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Review

Ökobau.dat 3.0–Quo Vadis?

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Abstract: Life cycle assessment (LCA) is the standard method for the quantification of environmental impacts within the construction sector, relying on available generic LCA databases. New developments, such as the increased influence of the building construction for LCA and the forthcoming of building information modeling (BIM), implicate new requirements on multiscale levels of development and complexity for LCA construction databases. At the example of the German "Ökobau.dat", one of the leading LCA construction databases, this publication discusses whether the database is able to meet these requirements. The analysis shows the strengths of the Ökobau.dat with regard to standardization conformity (EN 15804, ILCD), data provision in machine-readable XML format, and the provision of an application programming interface. Shortcomings include incorrect linking of building life cycle inventory data with environmental information, incorrect documentation of functional units, missing generic datasets, the modeling of energy use data or the lack of a uniform structuring, or material classification. The authors propose solutions such as the provision of appropriate functional units, the implementation of a top-down approach to investigate the completeness of data based on existing nomenclatures or the extension with an appropriate material classification. This would allow for future viability and adaptability of Ökobau.dat for digital LCA.

Keywords: LCA database; building construction datasets; environmental building assessment; viability and adaptability; digital building LCA; LCA for BIM

1. Introduction

The importance of limiting global warming below 2 °C has been an issue in society and politics, even before the Paris agreement in 2015 [1]. The building and construction sector is one of the most resource-intensive ones of the economy and is thus becoming the focus of attention [2]. In order to optimize greenhouse gas emissions, not only building energy requirements must be considered, but also environmental emissions over the entire life cycle. Life cycle assessment (LCA) has proven to be a sound tool to quantify environmental building impacts, starting from the extraction of the necessary resources for building materials and their production, over the energy demand in the use phase, and through the dismantling and recycling of building materials [3–5]. Over the last few years, LCA has therefore become increasingly important within emerging building sustainability assessment systems [6].

Environmental data sources and databases for building LCA referenced within such sustainability assessment systems show diverse characteristics. Mostly, they contain country-specific environmental information on building products or building energy supply systems. Some sources even provide for international environmental data. Hereby, information is made available on a generic level or on a specific environmental product declaration level (EPD). Furthermore, these environmental data sources are more or less machine-readable and may be integrated in respective LCA or other architectural software applications.

Due to current developments in the building construction sector, such as the strong reduction of the building energy demand [7,8] and the forthcoming of Building Information Modeling (BIM) [9,10], todays' LCA practitioners question if these LCA data sources are sufficiently viable and adaptable for the future. At the specific example of the German "Ökobau.dat" as one of the leading European LCA construction product databases, this publication discusses whether the database is able to address forthcoming structural, application, content, and scientific related developments in its current form or how it would have to be evolved to do so. For this purpose, the origin of the German database is explained shortly. Furthermore, the main important current developments the database has to face are described and strengths of the present database are pointed out. On this basis, a detailed analysis of current shortcomings within the German database is presented with regard to end user application, content, modelling, and automation, as well as the update process. For these shortcomings solutions are proposed that could support its development in a viable and future-oriented way. Afterwards, the outcomes of this specific analysis, their implications, and their transferability within the context of other international construction databases are discussed. Finally, the summary and outlook concludes with different future pathways for development for LCA databases in the building and construction sector.

In that way, the publication intends to stimulate a discussion between end users, reviewers, building certification, and database developers. An in-depth debate whether and how future changes have to be addressed by LCA databases in the building and construction sector in order to meet emerging requirements could potentially enable not only other (new) environmental databases to learn from.

2. Ökobau.dat—An Example of a German Development

In order to assess the current status of the German construction and material database Ökobau.dat as an example for LCA databases in the building and construction sector, its development is briefly reviewed.

2.1. Ökobau.dat 1.0

The first version of the database was created in the year 2009 to enable the comparison of building related environmental impacts. The idea behind was to open the complex field of life cycle assessment (LCA) also for non-experts (e.g., architects, planners, contractors) by giving them the possibility to calculate and conduct respective analysis themselves. For this purpose, existing and complex LCA models from various sectors (e.g., minerals, metals, plastics, energy, agriculture and forestry, building services, transport) and different life cycle phases (production, use, end-of-Life) were compiled on a generic level. The results were summarized in the form of a life cycle impact assessment (LCIA) database, containing approximately 680 individual generic datasets and representing thirteen environmental indicators.

LCA practitioners could now use these small "LEGO pieces" to create an environmental profile on building level by easily adding the pieces up. As market-uptake of environmental product declarations (EPD) just started, the database served as starting point for building life cycle assessment until further valid environmental information in form of manufacturer-specific EPD data would be available. From the perspective of environmental building optimization, it should be noted that the German energy requirements for buildings within the year 2009 based on natural gas. With a final energy demand of approximately 71 kWh per one square meter and one year [11], the building use phase was still the dominant factor in a life cycle assessment. From the perspective of quality, environmental information provided within this first version of the Ökobau.dat already considered respective international standards, such as the ISO 14040/14044 [12,13] and activities within the European standardization, such as CEN TC 350 [14] at that time. Furthermore, the possibility of gradually replacing the generic starter data with manufacturer and product specific data was co-considered, as the database was also intended to stipulate a market-demand. The data format chosen was the machine-readable Extensible Markup Language (XML) format [15,16].

After an update of existing and an intake of new data in the year 2011, the database contained approximately 950 datasets, thereof 288 new ones on externally verified EPD level. The update already considered the new European standard DIN EN 15804 from the year 2012 [17], which was intended to form the basis for future methodological developments. During the update, main errors within the environmental modeling that were fixed mostly related to the modeling of impacts from water use, the consideration of waste at the end-of-life phase, the scaling of environmental impacts during the update process or the incorrect documentation (e.g., recycling potentials) of information within the XML data files [18–20].

2.2. Ökobau.dat 2.0

The second version of the database was only born with the re-structuring of the existing XML data format in the year 2013, that followed strongly the changes of the European standard DIN EN15804 that was then released a year later in 2014 [21]. 724 generic datasets based (and still do today) on the best available technology and were not externally verified. The environmental information provided by 230 specific EPD data built on representative, average or product-specific data, being prepared by a group of associations and companies or single manufacturers.

Revisions performed related to the inclusion of additional environmental indicators on life cycle inventory level (e.g., non-renewable secondary fuels, components for re-use, and materials for energy recovery or exported energy) and on life cycle impact assessment level (e.g., abiotic depletion potential of fossil fuels). A new classification of environmental impacts according to the life cycle stages A1 to A3 (aggregated production), B6 (energy use), C3 (waste processing), C4 (disposal), and D (benefits and loads beyond the system boundaries from reuse, recycling, and recovery) was introduced. Furthermore, the previous safety margin on generic data within the production phase (that was assumed so far with 10% in general) was revised. Criteria of completeness and representativeness were used, leading in the end to a range for the safety margin between 10 to 30% [22–24].

These methodological adjustments were further intensified in the year 2015 [25], where the data format was adapted to allow for mapping of life cycle stages in one single dataset. In the past, environmental information for each life cycle stage had been stored in single data files, adding effort of consistent interlinking the environmental information e.g., between production and End-of-Life stage. In addition, the creation of the "soda4LCA software application and data hub service" [26,27], as well as the creation of a respective Ökobau.dat interface were the first important steps towards a machine-readable data implementation and central linking to other LCA databases.

In the years 2016 and 2017, the Ökobau.dat was updated again [28,29]. Currently, the database contains about 1186 multiple datasets. Life cycle information is further enhanced and today includes also credits for recycling, recovery or thermal incineration beyond the system boundaries in life cycle stage module D (according to DIN EN 15804). At the moment, Ökobau.dat intensifies activities for international linking of LCA data on construction based products in European member states. Therefore, it cooperates within the working group "International Open Data Network for Sustainable Building (InData)". Apart from the definition of a common standard on data formats, the network focusses on compatibility and transparency of environmental data [30]. Ökobau.dat also facilitates a standardized interface for data exchange (import and export) that provides access by external LCA software applications [31]. Its own developed principles for external data import [32,33] comply with the ILCD standards [34,35] and principles that are given within the European standard EN 15804 [36].

3. Which Developments and Challenges Ökobau.dat Has to Face?

To be able to answer the question if and how Ökobau.dat has to change in the future and how other LCA database initiatives could learn from, important past and current developments, as well as challenges for environmental building assessment practice will be shortly outlined in the following. The field of energy-efficiency will lead to changes within the LCA focus. Planning and construction related changes are influenced by building information modeling (BIM). Harmonization and standardization activities in the context of LCA form the framework. Last but not least, methodological challenges within LCA modeling will be addressed.

3.1. Changes in Energy-Efficiency Standards and Importance of Building Construction for LCA

In recent years, progress in energy saving has become clear. The German energy saving regulation in the 1990s required a primary energy demand around 150 kWh per square meter and year for a new built house. Todays' regulations require a yearly average value of less than 50 kWh per square meter. Lighthouse projects, such as zero-heating energy buildings, significantly fall below this value. The so-called plus-energy houses provide even more energy than they need themselves within the building operation phase [37].

Due to these changes in building energy regulations, considerations to minimize the environmental impacts over the entire life cycle of a building will increasingly come to the fore in the future [3–5]. Figure 1 illustrates changes within residential building life cycle assessment by exemplary opposing results for the building operation phase (grey bars) to results for the building construction phase (blue bars).

