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Rapid Environmental Assessment of Buildings: Linking Environmental and Cost Estimating Databases

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Abstract: Life cycle assessment (LCA) has become an important part of building design optimization. Design studios need tools that make the LCA of buildings faster and simple, and provide results that allow comparison between variants. The objective of this study was to show the possibility of LCA data integration into the existing building design tool, the DEK Building Library, which is already widely used in the Czech Republic, by connecting it to 1200 items of the largest Czech cost-estimating database, and the application of this connection into building information modeling (BIM) tools. This process also included the large-scale adaptation of 160 relevant LCA data. The main result was obtained using EnviBIM, a freely accessible BIM plugin, as well as a web interface that allows users to receive cradle-to-gate environmental impacts of DEK Building Library elements. Additionally, a semi-automated algorithms system for different groups of building materials and elements named EnviDataGenerator was developed in MS Excel, which enables the consistent linking of LCA data to the cost-estimating database items. This allows EnviBIM extensions and upgrades. The EnviBIM module was validated using case studies of three buildings modeled in ArchiCAD and REVIT. The difference in results compared to the manual calculation was 3.1% to 10.9%, which was considered a success.

Keywords: life cycle assessment; LCA; cradle-to-gate; environmental impacts of building structures; construction cost estimating; building information modeling; BIM; building design

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1. Introduction

Life cycle assessment (LCA) is the most widely used method for calculating the environmental impact of buildings [1]. Immediately after the operational stage, the production stage of a building's life cycle has the largest environmental impacts (e.g., global warming potential and primary energy consumption), hereinafter referred to as cradle-to-gate or embodied impacts [2,3]. The earlier in the project cradle-to-gate impacts are calculated, the greater the potential is to reduce them [4,5]. LCA at the design stage is time-consuming and costly because it requires a large amount of data, namely, two kinds:

- Environmental data on individual materials and components;
- Qualitative and quantitative information about the building—basically a bill of quantities.

Therefore, it is most often used after the building has been constructed and the data have been collected [6,7]. At present, stakeholders, developers, and scientists hope that LCA can be used at the earliest possible stage of building design in order to optimize it from an environmental point of view [8].

To provide a relevant LCA, the choice of the environmental data source is crucial. The data must be of sufficient quality, and the scope of the database must be large enough to cover the entire building. Combining data from different sources is problematic [9,10]. Nowadays, the best source of specific data for building products is Environmental Product Declarations (EPDs), but there are usually not enough of them in the market. Therefore, data from generic LCA databases are most commonly used. The main principle of applying such generic data is to use one consistent database.

For cradle-to-gate LCA, qualitative and quantitative information about the building (obtained from the project documentation) needs to be linked with data from the environmental database. Therefore, tools are being developed and used that link the various pieces of design software with LCA tools and data.

Review of Existing Tools, Limits and Gapss

Nowadays, the development of LCA tools for buildings focuses mainly on the connection of LCA and BIM. The advantages of designing buildings using BIM tools instead of conventional design have led many countries to take measures to spread BIM [11,12]. Such measures have also been taken by the Czech Republic, whose government approved a strategy for BIM implementation in 2018 [13]. From an LCA perspective, the implementation of BIM can greatly facilitate the integration of LCA into the design process [14] because it facilitates the sharing of building information necessary for LCA [15,16], e.g., because the BIM model can be used to automatically generate a bill of quantities, which is a key basis for LCA [17]. In 2007, Loh et al. [18] identified the main problems in linking BIM and LCA software: the LCA tools are complex and expensive, the process of inputting data into LCA is inefficient, and the compatibility of data from BIM and data in LCA software is problematic. Since then, a large amount of research has been conducted to find ways to overcome these and other problems in linking BIM and LCA.

