small residential buildings (BNK) and the DGNB system variant for small residential buildings allow the certification of buildings with less than six units, the Sustainable Housing Construction Quality Label (NaWoh) is designed for the assessment of buildings with six or more units. Since all three methods are based on the Sustainable Construction Evaluation System (BNB) and the guidelines for sustainable construction, which explicitly state the goals of material- and energy-efficiency, they largely follow the eco-efficiency approach [13]. All three certification systems were considered for the comparison as they show differences concerning the criteria.

2.4. Categorization of criteria

In a first step, the literature identified for the eco-effectiveness approach was analysed. For each of the mentioned guidelines or certification systems, criteria were identified and grouped in a table according to the three cradle to cradle categories “everything is a nutrient for something else”, “use current solar income” and “celebrate diversity” (table 1). Criteria with same or similar content from different guidelines or certification systems are shown in the same line. In a next step, the criteria were numbered consecutively from 1.1 to 1.23. Implementation criteria were not considered. Similarly, the assessment systems in the field of eco-efficiency were analysed. Following their inherent methodology, the criteria were grouped into the categories of ecological quality, sociocultural and functional quality and technical quality (table 2). The categories of economic quality and process quality were not considered as they correspond with the implementation criteria which are not considered in this paper. Criteria with overlaps between the three systems are presented in the same line of the table. The criteria were numbered consecutively from 2.1 to 2.30. Both, the eco-effectiveness and the eco-efficiency based criteria were scanned for overlapping topics. The respective criterion numbers from the table on eco-effectiveness were allocated to the matching eco-efficiency criteria in the column “corresponding criteria” and vice versa.

3. Results

In total, 23 criteria for cradle to cradle inspired buildings or products were found in literature (table 1). Within the sustainability assessment systems based on the eco-efficiency approach, 30 criteria were identified (table 2). Twelve eco-effectiveness based criteria and 21 eco-efficiency based criteria showed overlaps. While eleven of the identified cradle to cradle criteria showed no corresponding eco-efficiency based criteria, only nine eco-efficiency based criteria had no equivalent.

The comparison showed that the criteria following the eco-efficiency approach and the criteria based on the eco-effectiveness approach are arranged in different categories. While the cradle to cradle criteria are grouped into the categories of “everything is a nutrient for something else”, “use current solar income” and “celebrate diversity”, the eco-efficiency based criteria are grouped into the categories of ecological quality, socio-cultural quality and technical quality. Additionally, some of the cradle to cradle criteria host broad topics, e.g. the criterion 1.18 on conceptual diversity. As a result many of the cradle to cradle criteria had more than one corresponding eco-efficiency based criterion. This was only the case three times for the other way round.

Furthermore, it became evident that both systems show many criteria on energy related topics, but that the cradle to cradle criteria additionally show more criteria on materials than the eco-efficiency based systems. Additionally, many cradle to cradle criteria within the categories of “everything is a nutrient for something else” and “use current solar income” show more ambitious aims than the corresponding eco-efficiency based criteria. While the eco-efficiency based criteria aim for “less bad” solutions, the cradle to cradle criteria demand “good solutions”. In the field of “celebrate diversity” this was not the case as diversity per se is not measurable and the cradle to cradle criteria do not show a fixed aim.

The analysis also revealed that the examined eco-efficiency based assessment systems show detailed and stringent assessment matrixes demanding a comprehensive building documentation while the cradle to cradle guidelines give broader advice. On the one hand, this leaves room for creative solutions and innovation, but on the other hand also makes the implementation of the cradle to cradle criteria less tangible. Criteria from the cradle to cradle product certification turned out to be closer to the eco-efficiency based criteria than the criteria from the examined cradle to cradle based guidelines.

The detailed results of the analysis will be discussed in the following chapters. As the paper aims at identifying learnings for the future implementation of the identified cradle to cradle criteria, the comparison uses the cradle to cradle criteria and categories as a basis.

Table 1. Eco-effectiveness based criteria for buildings and building products.