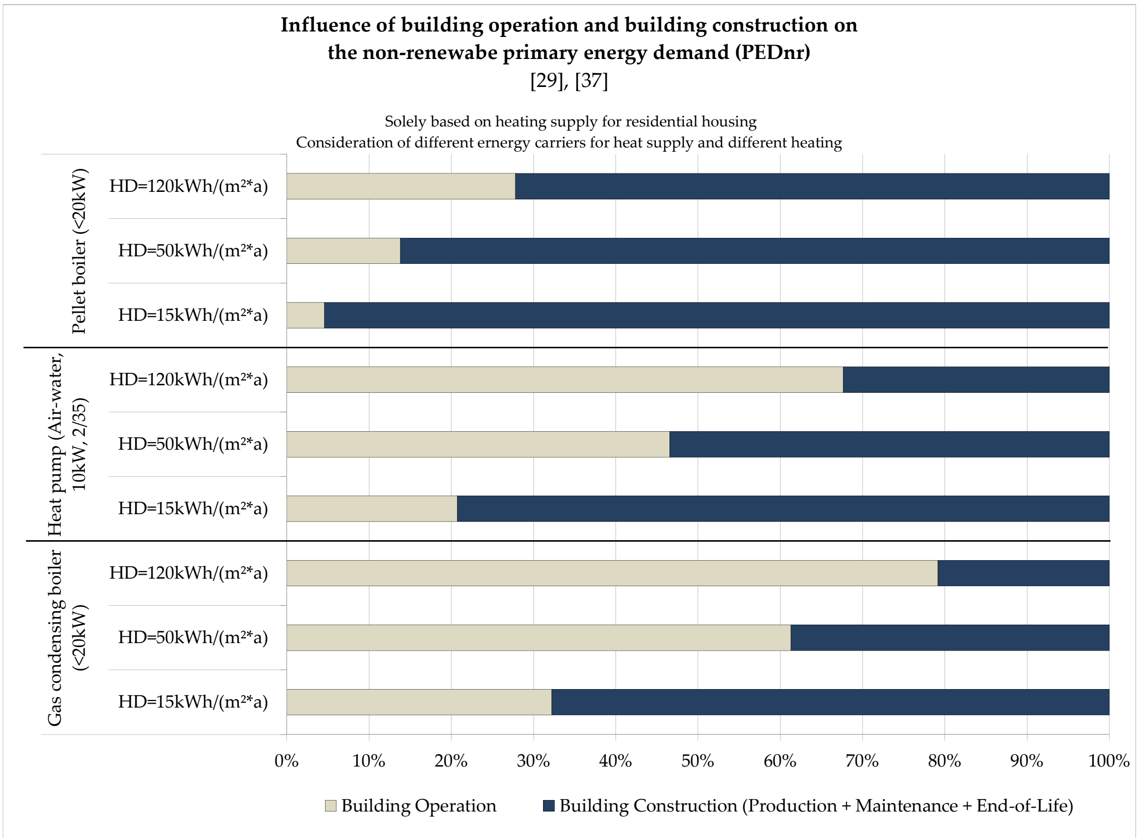

Figure 1. Influence of building operation and building construction on the non-renewable primary energy demand (PEDnr), solely based on heating supply for residential housing, different energy carriers (gas, district heat, wood pellets), and different heating energy demands (own depiction referring to [29,37]).

For the assessment of the building operation phase, different energy carriers and different heating energy demands (HD) have been considered. In the 1990s (see examples given with HD of 120 kWh per square meter and year), environmental impacts of buildings were dominated by the building use phase. This was due to the increased heating energy demand and the common use of non-renewable energy carriers (e.g., gas condensing boiler). Low-energy buildings (see examples given with HD of 50 kWh per square meter and year) or buildings including renewable energy systems (such as heat pumps) have almost balanced impacts between building operation and construction. When considering passive buildings (see examples given with HD of 15 kWh per square meter and year), the influence of the building construction phase on the overall environmental impacts becomes even more important. The same holds true when using exclusively renewable energy carriers for a heating purpose, such as wood pellets. This shift between life cycle phases brings the materials and construction related aspects into focus. As a result, the associated data quality for environmental assessment and the type of data used (generic, specific) will be the crucial factors for making reliable environmental decisions in the future for low-energy or plus-energy houses.

3.2. Environmental Building Assessment on the Way to BIM

The current changes in architectural planning methods towards holistic BIM-based approaches [9,10] are accompanied by challenges and potentials on different levels. On a strategic level, cooperation processes have to be integrated, where the changed methods have to be (newly) organized. On the data level, an adequate, object oriented, and semantic modeling is needed for their realization. This requires a rethinking of the methods and (information) structures that are applied in the context of LCA.

A current German BIM survey [38] indicates clearly the added value of the application of BIM in the context of sustainable building planning like reduced error potentials or enhanced communication and coordination of the project stakeholders. One of the most important motivations for using BIM is the enhancement of efficiency and a better integration of change management [39]. This, in turn, opens up possibilities for a better and more efficient process accompanying application of BIM-based simulation and assessment tools, for instance, a reduced effort for the acquisition of building information as their input data. Current research projects already show the high potentials of BIM-based interfaces for the field of sustainability and energy-efficiency [40,41]. Here, a central starting point lays in the enhancement of process overarching linkages (structural adjustment and interfaces) between these new methods of building modeling and LCA.

An important step towards a better market penetration of the BIM methods in the German building sector and an alignment of the German BIM practice to international developments is the specification and adaption of norms and standards in the context of BIM. The VDI 2552 series "Building Information Modeling (BIM)" of the German Association of Engineers (VDI) represents the national position in the international BIM standardization activities. Besides BIM basics, relevant terms and processes, the norms offer guidelines about data management, requirements for data exchange, model based quantities for cost calculation, tendering, offering and billing, as well as information delivery requirements, BIM Execution Planning, etc. In cooperation with the German DIN committee the German activities are mirrored in the international standardization bodies to the national and international committees.

Having a look at the German BIM practice reveals that the most favored cooperation method is–in contrast to the English-speaking countries–the open BIM approach, which is based on open BIM standards [38].

One important basis of these opened standardization efforts is the harmonization with the international object oriented IFC model standard. The Industry Foundation Classes (IFC) allow for type specific descriptions of buildings, building structures (e.g., topological and spatial structures), building components, as well as according representation of detailed element descriptions, e.g., properties, material information, etc. Since 2013, the IFC have been specified as ISO Standard 16739 [42] and are implemented and certificated in the version 2 × 3 in most commercial CAD and BIM systems [43] in the so-called "Coordination View" [44].

But, what are the relevant aspects of the IFC in the context of LCA? First of all, the object oriented representation of building components in the IFC schema allows for a better mapping on the level of elements, for instance, it enables coarse information during early design phase to be exchanged later in the process with product specific descriptions and declarations.

IFC also supports different approaches to represent information. The properties can be represented explicitly as free or specific property sets. Here, depending on the element type, different predefined property sets are provided as default within IFC. For instance, the property set '*Pset_ThermalLoad Aggregate*' is by default applicable to the IFC entities '*IfcZone*' '*IfcSpatialStructureElement*' and '*IfcSystem*'. The property set contains hereby the single properties '*TotalCoolingLoad*', '*TotalHeatingLoad*', '*LightingDiversity*', '*InfiltrationDiversitySummer*', '*InfiltrationDiversityWinter*', '*ApplianceDiversity*', and '*LoadSafetyFactor*'.

The IFC concept of *IfcMaterialResource* contains the types and classes, which are used to define materials. For the purpose of reuse, materials are defined generically in an IFC model. Hence, relevant classes that represent the building elements reference their materials through an objectified relationship. Also, different material layers can be specified and referenced to a building element in a simplified manner in case its single layers are not represented as standalone entities with their own materials referenced. Thus, with the offered structures, IFC enables material designation for a single material (*IfcMaterial*), a list of materials (without a specified configuration or structure) by *IfcMaterialList*, or a structured set of material layers (*IfcMaterialLayerSetUsage)* [45,46].

Also, measures and quantities can be handled generically in IFC. Here, the concept of *IfcQuantiyResource* defines a set of basic quantities, which can be associated with products by *IfcElementQuantity*. The basic quantities are used to assign quantities, which have a particular meaning within a referenced method of measurement. The IFC concept of *IfcMeasureResource* therefore specifies units and defined measure types that may be assigned to these quantities. The fundamental unit types used in this scheme are based on the SI system defined in ISO 1000+A1, 1992, 1998 [47,48]. Units in measurement systems other than SI may be derived while using this schema. Here, an adjustment to the LCA methods is necessary.

In addition to quantities, the IFC also allows for an implicit representation of properties. This can be done by using the '*IfcClassificationReference*' class to specify references to classification systems and entries, like, for instance, the Uniclass system. On level of materials a specific class '*IfcMaterialClassificationRelationship*' exists to describe the relationship for assigning classifications to materials. By this method, also EPD information could be integrated, respectively, referenced directly out of the IFC model. This approach is examined in an ongoing research project of the authors [49]. Thereby also the question of how to handle IFC-based references in the LCA system is treated.

However, a complete depiction of all LCA relevant information and structures is not yet possible with IFC 2 × 3. Thus, an important mission for research in the context of sustainability is the evaluation and further development of the IFC standard to enable an adequate representation of LCA relevant information. The new IFC 2 × 4 release contains enhancements that are of particular interest in terms of quantities, classifications, and energy, for instance, LCA-relevant property sets. Especially, the property sets '*Pset_EnvironmentalImpactIndicators*' and '*Pset_EnvironmentalImpactValues*' are of interest. The '*Pset_EnvironmentalImpactIndicators*' describes environmental impact indicators, which are related to a given "functional unit" of the ISO 14040 concept [12,13] and can be referenced to a specific type in the project or by 'FunctionalUnitReference' to a database or classification. Thereby, life-cycle phase and expected service life can be managed. The '*Pset_EnvironmentalImpactValues*' describes the accompanying values.

The Sustainable Building Alliance (SBA) elaborated a first mapping aproach from LCA to the new structures of IFC 2 × 4 [50,51] and prepared a collection of relevant properties sets, which can be found in Table S1 in Annex 1.

Besides this aspect of the product model itself, specifications about the methods and processes are important preconditions for the application of BIM. The ISO 29481 [52] defines the IDM (Information Delivery Manual) method, which is used for the specification of process oriented information demands, e.g., in the context of defining IFC-based domain specific Model View Definitions (MVD) [44]. Furthermore, the ISO/TS 12911 [53] (BIM Guideline Template) and context specific BIM guidelines and manuals [10] are important means for the dissemination and harmonization of the BIM method.