Although very often the linking of BIM with LCA is performed manually, using Excel sheets [17], it is realistic to link LCA and BIM in such a way as to eliminate the need for manual data entry into LCA tools [19]. A number of tools are also being developed to fully or partially automate this linking, making LCA in the building design phase significantly faster, cheaper, and more comparable. For cradle-to-gate LCA, several authors suggest exporting the bill of quantities to excel and linking it to environmental data [20] or LCA software. Pantelli et al. [21] inserted the BIM Bills of Quantities into the EcoHestia Database LCA tool adapted to the Cypriot construction industry. Ajayi et al. [22] inserted a bill of quantities exported from Revit into the Athena Impact Estimator. Shafiq et al. [23] optimized the design in terms of the carbon footprint of concrete and steel; they multiplied the quantities of both materials by the conversion factors for the carbon footprint from the ICE database. Basgabill [24] et al. proposed an automatic linking of BIM, environmental data, and optimization software. The disadvantage of this approach is that it considers the not very widespread BIM tool DProfiler, which is only suitable for very simplified models; for example, it does not allow modeling non-rectangular shapes. The proposed approach was tested but did not result in a tool that is publicly available. Yang et al. [25] used the tools for creating bills of quantities and cost estimates commonly used in China to obtain the detailed building information needed to calculate embodied impacts. However, linking these data with environmental data was performed manually. There are also cases where environmental data were assigned directly to elements in the BIM tool environment to individual model elements, but it is necessary to track down the corresponding environmental data for each element in order to automatically calculate the resulting carbon footprint in BIM. The environmental data were drawn from EPDs, and the authors anticipated that EPDs for a wide range of materials will soon be available [26]. Sous-Vedaguer et al. [27] proposed a semi-automated procedure where the bill of quantities from the BIM model was enriched with other data (transport, packaging, etc.), and then aggregated into a list of individual basic materials and their quantities, and this list was then linked to environmental data.

Although exporting a BIM bill of quantities from BIM to Excel and then inserting it into LCA software seems to be an effective method, there are still many obstacles to overcome. Among these problems is the inaccuracy of the automatically generated bills of quantities from BIM, because information models are still created mainly to represent the design of the building and to obtain project documentation, but not to obtain an accurate bill of quantities. Veselka et al. [28] pointed out that exporting a BIM bill of quantities from a BIM tool so that it is suitable for linking to environmental data is not straightforward, and the resulting bill of quantities always needs to be adjusted before inserting it into LCA software such as One Click LCA.

From the point of view of the quality of the bill of quantities—a key criterion for LCA—the linking of LCA to cost estimates, as already proposed by Kohler et al. in 1992 [29], seems to be very promising. It is common to use quantitative and qualitative information from cost estimates for LCA analysis, and is reported as an important source of information, for example, by K. Simonen et al. [30]. Borja et al. [31] presented a review of the literature on the use of cost-estimating databases for environmental assessment. He concludes that these databases are mostly used to complete missing information, but their potential for use in environmental assessment is much greater, and it would be advisable to make this use of cost-estimating databases more systematic, for example, by implementing environmental parameters directly into the databases. The implementation of environmental data directly into the budgeting database was performed by Freire-Guerrero et al. [32]. Ecological footprint information was added to some of the items in the Andalusian cost-estimating database by using the Ecoinvent database and SimaPro software.

The literature review shows that linking LCA and construction cost estimates is very promising for facilitating the assessment of environmental impacts in the design phase of a building. There is probably no correlation between the cost of a building and its environmental impacts, but the detailed qualitative and quantitative information about a building that construction cost estimates provide is very useful for assessing the environmental impacts of a building. Nevertheless, this potential of building cost estimates is not often exploited [31]. However, when it is, the resulting solutions, although of high quality, are always country-specific due to the local limitations of cost-estimating databases, which is the case in the research of Freire-Guerrero et al. [32]. In the Czech Republic, it is common to use the cost-estimating databases for creating budgets for practically all buildings, including family houses, while environmental calculations are very sporadically performed. Therefore, this research is focused on linking environmental data with a cost-estimating database, which will enable automated cradle-to-gate LCA for most buildings in the country.

The literature review and the interest of the professional community in the Czech Republic show that the linking of the cost-estimating and environmental datasets should also include a link with BIM. Therefore, in this research, the developed methods for linking environmental and cost-estimating databases were applied to BIM tools.

This paper describes the development of a method for linking environmental and cost-estimating databases, its application to a set of cost-estimating items used in a construction library for BIM, the resulting BIM tool, and finally the validation of the output from this tool (and consequently the methods for linking the databases) in case studies.

2. Methods

First, a study to prove the feasibility of the interconnection of available costing and environmental databases was carried out. Next, a method for linking the environmental and cost-estimating databases was developed to unify and partially automate the process. This was developed for a group of cost-estimating items usedin the DEK Building Library, which allows its use with BIM tools and provides information on the cost of building compositions. By linking the cost-estimating items with environmental data, a new environmental module of the DEK Building Library named EnviBIM was created. It provides information about the embodied environmental impacts of constructions in BIM tools and in the web interface. The functionality of the EnviBIM module and the relevance of the results it provides were tested in several case studies.