Category	Number	Mulhall et al. (2010): Cradle to Cradle Criteria for the built environment	Salfner et al. (2017): Development and evaluation of a cradle to cradle inspired plus energy house by the example of the competition entry for Solar Decathlon 2015	Cradle to Cradle Products Innovation Institute (2014): Cradle to Cradle certified ™. Product standard version 3.1	Correspon-ding criteria
Everything is a nutrient for something else	1.1	Define materials and their intended use pathways	Material flows	Material reutilization	---
	1.2		Ingredients and health	Material health	2.2
	1.3		Dismantling and recycling potential		2.27
	1.4		Environmental impact		2.1 2.3 2.4
	1.5	Integrate biological nutrients			---
	1.6	Integrate CO_2 in biological and biochemical processes			---
	1.7	Enhance air and climate quality			2.10
	1.8	Enhance water quality	Water quality Water cycles Water footprint	Water stewardship	2.6 2.12
	1.9		Innovation		---
Use current solar income	1.10	Integrate renewable energy	Regenerative energy sources	Renewable energy	2.5
	1.11	Consider energy effectiveness			---
	1.12		Planning foundations		---
	1.13		User scenarios		---
	1.14		Energy storage		---
	1.15		Passive and active measures		2.9 2.11 2.25 2.26
	1.16	Use materials with defined pathways for energy generation			---
Celebrate Diversity	1.17	Actively support biodiversity	Biodiversity		---
	1.18	Celebrate conceptual diversity with innovation	Conceptual diversity		2.11 2.14 2.18 2.19 2.20
	1.19		Cultural diversity		2.16
	1.20		Technological diversity		2.29
	1.21		Comfort requirements		2.9 2.10 2.11 2.21 2.26
	1.22		User awareness		2.13
	1.23			Social fairness	---

3.1. "Everything is a nutrient for something else" – Criteria with and without correspondence

Within the category of "everything is a nutrient for something else", nine criteria were identified. While five of them showed content-related overlaps with the eco-efficiency based criteria from the examined sustainability assessment methods, four criteria had no matches. The five criteria showing content-related overlaps deal with the topics of material health, dismantling and recycling, environmental impact, air and climate quality as well as water quality (criteria 1.2, 1.3, 1.4, 1.7, and 1.8). While the eco-efficiency based criteria in this category aim for a less negative impact, the eco-effectiveness criteria aim for a positive impact and follow more ambitious aims. For example, the eco-effectiveness based criteria on material health aim at identifying one hundred percent of the contained chemicals of the used building materials and substituting all substances which are possibly harmful for humans and the environment in order to generate a beneficial product. The eco-efficiency criteria on material health state the goal of reducing or banning certain chemicals which are harmful for the local environment depending on the type of material. Material health concerning humans is not considered in these criteria, but only within the criteria on indoor air quality.

The four cradle to cradle criteria which showed no correspondence deal with the topics of material flows, the integration of biological nutrients into buildings, the integration of CO_2 into biological and biochemical processes and the implementation of innovations (criteria 1.1, 1.5, 1.6 and 1.9). Moreover, the eco-efficiency based assessment systems only contained one further material related criterion without correspondence (2.10 Durability). This shows that the cradle to cradle criteria focus more on materials and nutrients than the examined eco-efficiency based criteria. Additionally, the criterion on innovations promotes creative solutions.

Table 2. Eco-efficiency based criteria for buildings.

Category	Number	Sustainability Evaluation System for small residential buildings (BNK) V1.0	DGNB system variant for small residential buildings, version 2013.2	Sustainable Housing Construction Quality Label (NaWoh), version 3.1	Correspon-ding criteria
Ecological quality	2.1	Life cycle assessment: global warming potential and other environmental impacts	Building life cycle assessment - emissions-related impacts	Life cycle assessment – part 1 Life cycle assessment – part 2	1.4
	2.2		Local environmental impact	Avoidance of harmful substances	1.2
	2.3	Use of local/certified wood	Sustainable resource extraction	Use of certified wood	1.4
	2.4	Life cycle assessment: primary energy	Building life cycle assessment – primary energy	Primary energy demand	1.4
	2.5	Decentralized energy generation		Energy generation for tenants and third parties	1.10
	2.6	Use of water-saving taps and mixers	Potable water demand and waste water volume	Potable water demand	1.8
	2.7		Land use	Land use and land sealing	---
	2.8	Efficient use of available space		Area ratio	---
Sociocultural and functional quality	2.9	Thermal insulation in summer	Thermal comfort	Thermal comfort	1.15 1.21
	2.10	Interior hygiene	Indoor air quality	Indoor air quality	1.7 1.21
	2.11	Available daylight	Visual comfort	Visual comfort/available daylight	1.15 1.18 1.21
	2.12	Healthy drinking water			1.8
	2.13	User friendliness and information content of controls	User control		1.22
	2.14		Quality of outdoor spaces	Open spaces Outdoor seating/ space	1.18
	2.15	Anti-intruder measures	Safety and security	Security	---
	2.16	Accessibility	Design for all	Accessibility - entrance and apartments	1.19
	2.17			Parking spaces	---
	2.18			Urban development and design quality	1.18
	2.19			Functionality of apartments	1.18
	2.20		Quality of indoor spaces		1.18
Technical quality	2.21	Sound insulation	Sound insulation	Sound insulation	1.21
	2.22			Energy performance	---
	2.23			Efficiency of building services	---
	2.24			Ventilation	---
	2.25		Quality of the building envelope	Moisture protection	1.15 1.21
	2.26			Airtightness of building envelope	
	2.27		Ease of recovery and recycling	Ease of recovery and recycling	1.3
	2.28	Fire alarms and fire fighting	Fire protection	Fire protection	---
	2.29			Maintainability and retrofitting capability of building services	1.20
	2.30			Durability	---