Also relevant for the LCA context is the intersection between standardized descriptions of construction work and standardized LCA [51]. With the DIN SPEC 91400 [54] (BIM classification according to the German standard service book for construction (STLB-Bau)) references for catalog information are developed, which bind structured data of both domains uniformly to the established BIM model standard ISO 16739 (IFC 2×4) [42,55]. Also, the new German DIN SPEC 91350 [56] defines a linked BIM data exchange of standardized building models, for instance, of the ISO 16739 (IFC) and cost schedules and cost items of the PAS 1067 GAEB DA XML [57,58].

Despite these first enhancements and potentials of IFC, a consistent support of LCA to BIM integration is not yet possible, because a reliable process oriented analysis of the information demand is still missing. Especially practicable technical interfaces, which are able to map the described data structures, are missing on both sides: BIM-Tools as well as LCA and sustainable building assessment systems.

3.3. Harmonization Activities and Internationalization for Modeling of Building Related Environmental Impacts

One of the main developments that Ökobau.dat has to face are recurring efforts and initiatives for harmonization within building related environmental assessment. Most often, these initiatives do not necessarily lead to official standardization or are not initialized by respective bodies or organizations. The major challenge hereby is always how to combine the different methodological perspectives and how to transfer them into a high-quality and consistent data basis to enable for a comparable building assessment. Following, important initiatives are briefly summarized.

ISO/TC59/SC17–The Technical Committee (TC) 59 and its Sub Committee (SC) 17 of the International Organization for Standardization (ISO) is the international standardization body dealing with activities in the field of sustainability of the built environment in general. Its activities include hereby environmental, economic, and social aspects of sustainability and set the core frame for further development on European level [59].

CEN/TC350–The Technical Committee (TC) 350 of the European Committee for Standardization (CEN) is the main responsible European standardization body for the development of harmonized methods for the assessment of the sustainability aspects within construction works on the building and civil engineering level within different working groups. Its activities include the setup of horizontal core rules for the development of environmental product declaration of construction products (EPD) [60].

The Sustainable Building Alliance (SBA) integrates (mainly) European building certification systems for working on a harmonized building sustainability assessment. In the past, the alliance set up own metrics and piloted them with regard to international feasibility and comparability [61], their linkage to building information modeling (BIM) [50], and construction products manufacturers' e-Catalogues [62].

The ECO Platform is an alliance of different environmental product declaration (EPD) program operators with the goal for transnational mutual recognition of EPD data and consistent, reliant, and transparent environmental building construction product information [63].

Besides, the European Commission enforces efforts for harmonized environmental foot printing for products (PEF) and organizations (OEF), which potentially will lead to additional free available construction LCA data that does not yet meet the standards of the EN 15804 [64]. The European Energy-Efficient Buildings Initiative (EeB Initative) provides for operational guidance on LCA studies with its past project "EeBGuide" [3,65,66]. The SETAC Working Group on LCA, being mainly active in the early 2000′s, dealt with LCA specificities and methodological harmonization within the building and construction sector [67].

The before mentioned Working Group "InData" (see Section 2) brings together EPD program operators, dataset and data base providers, data format developers, and building assessment operators. Apart from the definition of a common standard for the data format, compatibility, and transparency of environmental data is one of the focus areas of this network [30].

On international level, the International Energy Agency (IEA) is to develop harmonized methodology guidelines for life cycle based environmental impacts of buildings within its Energy in Buildings and Communities Program (EBC) and the international research and development project, 'Annex 72: Assessing Life Cycle Related Environmental Impacts Caused by Buildings' [68]. Amongst others, the Annex will analyze building assessment tools, the integration of environmental information, and the requirements for linking with BIM in different planning stages (see also Section 3.2). Furthermore, the IEA EBC Annex 72 will discuss the issues of service life consideration, the inclusion of technological developments, and potential impacts of different aggregation levels for current and future emissions (see also Section 3.4). It also targets the sharing of experiences with the setup and update of respective databases, as well as their development. The present publication, as well as participation of its authors within the IEA EBC Annex 72, may lead to fruitful cooperation and may give valuable hints.

3.4. Uncertainties and Developments within Environmental Modeling for Life Cycle Assessment

Uncertainties within environmental modeling may occur at different stages within life cycle assessment and may affect various aspects [69]. They may have a substantial influence on the overall results, interpreting and final decision making [70].

The number of applied life cycle assessment indicators has steadily increased over the last years. The Ökobau.dat from 2009 offered information on 13 indicators [16] whereas the version from 2016 already included 25 different ones [28]. The environmental core information to be reported will be further enlarged (e.g., definition of additional environmental indicators) with a current revision of the European standard DIN EN 15804 [71]. First of all, uncertainties within the scientific models (characterization and effecting of different substances) of environmental indicators or impact categories are therefore exemplified. The reason why specific impact models for specific environmental indicators may be called "uncertain" is due to their novelty (e.g., UseTox [72] or LANCA [73]) or their continuous development or incorporation of new substances (e.g., ozone depletion potential [74]). As a result, underlying impact models have a diverse degree of maturity or integration within existing LCA software applications, thus complicating the interpretation of LCA outcomes even by experts [75].

Deviations in the definition, the assessment methodology or applied indicators for the renewable primary energy use are also quite common [76]. The system boundaries are either limited only to the energy conversion or set along the entire value chain. Accounting methods for the renewable part of primary energy may include e.g., 100% equivalence between renewable primary energy used and energy produced or may consider physical energy content dependencies (e.g., heat produced from biomass), as well as technical conversion efficiencies (e.g., heat or electricity produced from solar power). Depending on the assessment methodology, a miscalculation may occur when comparing different options for energy production and thus results may be misinterpreted.

Another challenge is the environmental modelling of new building products and construction materials from research activities. In most cases, environmental information for these products is not yet available in corresponding databases. Often there is also a lack of reliable information on the necessary preliminary products, which can only be estimated. In addition, novel manufacturing processes on a laboratory level may need to be scaled to a large-scale industrial application. This leads to respective uncertainties (e.g., scaling of amount of resource or energetic inputs), which must be taken into account with corresponding factors.

Service life considerations and uncertainty in assumed lifetimes are also a challenge within environmental building assessment. Extensive sources are available that prescribe theoretically how to determine the service life of buildings as well as for related constructions and products. In practice, these lifetimes may significantly vary, affecting environmental decision making for or against different building layouts [77,78]. The international ISO 15686 series (especially part 1 and part 8) might serve here as framework, as they define general principles for systematic service life planning in building construction throughout the life-cycle. It provides for guidance on the provision, selection, and formatting of reference service-life data and on the application. Hereby, a factor method is suggested that allows for including different parameters (e.g., exposure conditions) for the purposes of calculating an estimated service life [79,80]. One of the most discussed topics is the integration of future technological developments within decision making from an environmental perspective, as buildings are assumed to last for several decades. These developments mainly relate to changes in energy supply mixes, in efficiencies for on-site energy production or future waste treatment options [78,81].

On the background of before mentioned uncertainties and potential changes, the question also raises, whether and how to handle aggregation of current and future emissions. Discussions relate hereby mainly to the necessity for, or the possibility of, discounting [82].

4. What Ökobau.dat Is Able to Handle Today?

Based on developments and challenges that are mentioned within Section 3, this paragraph will point out the current strengths of the Ökobau.dat. Hereby, it is addressed for what purpose the database is suitable today and what it is already able to handle. The specific analysis of the Ökobau.dat hereby serves as an example also for other database initiatives for LCA data in the building sector.

4.1. Life Cycle Approach and Standardization Conformity

Ökobau.dat is a suitable (German) data basis for calculating the environmental impacts over the entire life cycle of buildings. Information that are provided within the datasets are in line with respective standardization activities (e.g., EN 15804 or EN 15978) [83] as well as conform to the International Reference Life Cycle Data System (ILCD) data format [32]. Environmental impacts are shown for different life cycle stages. This differentiation enables for an analysis of relations or a potential shift of burdens between them on building level. Furthermore, it is up to the end user to choose between 25 different environmental indicators and impact categories to be optimized for the overall building layout. Data are provided free of charge. From a quality perspective, data incorporated are externally verified and undergo a check for plausibility and completeness before release. Basically, Ökobau.dat offers generic datasets and EPD data (Figure 2) [23,32,83,84].

Generic life cycle assessment data (Figure 2) relates to information from publically available statistics and other literature sources. Generic datasets are not verified, but have undergone an internal quality check. They represent estimates under worst-case assumptions by containing a safety margin of 10%, 20%, or 30% for the production phase. Safety margins are not applied on generic data that are provided for the building energy supply, as well as for the End-of-Life phase. Often, environmental credits for material recycling or thermal recovery are considered within the End-of-Life phase. If safety margins would be taken into account, additional credits would be incorrectly included. Generic data are to be used when no specific information is available.

Unlike generic datasets, environmental product declaration (EPD) datasets are based on primary data from manufacturers or groups of manufacturers (associations). Ökobau.dat distinguishes verified EPD data according to DIN EN 15804 that are set up within an EPD program under operation (according to DIN EN ISO 14025 [85]) and that are set up without such a program. They undergo verification by an independent external review. Safety margins of 10% are applied on environmental information provided from cross-industry life cycle assessment studies or when only representative products or sample formulations are declared by several manufacturers. EPD information is divided into product specific and average product information. Furthermore, a distinction is made between data obtained from a single plant or from several plants (Figure 2, 1a to 2b).