2.1. The Feasibility Study

The aim of the feasibility study was to check whether it is possible to link the building cost estimation process with a simplified cradle-to-gate (and in the future more complete) LCA of the building in Czech conditions and to determine how demanding it would be. Therefore, the structure and scope of the selected cost-estimating database was analyzed in detail. Furthermore, the environmental databases that were available and relevant to the Czech Republic were analyzed, and the most suitable one was selected for its linking with the cost-estimating items. Finally, a case study was conducted to verify that environmental data can be determined for each construction cost-estimating item based on the selected environmental database. This feasibility study was previously discussed in more detail in [33].

2.1.1. Structure of the Costing Database

This research dealt with the most commonly used construction cost-estimating database (hereafter referred to as CCED) that is currently available on the Czech market. It is provided by the company ÚRS, and it can be accessed using the KROS software ÚRS a.s. KROS 4 [34]. There was a close cooperation with ÚRS, which provided the direct access to some source data, without needing to use the KROS software [34].

The CCED comprises several databases at different levels of detail. The most commonly used is a database named the Costing Catalogue of Construction Works (hereafter referred to as CCCW). Each item of construction work is assigned a price, which has six components, as shown in Figure 1. The items and their corresponding prices for materials, machine labor, and wages are grouped in special catalogues, with which the CCCW is linked. The suitable catalogue for the cradle-to-gate LCA is the Costing Catalogue of Materials (hereafter referred to as CCM), which contains many items with descriptions of material identification, properties, and costing information. The CCM provides a mix of generic and specific data and features approximately 38,000 items.

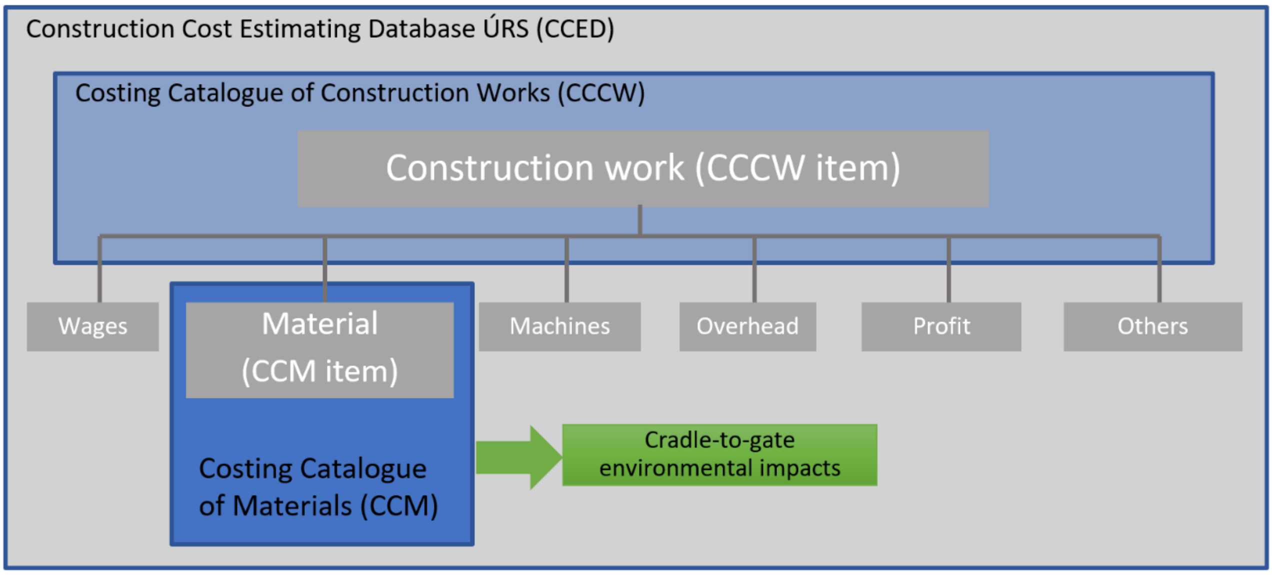

Figure 1. Structure of the cost-estimating database and its relation to the cradle-to-gate inputs.