3.2. "Use current solar income" – Criteria with and without correspondence

Seven criteria were identified in the category of "use current solar income". Only two of them showed content-related overlaps with the eco-efficiency based criteria from the examined sustainability assessment methods for buildings. Seven criteria showed no direct equivalents.

The two criteria showing content-related overlaps deal with the topics of renewable energies and passive and active measures within the building (criteria 1.10 and 1.15). While the cradle to cradle criteria on renewable energies aim at producing more renewable energy at the building than it consumes including the embodied energy, the eco-efficiency based criteria only take the energy demand in the use phase into consideration. The criterion on passive and active measures hosts four eco-efficiency based criteria. Both approaches follow the aim of improving the user comfort through passive measures like the reduction of transmission heat losses.

The five criteria which showed no correspondence deal with the topics of energy effectiveness, planning foundations, user scenarios, energy storage and the use of materials with defined pathways for energy generation (criteria 1.11, 1.12, 1.13, 1.14 and 1.16). While the eco-effectiveness based systems show a criterion on energy effectiveness and state exergy as a way to guide effectiveness, the eco-efficiency based systems show a criterion on energy efficiency of building services. This clearly reflects the essence and the difference between the effectiveness and efficiency approach. The criteria on planning foundations and user scenarios are energy related implementation criteria and therefore not further discussed although they were found in the category of "use current solar income". The criterion on materials of energy generation systems again shows the focus of cradle to cradle criteria on materials.

3.3. "Celebrate diversity" – Criteria with and without correspondence

Within the category of "celebrate diversity", seven criteria could be derived from literature. Five of them showed content-related overlaps with the eco-efficiency based criteria from the examined assessment methods. Due to the inherent nature of "diversity", the related criteria host broad topics under which many eco-efficiency based criteria can be unified. Two cradle to cradle criteria had no corresponding eco-efficiency based criterion.

The five criteria showing content-related overlaps deal with the topics of conceptual diversity, cultural diversity, technological diversity, comfort requirements and user awareness (criteria 1.18, 1.19, 1.20, 1.21 and 1.22). As some of the criteria host broad topics, they have more than one corresponding criterion. An example can be found in the criterion on conceptual diversity which unifies the eco-efficiency based criteria on visual comfort, urban development and design quality, functionality of apartments and quality of indoor spaces.

The two criteria which showed no correspondence deal with the topics of biodiversity and social fairness (criteria 1.17 and 1.23).

3.4. Eco-efficiency based criteria without correspondence

Additionally, nine criteria from the eco-efficiency field were identified which did not show related contents with the cradle to cradle criteria (2.7, 2.8, 2.15, 2.17, 2.22, 2.23, 2.24, 2.28 and 2.30). In the field of ecological quality these were criteria on land use and area ratio. In the category of socio-cultural quality the criteria on safety and security and parking spaces were concerned. Within the technical quality these were criteria on energy performance, efficiency of building services, ventilation, fire protection and durability.

4. Conclusion

The literature review gave an overview about existing eco-efficiency and eco-effectiveness based criteria for the construction of single-family homes and showed similarities and differences between the two approaches. Many of the examined cradle to cradle criteria show overlaps with the eco-efficiency based criteria, but in many cases have more ambitious aims. Furthermore, most of the eco-efficiency based criteria are already very elaborate and demand a detailed building documentation which can also be a valuable contribution for the future implementation of the cradle to cradle criteria. For example, to design beneficial buildings, it is essential to know one hundred percent of all ingredients of the used building products so that harmful ingredients can be substituted. With proceeding digitalization in the built environment it is likely that building documentation will become standard during the next years which will facilitate the implementation of cradle to cradle criteria. In this regard, eco-efficiency criteria can be seen as a first step on the way to design eco-effective buildings. However, it is important to evolve further and loosen from the fixed framework given in sustainability assessment methods in order to generate innovative and individual cradle to cradle inspired solutions that are adapted to the local context. In addition to guidelines, best practice examples and databases like the Registry of Cradle to Cradle Inspired Elements for Building Developments can contribute to this. Since many of the examined criteria are also valid for other building typologies, the results can be transferred and expanded to bigger buildings in a next step.

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