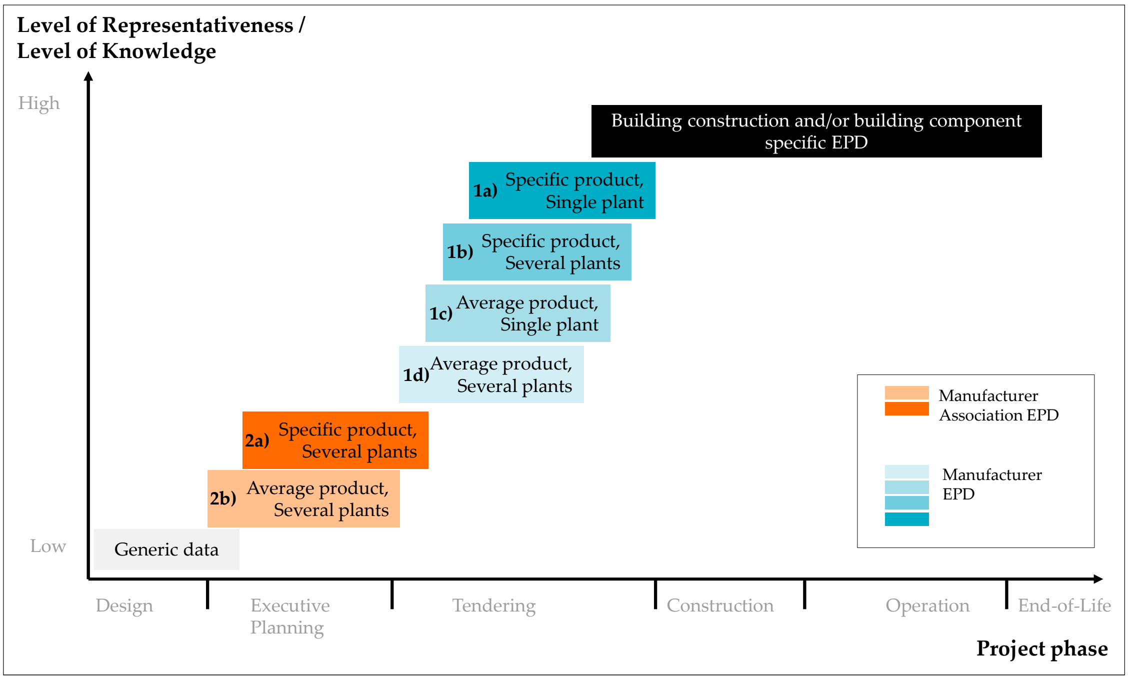

Figure 2. Overview on possible environmental product declaration (EPD) data types and their application for LCA purpose in different project phases.

Figure 2 furthermore maps the types of environmental datasets and their application in different building project phases based on representativeness and uncertainty in informational content [86]. It illustrates when environmental information from the Ökobau.dat might be used to be as precise as possible within environmental assessments. In early project phases (design, planning), generic datasets should be used due to an often very limited level of knowledge. Most important technical data that are present may be the building cubature, an idea of the overall constructional design (glass structure, light-weight, solid) and first energetic calculations (e.g., according to German energy saving regulation (EnEV) for buildings [87]). Within the tendering phase, details on constructional structures are available, even if specific products are not yet known. EPD data from manufacturer associations (2a and 2b) might be used to generate a much more accurate building LCA result. Within the construction phase these associations' information may be exchanged with manufacturer specific or average product information (1a to 1d), as all building products are known after completion. A specific building LCA result, including materials and products as in-built is the consequence. In that way, Ökobau.dat provides for environmental information on different levels (generic, manufacturer association specific, product specific) and enables for building assessment in different project phases even today.

4.2. Use for Estimates and Comparison Purpose on Building Construction Level

Environmental information provided within the Ökobau.dat may be used for comparison purpose of assembled building constructions in the context of the whole building [21]. The results of such an assessment should only be used as an estimate and can give an idea of the environmental advantages and disadvantages of different construction methods. The LCA end user is responsible to ensure that the functional equivalence is given or that the effects of changed functionality (either qualitative or quantitative) are recorded and evaluated in the building context within such a comparison.

As an example, a typical design comparison of two external wall constructions is mentioned. A light-weight timber frame construction shall be opposed to a solid construction in concrete. Even when assuming the same heat transmission coefficients (U-value), both constructions might differ greatly in terms of heat storage capacity, static load-bearing capacity, sound insulation, and other technical properties [88,89]. Depending on the application and framework conditions it has to be investigated which of the before mentioned technical or physical properties are of importance and in which way their changes may affect the environmental or even sustainability assessment on the building level. An increased heat storage capacity can possibly lead to lower heat loads and thus to a lower cooling energy demand. This reduction also influences the environmental impacts within the use phase. An offset between lower environmental impacts within the construction phase and higher environmental impacts within the building operation phase is thus conceivable for the timber frame construction. It is absolutely crucial to know about the influence and dependencies of individual technical properties on the overall LCA results and to take them into account throughout the entire life cycle.

4.3. Digital Readability and Data Networking

Already the first version the Ökobau.dat provided the potential of digital readability through the choice of the machine-readable Extensible Markup Language (XML) as format. In the last years, the XML format of the Ökobau.at has been transferred to an extended version of the ILCD data format provided by the European Commission and thus provides the prerequisites for digital application in the context of LCA databases [90]. However, the Ökobau.dat is not yet registered as node in the Life Cycle Data Network (LCDN), which may be due to the additional information in the Ökobau.dat and thus structural differences to the ILCD format. Through the interface Soda4LCA it is possible for software operators to integrate the data of Ökobau.dat and thus in theory automatically update after a version update. In addition to that, a RESTful advanced programming interface (API) under the GNU Affero General Public license ensures direct and open access for programmers [91].

The decision for the common XML format also facilitates the mapping to the established ifcXML format [92] in the context of BIM (see also Section 3.2). An easier development of interfaces and product neutral converting tools is therefore possible. One example for such an XML-based mapping in the context of sustainable planning is the XSLT-converter that has been developed in the Annex 60 to convert ifcXML4 files into the SimModel XML format, allowing for connecting energy simulation models to IFC based models [40].

4.4. On the Way to Transparent Update Processes and Enhanced Quality in Documentation

Even if there are still shortcomings with regard to the documentation of the Ökobau.dat (see Section 5.2), the transparency and quality for documentation within update processes has improved steadily. Gradually, gaps in dataset information were and still are closed. An example is the partial provision of specific conversion factors, such as the surface weight or the density to allow for a correct application of environmental information depending on the declared unit. In the past, end users always faced difficulties in converting correctly the environmental information (e.g., between volume and weight), as these additional information was missing.

Some of the improvements since the year 2013 are summarized within Table 1. These improvements relate to the documentation of the update process or the informational content of single datasets. In addition, the table indicates to what extent this improvement has been relevant as well as necessary to enhance transparency and quality in documentation.

Table 1. Examples for previous improvements to enhance transparency and quality in documentation.

Example for Previous Improvements	Relevance A = High B = Medium C = Low	Degree of Implementation A = Full B = Partial C = Insufficient
Set up and update of a guidance document on the principles for the acceptance of environmental data within the Ökobau.dat [32]	A	A
External pre-verification of the LCA background modeling database GaBi [93] for use of generic and EPD dataset production as well as a simplified update [94]	A	A
More detailed specification of LCA relevant adaptions within the modeling (WHAT and WHICH dataset) since 2017, e.g., according to actual requirements such as changes in product category rules or according to changes in the general energy supply chain [95]	A	B
Inclusion of conversion factors for single datasets, e.g., weight per declared unit	A	B
Provision of explanatory information for interim updates since 2017 (e.g., news stream when updating single datasets)	A	B
Provision of explanatory documents for annual updates, e.g., reports or website information	A	C
Disclosure of data sources for LCA modeling, including their year of reference within each dataset	B	C

5. Current Shortcomings within Ökobau.dat

Despite the great success story of building life cycle assessment and in particular of the Ökobau.dat itself in Germany, there are shortcomings and limitations that turned out in practice. They can be differentiated into the areas "end user application", "content", "modeling and automation", as well as "update process". All four areas of shortcomings show strong interdependencies, e.g., data information related shortcomings are often the reason for a wrong application of Ökobau.dat data and the interpretation of LCA results.

Examples on shortcomings with a high prioritization ("A") and occurrence ("A" or "B") are highlighted in light grey. They are explained in detail within the Sections 5.1–5.4. Examples on shortcomings with a low prioritization ("B" or "C") and occurrence ("C") are presented within Annex 2 of this publication.

A short tabular overview is given at the beginning of each of the following paragraphs. The tabular overview outlines examples for limitations within each area and a qualitative prioritization that indicate the need for the development of a solution (e.g., a high prioritization leads to a high need for solution). Furthermore, a qualitative estimate on the frequency of occurrence for the examples of limitation is given based on the feedback of LCA practitioners. The characteristic "general" hereby indicates a limitation that is present in general within the Ökobau.dat but cannot be expressed in numbers.

5.1. End User Application Related Shortcomings

End user application related shortcomings (Table 2) of the Ökobau.dat do not represent deficiencies of the database itself. They become apparent by end users due to a lack of understanding for life cycle assessment and the limitations when utilizing Ökobau.dat datasets. Nevertheless, it is necessary for any further development to not ignore these application errors. Many of these can be avoided by creating appropriate structuring of the LCA datasets, appropriate documentation or assistance in a software application.

Table 2. End user related shortcoming–Examples and their prioritization for solution-oriented handling.

Examples (End User Related Shortcomings)	Prioritization A = High B = Medium C = Low	Occurrence A = General B = Frequent C = Rare
Incorrect linking of life cycle inventory data with environmental information of the use phase	A	A
Incorrect comparison on material level	A	B
Application of inappropriate End-of-Life scenarios on material level	B	B
Incorrect application of generic and EPD datasets	B	B
Wrong interpretation of LCA results on building level	C	B
Application of inappropriate useful service lives on material level	C	C

5.1.1. Incorrect Linking of Life Cycle Inventory Data with Environmental Information of the Use Phase

A prominent example for an incorrect linking of life cycle inventory data with environmental information of the use phase is the assessment of the building heat supply. Ökobau.dat provides for different environmental profiles for the assessment of the building heat supply [29].

On the one hand, environmental profiles are available on the basis of specific German energy regulations (EnEV) for buildings. These profiles are determined in correlation with the calculation of the final energy demand according to the national standard DIN V 18599 [96]. The national standard describes the final energy demand as the amount of energy that is supplied to the building energy generating equipment at the intersection of the building envelope. It also includes the amount of necessary auxiliary energy, e.g., electricity for a pump. The national standard determines further, that e.g., heating boiler efficiency factors for combustion of fossil fuels shall be also considered while calculating the final energy demand. Therefore, environmental profiles of the Ökobau.dat with the suffix "according to EnEV" do not consider these efficiency factors nor do they include environmental impacts due to auxiliary energy for the operation of the equipment itself.

On the other hand, environmental profiles are provided on the basis of a generic, average heat supply, including pre-defined heating boiler efficiency factors and auxiliary energy. When coupling now, the final heating energy demand according to the national regulations with the generic heat supply data of the Ökobau.dat, an error occurs, as the heating efficiency factors or auxiliary energy are accounted for twice.

The use of the existing heat pump datasets of the Ökobau.dat represents another example for an incorrect linking. The environmental impacts within the heat pump datasets are scaled to 1 kWh of thermal energy provided by the equipment and consider a pre-defined annual coefficient of performance (COP). Some LCA practitioners now link the final energy demand according to the German national regulation EnEV incorrectly with the impacts that are provided per thermal energy. To use the data in a correct way, the calculated thermal energy provided and the pre-defined COP of the heat pump according to the national regulation EnEV would have to be corrected using the pre-defined COP of the heat pump dataset according to Ökobau.dat. Another possibility would be to link the final energy demand according to the national regulation EnEV (which represent the amount of electricity necessary for providing a specific amount of thermal energy) with the dataset for the electricity grid mix of Germany. But, even if LCA practitioners do so, they often forget to account manually for additional renewable primary energy by the help of the annual COP according to the national regulation EnEV.

5.1.2. Incorrect Comparison on Material Level

Even if current principles for the acceptance of LCA data within the Ökobau.dat state that data shall not be used for the creation of product life cycle assessment studies [21], many end users apply the environmental information for incorrect material or construction product comparison purpose. Data provided within the Ökobau.dat do not meet the requirements of comparative life cycle assessment studies according to ISO 14044/14040 [12,13]. Differing system boundaries, cut-off criteria and allocation procedures, as well as applied safety margins, are only a few reasons for not complying with the ISO standards, even when using EPD data. According to requirements made in DIN EN 15804 [21] and DIN EN 15978 [97] comparisons shall only be carried out in the context of the building. Comparisons shall further consider the same functional equivalents and shall be based on environmental information that is provided according to DIN EN 15804.

5.2. Content Related Shortcomings

Besides application errors with environmental data of the Ökobau.dat, there is also potential for improvement in the informational content of the datasets themselves. Content related shortcomings of the Ökobau.dat (Table 3) show strong interdependencies with the before mentioned end user related shortcomings. They are often the reason for a wrong application and interpretation of LCA results.

Table 3. Content related shortcoming–Examples and their prioritization for solution-oriented handling.

Examples (Content Related Shortcomings)	Prioritization A = High B = Medium C = Low	Occurrence A = General B = Frequent C = Rare
Insufficient, inconsistent, incorrect or confusing documentation on:		
• The declared unit, reference flow or functional unit	A	B
• The use of datasets with reference "according to EnEV" and without	A	B
• The calculation rules for determining average values for the foreground system	A	C
• Allocation rules	B	B
• Consideration of uncertainty	B	B
• Technical fore- and background system description	B	B
• The independent external review	B	B
• The transport losses for energy use data free ex-consumer	B	C
• Naming/nomenclature	B	C
• The completeness of the LCA product model	C	A
• The traceability of the dataset subtype (category A and B according to [32]	C	B
Inclusion of technological advances during update for:		
• The background energy system in general	A	A
• Specific foreground production processes	A	B
Incompleteness of data basis–Missing datasets for:		
• Generic building construction products	A	A
• Technical building equipment	A	A
• The non-energy use phase	B	A
• Life cycle module A4	C	A

5.2.1. Insufficient, Inconsistent, Incorrect or Confusing Documentation

Even if the quality of documentation has improved (see Section 4.4) in the last years, there are still shortcomings that lead to a lack of transparency. These shortcomings concern, in particular, the information that are provided by the datasets themselves.

- The declared unit, reference flow or functional unit: The energy use phase data for heating reference to the functional unit (declared unit or reference flow) of 1 kWh of thermal energy provided by the service equipment (e.g., heat pump, gas condensing boiler after combusting, district heating station, etc.). This is the case for the generic, average energy use phase datasets and the specific datasets provided according to the German national regulation EnEV. The German building sustainability assessment system requires coupling fitting environmental profiles with the final energy demand, according to EnEV. The final energy demand according to EnEV relates to the energy amount BEFORE the service equipment (see also Section 5.1). The question raises whether the Ökobau.dat datasets for the energy use phase according to EnEV are incorrectly documented or whether the datasets should be better and appropriately linked with other energy amounts. Unfortunately, it is not plausible if the functional unit is documented incorrectly or if it relates indeed to final energy demand calculations in accordance with the national EnEV regulation. In the case that the functional unit does not relate to the final energy demand calculation according to the national regulation EnEV, an appropriate linking is only possible when coupling the environmental profile of the datasets with the useful energy demand according to EnEV (including additional losses for delivery, distribution and storage between service equipment and the single room).

- Use of datasets with reference "according to EnEV" and without: Information is missing on how to use correctly the generic, average datasets for the energy use phase and the specific datasets provided according to the national regulation EnEV. It is hereby of importance to give advice for the end user what information (e.g., specific factors/values of the energetic calculations) has to be mapped to the environmental profile to allow for an accurate assessment of the building operation phase.

5.2.2. Inclusion of Technological Advances

The documentation, if technological advances for generic datasets have been considered within the update processes are of importance. This is especially crucial for products that are subject to significant technological and, in some cases, geographical changes (e.g., due to shifting of production locations). The technological changes may relate either to the background system (e.g., advances in the general energy system of Germany) or to the foreground system (e.g., advances in the development of product specific technologies).

An example for a technological advance in the foreground system constitutes the field of photovoltaics (PV). Technologies for the production of PV modules, their efficiency rates and the production location have changed significantly in recent years [98–100]. This has a drastic effect on the corresponding datasets and their environmental impacts. The current photovoltaic (PV) datasets (as mixture of different PV technologies) of the Ökobau.dat seem not to reflect previous changes.

An example, for technological advances in the background system is the German energy grid mix. The German energy transition with increasing shares of electricity from wind and photovoltaics has relevant impacts on the operation of thermal power plants and their environmental profiles. Thermal power plants are operated in a fluctuating manner, which leads to varying power plant efficiencies, emissions, and operation times [101]. Additionally, the power plant fleet is changing over the years that result in increasing efficiencies and decreasing emissions. For both reasons, it is important not only to update the electricity mix but also to constantly update the efficiencies and emission factors for all energy carriers. These updates need to be transparently documented. From the current documentation for revisions of the Ökobau.dat 2017 [95], this information seems not to be included.

5.2.3. Incompleteness of Data Basis

With regard to data availability Ökobau.dat lacks some important environmental information.

- Generic building construction products: Generic datasets for individual construction product categories are sometimes missing. For example, important synthetic floor coverings such as carpets and PVC flooring are not available in Ökobau.dat 2017. The database in 2017 only contains some EPD data on carpet tiles and rubber floorings, as well as one generic dataset for linoleum flooring. Synthetic floorings are estimated with a useful service life between 10 to 40 years [17,77]. Assuming a building assessment horizon with around 50 years, synthetic floorings have to be exchanged between two to four times. With regard to repair and their large amount of surface area covered, even simple floorings may play a role within low-energy environmental building assessment.
- Technical building equipment: In addition to the lack of generic LCA datasets, EPD datasets for the technical building equipment are also missing. Currently, there is only the possibility

for users to calculate the use phase of the building based on generic use datasets. Project- and product-specific adaptations with e.g., the efficiency of the equipment in according with national energy calculations according to EnEV do not take place in this way.

5.3. Modeling and Automation Related Shortcomings

The most important shortcomings of the Ökobau.dat do relate to modeling and automation. Especially within the past, noticeable but suspicious results have been detected when using the generic datasets provided by the Ökobau.dat. Other critical remarks within this paragraph relate to the ability for automation of the Ökobau.dat and each single dataset that is provided. Table 4 provides for examples on modeling and automation related shortcomings.

Table 4. Modeling and automation related shortcomings–Examples and their prioritization for solution-oriented handling.

Example (Modeling and Automation Shortcomings)	Prioritization A = High B = Medium C = Low	Occurrence A = General B = Frequent C = Rare
Lack of uniform structuring or material classification	A	A
Modeling of:		
• Heat pump datasets	A	A
• Solar thermal energy datasets and photovoltaics (PV)	A	A
• Air-ventilation system datasets	A	B
• Energy use datasets according to EnEV	A	B
• Life-cycle module C and D	A	B/C
Use of inconsistent definitions with regard to:		
• Impact-free waste products	A	C
Major changes in modeling between Ökobau.dat version 1.0 to 2.0 with regard to:		
• Allocation rules	A	C
Partial lack of updateability	B	A
Very simplified methodology to derive safety surcharges	C	A

5.3.1. Lack of Uniform Structuring or Material Classification

One of the main shortcomings with regard to automation is the lack of a uniform structure or use of a uniform material classification. The current structure of the Ökobau.dat allows for a first rough material classification [102], but a multitude of construction products can only be integrated into the current structure with difficulty. In addition, the lack of material classification is a major obstacle to automated connection with building information modeling (BIM) data. Examples for a weak classification and hierarchy within the Ökobau.dat are given below:

- 8. Building service equipment/8.3 Sanitary service equipment/8.3.01 sanitary ceramics;
- 9. Others/9.2 Energy carriers free ex-consumer/9.2.05 Electricity/PV system(s); or,
- 100.End-of-Life/100.1 Generic/100.1.08 Building service equipment/End-of-Life–Stoneware pipe.

5.3.2. Modeling of Heat Pump Datasets

The heat pump manufacturing datasets include not only the heat pump itself, but also additional components, such as the heating circuit (including the buffer storage tank), electronics, as well as an expansion tank. An example is the dataset "Electricity heat pump (brine-water, earth collector) 10 kW". The heat transfer circuit (earth collector and piping) is declared in a separate dataset. Even if DIN

EN 15804 allows for the declaration of environmental impacts for assembled building construction products, detailed, project-specific mapping of the single system technologies is not possible. In the past, all three main elements (heat pump, transfer circuit, heating circuit) had been modelled in one single dataset, making it impossible for end users to account for maintenance and exchange during the building operation phase. Furthermore, these datasets do not seem to reflect current technological designs, as internal environmental estimations for this technology by the authors have shown strong differences within the environmental profile for manufacturing. One reason may be the material mix that is considered for metal components. An internal, unpublished survey at heat pump manufacturers indicated a mix of copper and stainless steel for present technologies. This material mix seems not to be represented by the present Ökobau.dat datasets.

5.3.3. Modeling of Solar Thermal Energy Datasets and Photovoltaics (PV)

The datasets for solar thermal energy and photovoltaics are given by square meter collector area. This complicates to use the datasets and to project-specific adapt them by the end user. Especially, adaptions within the use phase due to realistic decrease in module efficiency (that are currently assumed to be fixed) over lifetime are not possible. Furthermore, solar radiation is not adjustable, but fixed, which also influences the energy production.

5.3.4. Modeling of Air-Ventilation Systems Datasets

The generic datasets for the central air ventilation systems without heat recovery only represent a cooling fan. They seem not to be technological representative. Their weights range from 43 kg to 68 kg and seem not to represent the units themselves. The generic datasets for the central ventilation systems with heat recovery document a weight, approximately 10 times higher than the ventilation systems without. However, a comparison with current devices available on the market (internal unpublished information provided by manufacturers to the authors) still seems to indicate a weight that is too low. Another weak point is the use of different reference flows in the generic datasets for air ventilation and the generic dataset for an air conditioner with direct evaporation. The environmental profile for the generic air-conditioner relates to 1 kW of performance. The environmental profiles for the air ventilation systems do relate to one piece of air ventilation unit and it may not be scaled to a specific weight or performance.

5.3.5. Modeling of Energy Use Datasets According to EnEV

With regard to the energy use datasets according to EnEV, the question raises why the datasets reference to 1 kWh of thermal energy provided by the building service equipment if in contrast thermal energy values that were provided by the EnEV do relate to the energy amount entering on the input side of the service equipment. Here, a mismatch is found leading to errors in applying the datasets by end users and leading to errors in the overall building LCA result. A correct application of the datasets is almost impossible, if LCA and EnEV background knowledge is missing by end users.

5.4. Update Process

Up to now, the update processes of the Ökobau.dat database are cumbersome and difficult due to different factors. Significant improvements to data quality do not come about because of the lack of setting priorities on strategic level, which furthermore adds to the problematic situation of missing financial and time budgets. Standardized processes or activities for documentation are at the very beginning and have been initialized only in the year 2016. Still, loss of information or the retrieval of methodological artifacts is one of the main challenges during the whole process. Table 5 summarizes these shortcomings within the update process.

Table 5. Update process related shortcomings–Examples and their prioritization for solution-oriented handling.

Example (Update Process Related Shortcomings)	Prioritization A = High B = Medium C = Low	Occurrence A = General B = Frequent C = Rare
Lack of prioritization	A	A
Missing financial or time budgets	A	A
Missing standardized processes or activities for documentation	A	A
Dependency on the quality of specific background databases, e.g., GaBi database	B	A
Loss of information	B	B
Retrieval of methodological artifacts	B	B

As of June 2018, the last documentation available on update processes before the year 2017 references to the year 2013 [20,23,83,95,103]. In the meantime, the Ökobau.dat was updated at least two times more within the years 2015 and 2016. However, a transparent and plausible documentation is only provided again for the year 2017 [95,103]. Furthermore, the reports and documents for the update process show inconsistencies. Whereas, in the year 2013, applied security margins for generic datasets have been provided, the documentation of the year 2017 does not. On the other hand, the documentation within the year 2017 gives more specific insights into LCA relevant adaptions within the modeling as compared to the documentation within the year 2013. The documentation tries to focus more on what has changed within the single datasets and not only on which datasets have been affected.

Nowadays, the database has become one of the most popular open sources on LCA data for building construction in Germany. So, their providers enforced transparency in the update and documentation process with respective background documents [20,32]. Nevertheless, the database and its fore- and background models, as well as a lot of EPD information contained therein, are mostly relying on the industry-related LCA expert database GaBi [94,104]. Changes in methodological background processes of the GaBi database may lead to the necessary updates in the Ökobau.dat itself. The better documented these changes are and the better replicable, the more plausible are changes in data for potential end users.

6. Suggestions and Solutions for a Viable and Future-Oriented Ökobau.dat

The following paragraph proposes solutions and describes suggestions on how to handle specific shortcomings and limitations discussed. Table 6 summarizes proposed suggestions for solutions, as well as their implementation-oriented prioritization and maps solutions to area of shortcomings addressed within Section 5.

In order to exploit the great potential of building LCAs that may be facilitated through Ökobau.dat, the challenges and shortcomings that are mentioned above must be solved. As Ökobau.dat is a complex multi-stakeholder project, solution to address the abovementioned shortcomings must be shown in dialogue with relevant stakeholders and experts. Therefore, the following points merely represent initial ideas that need to be discussed, rejected, or further developed with other participants.

Table 6. Solution catalogue, implementation-oriented prioritization and mapping to area of shortcomings.

Improvement in …	Suggested Solution Approach	Prioritization A = Short-Term B = Medium C = Low	Area of Deficit Addressed
Consistency	Provision of appropriate functional units (reference flows) and system boundaries according to the energy related use phase models	A	End user application
	Revision of the structure of Ökobau.dat	B	Modeling and automation
	Set up and publication of appropriate Ökobau.dat "Developers Guideline and quality assurance process"	B	Update process
Comprehensiveness	Implement top-down approach to investigate completeness of data based on existing nomenclatures	A	Content
	Extension with an appropriate material classification	A	Content
	Integration of non-manufacturer EPDs	B	Content
	Integration of additional generic datasets	B	Content
	Integration of building service equipment EPD	B	Content
	Integration of datasets for the non-energy use phase	B	Content
Applicability	Introduction of fixed GUIDs for datasets	A	Update process
	Provision of user guide including best practice case studies for different applications	A	End user application
Scientific basis	Revision of the definition and modeling of modules C and D	B	Modeling
	Integration of standardized useful service life according to ISO15686 [79,80] in Ökobau.dat	B	Content
	Use of automatic EPD cores	B	Modeling
	Use of a scientifically verified safety margin	C	Modeling

6.1. Consistency

6.1.1. Provision of Appropriate Functional Units (Reference Flows) and System Boundaries According to the Energy Related Use Phase Models

The inappropriate provision of reference flows especially for the use phase has been shown with regard to several fundamental issues and sources of inconsistent modeling. To adequately address the inconsistencies arising through coupling of energy models, such as EnEV or DIN V 18599, the data sets of Ökobau.dat have to be either defined accordingly (as partly applied through the implementation of "EnEV" datasets) or supplemented by an approved cross calculation metric. This would allow for mapping the datasets and scaling them in a transparent, comparable approach. In addition to that, the existing nonphysical reference flows should be at least complemented by additional machine readable information on their physical quantity (either mass or energy content). In addition to the appropriate reference flow choice of single data sets, they should be harmonized between themselves as well. This especially applies to the existing data set types, which should be fully consistent in terms of their reference flow and their system boundaries applied.

6.1.2. Revision of the Structure of Ökobau.dat

An important point is to develop a structuring and hierarchy of the LCA data sets. According to the contained uncertainty and the type of LCA data set (generic, manufacturer EPD, association EPD), the use of the data sets at different points in time should be consistently represented. Furthermore, the existing Ökobau.dat structure is ambiguous, and it does not represent the already existing classification schemes in building digitalization. Thus the authors suggest revising the content related structure and creating a structure based on dataset types, complemented by an approved classification scheme [105,106]. The resulting matrix would allow for fully digital accompanying of the building construction phases, as already described in Figure 2. However, this ideal can only be implemented in very few cases due to the limited amount of data addressed. In practice, therefore, due to missing generic data sets (see "missing data sets" below), a similar EPD data set from another manufacturer is often used. However, this is not permitted. As a practical solution, a general mass surcharge of 20% would be conceivable in the absence of a generic data set and the use of an unsuitable EPD.

Overall, a kind of mapping system as structured in Figure 3 should be created that assigns a manufacturer EPD to each building EPD, a manufacturer group (association) EPD or a generic data set, if available. This would make it much easier and more detailed to draw up building LCA at different planning stages. It should be considered whether the actual spread of input data for manufacturer group (association) EPDs and manufacturer EPDs will be addressed in the future and whether the uncertainty contained in the data will also be reported instead of the mean value of the data. These reported uncertainties could be included in the calculation of life cycle assessments, target achievement corridors, and the likelihood of target achievement calculated. This would greatly improve the certainty of achieving sustainability certification targets.

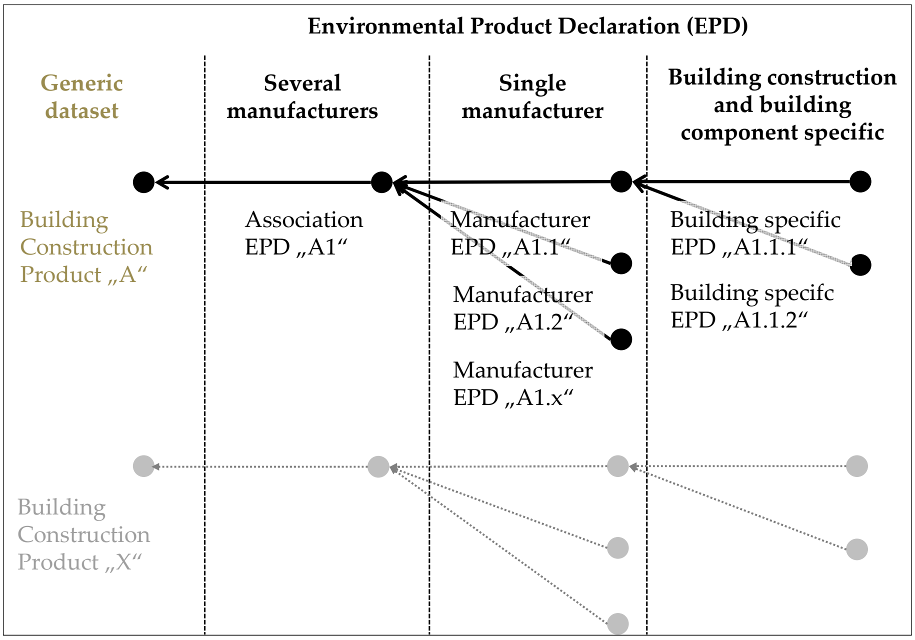

Figure 3. Structural approach to map life cycle assessment (LCA) data set types, ensuring the appropriate utilization and exchangeability of generic and specific data.

6.1.3. Set up and Publication of Appropriate Ökobau.dat "Developers Guideline and Quality Assurance Process"

To overcome the still existing inconsistencies within Ökobau.dat, the authors proclaim a transparency strategy in line with the general guidelines of the BBSR. This is seen as one of the main requirements for Ökobau.dat to provide stable, transparent, and reliable LCA data and thus facilitate its streamlining. The following aspects may be covered by such a guideline:

- transparent provision of requirements to the versioning of the Ökobau.dat, including a comprehensive update log to prevent misleading interpretations of the database;
- database design, including data handling, interfaces, processing, reporting, and documentation;
- data management, including a statement on long-term support, archiving procedures and ongoing data evaluation and quality management; and
- specification on data ownership, declaration on neutrality with regard to database application.

6.2. Comprehensiveness

6.2.1. Implement Top-Down Approach to Investigate Completeness of Data Based on Existing Nomenclatures

A targeted approach based on existing and applied nomenclature is suggested to close data gaps comprehensively cover the data required for building LCA practitioners. The approach should aim covering all the relevant materials, components, and processes with generic data, but also identify gaps in the provision of other LCA data types that are available. To align the approach with the digitalization efforts, it is recommended to utilize a standardized nomenclature in consistency with IFC, such as DIN SPEC 91400 [42,54].

6.2.2. Extension with an Appropriate Material Classification

A further extension with regard to the digitalization of LCA would be not only to automate the creation of EPDs and their integration into Ökobau.dat, but also to facilitate the use of the LCA data in other programs. Integration into BIM or the link to BIM would greatly simplify the workload and thus contribute greatly to the dissemination of the building LCA. By using the described mechanisms (see Section 3.2) an unique material and product classification, a link to the Ökobau.dat, IBU database or manufacturer catalogues could be stored in BIM as an external reference and thus a unique assignment of a building material or product to its environmental profile could be provided. This would eliminate the time that is required to create a component catalog (including the layer structures and materials used) which could contribute to considerable savings in personnel and financial resources and strongly improve the consistency of data choices. To achieve this, however, a material classification must be developed that is adjustable to the existing methods for element and product specifications in IFC [54]. To put this into practice, the LCA tools must be enabled to handle and interpret such an external reference and classification. In the research project BIM2LCA4IP (BIM-based integral planning) [49], the first steps are being taken together with various stakeholders from the LCA and BIM domain and the worlds of "BIM" and "integral planning" are being linked to life cycle assessment.

6.2.3. Integration of Non-Manufacturer EPD

As there are still discussions ongoing on how to fill the gap between specific product EPDs on the basis of the narrow interpretation of EN 15804 by program operators and an ideal-typically building EPD. Here, the Ökobau.dat may take over a pioneering role and close the gap between building and product assessment by providing also for EPD information on complex products (Figure 4).

6.2.4. Integration of Additional Generic Datasets

With regard to the shortcoming of updatability and the potential for especially missing EPD datasets between different update versions of the Ökobau.dat, it is advisable to integrate further generic datasets. Enhanced with a quality check if still main building products are available or a check on how to provide for temporary solutions (e.g., provide a generic dataset because an EPD dataset is no longer available) should be carried out.

6.2.5. Integration of Building Service Equipment EPD

The integration of building service equipment EPDs into Ökobau.dat would bring decisive added value for project-specific building life cycle assessment. For this purpose, manufacturers of service providing equipment must be won who are willing to gain experience and to provide data as pioneers in their industry.

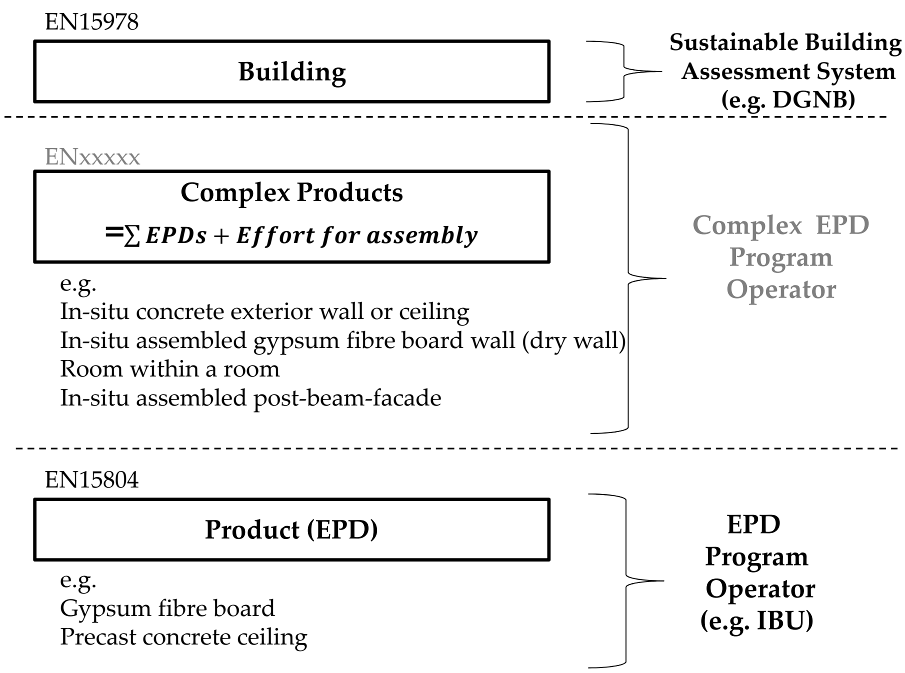

Figure 4. Current framework of standards with regard to the different levels of EPD data, depicting the gap between product EPDs and building EPD.

6.2.6. Integration of Datasets for the Non-Energy Use Phase

The integration of non-manufacturer EPDs would also provide enormous added value for the life cycle modules B2 (maintenance), B3 (repair), B4 (replacement), and B5 (refurbishment), according to DIN EN 15804 [21]. This information becomes increasingly important on the background of specific sustainable building assessment systems for the building operation, current certification activities of the German Facility Management Association (GEFMA) [107], as well as current sustainability facility management research [108].

6.3. Applicability

6.3.1. Introduction of Fixed GUIDs for Datasets

The currently applied practice of reassigned GUIDs for each version of the Ökobau.dat prevents an automatic updating process through practitioners. The data sets have to be matched through their name, which is more likely to cause inconsistencies. However, to provide a versioning of the database, the fixed GUIDs should be complemented through a versioning number.

6.3.2. Provision of User Guide, Including Best Practice Case Studies for Different Applications

To reduce misunderstandings in Ökobau.dat applications, a user guide is proposed. Within this guide a differentiation of the standard application contexts could be provided, including best practice examples and guidance on how to apply the different LCA data types within different phases of the assessment.

6.4. Scientific Basis

6.4.1. Revision of the Definition and Modeling of Modules C and D

With regard to the modeling of scenarios for repair and End-of-Life, it will be interesting to review the results of the research project "Resource-saving structures–EPD for construction products: deconstruction and recycling information (modules C and D), as well as "pollutant information" [109].

Overall, the use of time-dynamic life cycle assessment models could be considered. This would also make it possible to consider various energy sources with regard to future developments (pellets vs. electric heat pump), and thus avoid possible disinvestments (under a presumed useful life of the system technology of approx. 20 years). Due to this fact and the uncertainty of the underlying scenarios, the BBSR has decided in the NBB evaluation system not to consider the credits (module D) at all. At first glance, this seems to be the right thing to do, but it comes along with new problems. On the one hand, it is no longer possible to reasonably represent recycling and circular added value, on the other hand, the current modeling practice needs the Ökobau.dat module D to be able to make self-contained statements.

6.4.2. Integration of Standardized Useful Service Life According to ISO 15686 in Ökobau.dat

The utilization of standardized, transparent useful service life specifications are inevitable for broad scale application both with regard to automation and to regulatory framework integration. The authors propose to therefore apply the existing ISO°15686 series, and more specifically the factor method described in ISO°15686-8 [80]. This requires the provision of a matching list for different application contexts such as material level, component level in different applications that should meet the same requirements as the Ökobau.dat itself with regards to updateability and readability.

6.4.3. Use of a Scientifically Verified Safety Margin

The safety margin applied within Ökobau.dat is so far not based on a statistical basis or using statistical methods such as error propagation. It seems to be solely based on the qualitative classification of the ILCD handbook with regard to the completeness of the product system and its technological, temporally, and geographical representativeness [83]. The safety margin is used for all environmental impacts, without gradation. This issue may be seen as a minor point but gains major importance if future decisions and legal requirements are based on LCA results. Questions like “How different do options do have to be in order to be really different?” are crucial. Based on the safety margins so far within the life cycle phase production, the results need at least to have to differ in magnitude between 10 to 30% depending on the used generic and EPD data. There is already some work available regarding uncertainty quantification in LCA [110,111]. In order to allow for a more scientifically sound and still applicable safety margin, the authors propose a provision of a range of the main important parameters of the foreground model (e.g., electricity consumption of minimum 2 kWh/product, mean 3 kWh/product, maximum 4 kWh/product), and Monte Carlo simulation of this parameters in order to provide a range of possible outcomes.

6.4.4. Use of Automatic EPD Cores

All of the abovementioned improvements would increase the effort considerably if EPD creation were to continue as before. For this reason, an automatic EPD creation via a calculation kernel certified by the German EPD program operator IBU is being considered. Based on these EPD cores, manufacturer group, manufacturer, and building EPDs are automatically created in connection with data from project lifecycle management systems (PLM), depending on requirements. An annual update of the EPDs would also be conceivable and the effort would be manageable. The input of building-specific data can be done via a web interface directly at the respective company. Thus, this is not a complete innovation, but serves as a supplement to existing product catalogs and is only a first step towards a complete, digital product catalog or data-on-demand.

7. Discussion

All of the mentioned issues above should be seen as a discussion basis to improve the German Ökobau.dat and maybe to support others that are currently setting up their own country specific LCA construction databases. For this reason, it may be necessary to transfer the specific analysis that is presented within this publication into a common valid methodology, determining also relevant boundary conditions with regard to building construction LCA. Such methodology could enable for a comparison of LCA building construction material databases in the international context, which has not been focus of the present publication.

One could also wonder if the publication may give an answer to the question: Should we "refurbish" the current version of the Ökobau.dat or "rebuild" it from scratch? Indeed, the results of the analysis provide for following suggestion: A list of requirements and qualities would have to be set up that the Ökobau.dat has to fulfill today and in future. Some of the issues are already raised within this publication. Nevertheless, suggestions and requirements that are made within this publication shall be seen as first list from the viewpoint of LCA research. The list does not claim to provide for final or entire solutions. The following points have to be addressed in more detail within future and with regard to setting up a profound list of developments:

- requirements (End user, software tool developers, BBSR, etc.);
- external factors (standardization activity, digitalization in construction sector); and,
- internal factors (strategical objectives, financial resources, embedment in other activities).

A workshop with interested bodies and expert would be beneficial to clarify the objectives of the different stakeholders and develop a roadmap of improvements that is necessary to achieve a more consistent, transparent and quality assured Ökobau.dat that is fit for the digitalization of the construction industry. Based on this analysis and object statement in the end, an evaluation can be done as to whether the current Ökobau.dat should be "refurbished" or "newly built".

Another question that is often raised is: Can we not just use EPD specific datasets? There is no common answer to this question. As mentioned, the Ökobau.dat was developed to trigger the need for product specific EPDs. Replacing generic data by numerous EPD once was the original idea behind, thus making the generic database obsolete itself. This stage is still not reached, as product specific or association specific EPD information for a statistically sufficient number of construction products are still unavailable. The upcoming European product environmental footprint (PEF) and current standardization activities could increase the pressure to publish LCA based information. In addition, while using the provided LCA average datasets in early planning and design stages offers high value. As the data basis on EPD is still too small to use them for the calculation of averages, there is a need for generic data based on values from literature. To substitute these generic averages with specific EPD averages in the future seems to be necessary for reliability of LCA results in early planning phases.

In general Ökobau.dat is very well positioned in terms of interface and server infrastructure. This is an elementary prerequisite for the successful implementation in a digital LCA environment. This requirement enables Ökobau.dat in principle to overcome the challenges presented in the publication. From the authors' point of view, the necessary adjustments that are described here are core elements of these adjustments, but they are neither exhaustive nor exclusive.

8. Summary and Outlook

The present publication provides for a critical review on the German construction database Ökobau.dat from different point of views. First of all, end users are addressed that apply the database and its environmental data in daily business for e.g., building LCA purpose. On the one hand, these end users must be aware of the quality of data they use. On the other hand, they shall be also able to rely on the credibility of the LCA results that were obtained. The same is true for the second relevant user group, which is reviewers and certifiers, enabling the creation of trustworthy environmental information. Last but not least, database developers are addressed, which are responsible for set up and integration.

The quality of the environmental statements and thus the sustainability assessment of buildings are determined on the one hand by the information on the building. On the other hand, it is determined by the quality of the environmental data of the building materials and systems used. Therefore, a uniform approach regarding data collection, modeling, and background data used in the creation of the datasets of the construction products is necessary. A uniform procedure facilitates the evaluation of different design concepts in the context of a building. This prevents a comparison between different assumptions and boundary conditions, for example, between different background data of different quality. This ensures that the environmental decision support can be made based on comparable and reliable results. Another reason for proposing a consistent method is the fact that different assessment tools are used in the sustainability assessment of buildings. A uniform format for the environmental profiles is the basis for efficient and consistent integration of the data into the various tools. Closer integration and adjustment with the BIM method has the potential to considerably reduce the effort for a process-accompanying evaluation of the planning object with regard to LCA, especially through the availability of improved interfaces for the LCA input data, concerning project-specific information about the building as well as (linked) more generalized product information and classifications.

In the future, the importance of the building LCA will increase due to the optimization of the use phase (passive houses, plus-energy houses), and at the same time, ever stricter requirements for Germany's climate protection goals. Developments in the digitization of construction companies and the construction process (BIM) offer great potential for the life cycle assessment to improve and greatly simplify data acquisition and thereby greatly reduce the effort involved in preparing the life cycle assessment. This would move EPDs from a niche product to a mass market. But, for the further integration of BIM and LCA, there are some issues to be handled and problems to be solved in the future–also on the BIM side: To convert the LCA approach to a process accompanying evaluation method, the focus has to shift to the early planning phases. That means that both sides (BIM and LCA) should be enabled to handle the fuzziness of knowledge in order to represent and map multiscale levels of development and granularity of information. Based on this, the question arises as to how product and component-related data, such as EPD, should be described and managed with regard to multiscale representation and possibly parametric modeling in order to facilitate simplified referencing in the different levels of concretization.

A very interesting point here for future research is the integration of the buildingSMART Data Dictionary (bSDD, former IFD). This dictionary is a referencing database and supports a flexible and reliable method for a definite and unambiguous reference (single source of truth) on terms and features, their relations and specifications. The bSDD serves as a translingual extension and name space of the IFC data model. A similar approach for a server-based classification system was examined for the Austrian state in the project 'free BIM'. Thereby, for the German speaking countries, the data dictionary approach could be already evaluated by developing the FreeClass as a classification base for the national feature server ('Merkmalsserver'). In preparation for (international) harmonization, the developed classification system is streamlined to IFC, as well as to bsDD (regarding the terms where it was applicable).

Another very interesting question is whether and how BIM models are capable of describing the spatial constructive context of building components and how such a context-sensitive description can enhance the assessment methods of LCA. Speaking of integrated and integrative planning approaches (in German: 'Integrale Planung'), not only one-directional interfaces to simulation tools are to be supported, but also the roundtrip back with the re-integration of simulation and assessment results into the planning processes respectively into the BIM model. This would open up great possibilities for integrated model analysis (e.g., model checks) and quality assurance.

Overall, the publication is intended to encourage joint work on the further development of Ökobau.dat and of building LCA in general. This should serve as a first proposal for improvements. In the future, a requirement and solution proposal for the creation of a Ökobau.dat 3.0 needs to be created through participation of stakeholders from research and practice. So far the building LCA and the Ökobau.dat were the playground of LCA experts, who raised specifications from their point of view. This may stimulate further developments and enabling the Ökobau.dat to find its way between expert tool, niche tool, or digital LCA (Figure 5).

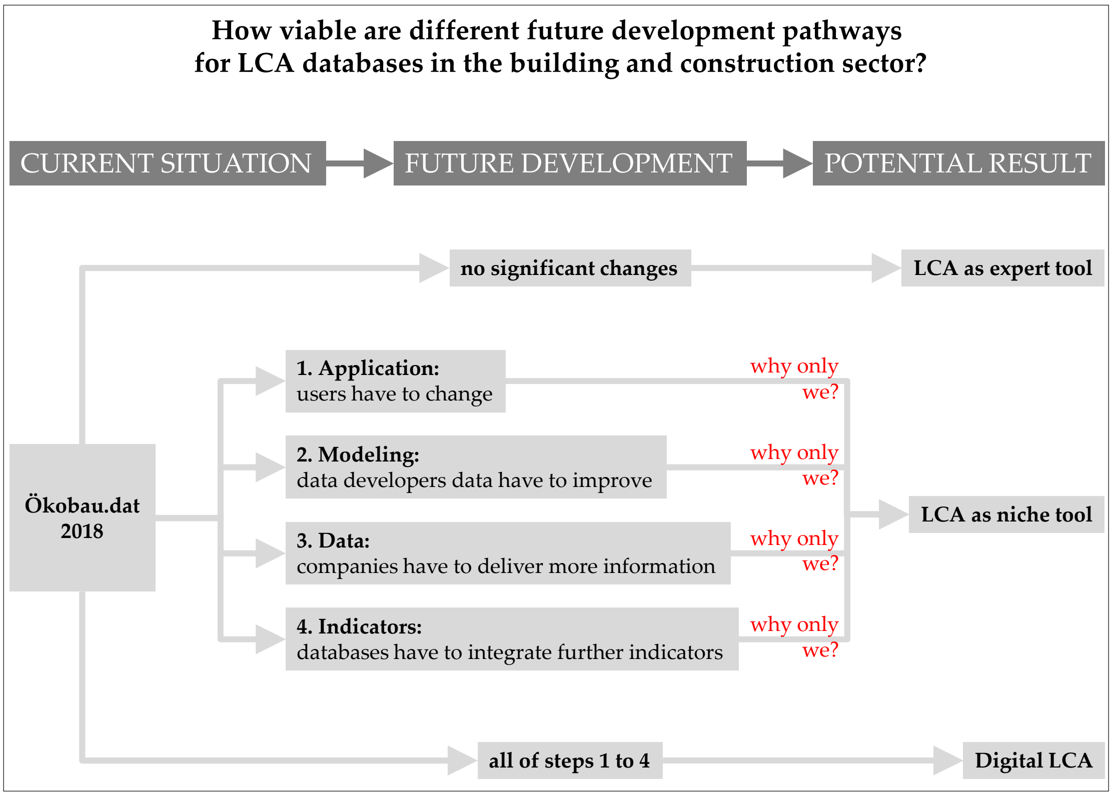

Figure 5. Future options for development of Ökobau.dat and other LCA databases in the building and construction sector.

Supplementary Materials: The following are available online at http://www.mdpi.com/2075-5309/8/9/129/s1, Annex 1: Mapping Approach of the SBA from IFC 2x4 to LCA, Annex 2: Current shortcomings with low prioritization within Ökobau.dat.

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