2.1.2. Environmental Database Selection

Given the level of detail and the granularity of the CCM, the most relevant environmental data would be specific data, i.e., EPDs directly for specific products listed in the CCM. However, there was a significant gap in available data, because EPD databases, Czech or foreign, are not of such a scope and extent that would cover the variety of building products so far. Therefore, it was decided to search for a suitable generic database. The main criterion was that the database should be able to cover the whole range of building products used in the Czech construction industry and included in the CCM. Ecoinvent 3 [35], GaBi [36], and Ökobaudat [37] were considered, and finally, it was decided to use Ecoinvent 3 because it contains a very wide range of items from various industrial sectors and also includes a special group of items for the construction industry. The data are adapted for different localizations, where the broader localization (European or global) is applicable to the Czech Republic. Thanks to its considerable scope, Ecoinvent allows the modeling of any product system on the basis of individual material and energy flows, so that it should be possible to cover the entire CCM using this database.

2.1.3. Testing the Workability of Linking Databases

The scope of possible database linkage was tested, both in terms of the category of building materials (i.e., whether there are any groups of materials that will not be covered by the environmental data) and in terms of the life cycle phases covered. The basic assumption was that it would be possible to include the production phase of materials (cradle-to-gate), but the possibility of including other life cycle phases was also explored. A case study of a construction cost estimate for a small apartment building was developed to verify whether it would be possible to assign environmental impacts to each item in the construction cost estimate. This case study also tested the possibility of including the construction process, but the results showed that it is problematic. Thus, the research continued considering only the production (cradle-to-gate) life cycle phase.

2.2. Method for Interconnection of Databases

The testing of the linking of the environmental and cost-estimating databases revealed that to link the cost estimation and environmental databases consistently and to allow for a regular updating process with minimized labor intensity, a robust method would need to be developed. The method was divided into two parts:

1. General part: This part of the method establishes a general methodological framework for the concept of a construction cost estimate extended by environmental impacts, in the context of the existing rules for the LCA of construction products and buildings. The basic provisions of the general method refer to standard EN 15978 [38], which describes in a relatively detailed way how to carry out the LCA of buildings and, at the same time, reproduces provisions from more general LCA standards. In addition, the provisions of the method refer to standard EN 15804 [39], which provides detailed guidance on the LCA of products. Another source is the EEB Guide [40], in which a large amount of detailed guidance on how to proceed with the LCA of buildings and construction products can be found. Another source of information was the authors' participation in the international projects IEA EBC Annex 57 [41] and the follow-up Annex 72 [42], which deal specifically with the LCA of buildings.

Based on the sources mentioned above, the general method defines the system boundaries, i.e., the parts of the building covered and the life cycle phases covered; addresses the issue of cut-off criteria (neglecting certain items); and establishes a set of environmental indicators using which the environmental impact is expressed.

2. Specific part: When selecting or modeling environmental data for the cost-estimating items (more precisely, for the items of costing catalogue of materials (CCM)), it is necessary to ensure consistency in the procedures used to allow for data expansion and updates. Furthermore, given the number of CCM items, it is advisable to automate at least part of the development of environmental data. The specific method is, therefore, developed as a set of instructions and mainly semi-automated algorithms in MS Excel for different groups of building materials and elements (this algorithm was named EnviDataGenerator). These guides are accompanied by a classification system named EnviDataClassifier, which allows each new item to be classified into a specific group and the environmental impacts to be calculated using the available guides and algorithms in EnviDataGenerator.

2.3. Modelling of Environmental Data for DEK Building Library

The methods mentioned above were related to the creation of environmental data for the entire CCM. To date, these methods have been applied to the set of CCM items contained in the DEK Building Library. This is a library of building compositions, developed and maintained by the private company DEK and mainly used in BIM tools (via a free plugin) to create models, and it can also be accessed via a web interface outside BIM software. For each composition, the building library provides many useful characteristics (physical, fire, or acoustic properties) and also its cost. Information on the cost of the compositions is provided by linking the compositions to the corresponding items of the cost-estimating database, more precisely, to the CCCW items presented in Section 2.1.1. However, the linking is realized in the development interface; the user only sees the total cost of the composition. The CCCW items provide very detailed and accurate quantitative and qualitative characteristics of the individual construction compositions, which is essential for the determination of embodied environmental impacts. Therefore, the linking of environmental data from the Ecoinvent 3 database with the cost-estimating items was used to determine the environmental impacts of the construction compositions in the DEK Building Library. The linking of the DEK Building Library, cost-estimating items, and environmental data is shown in Figure 2.

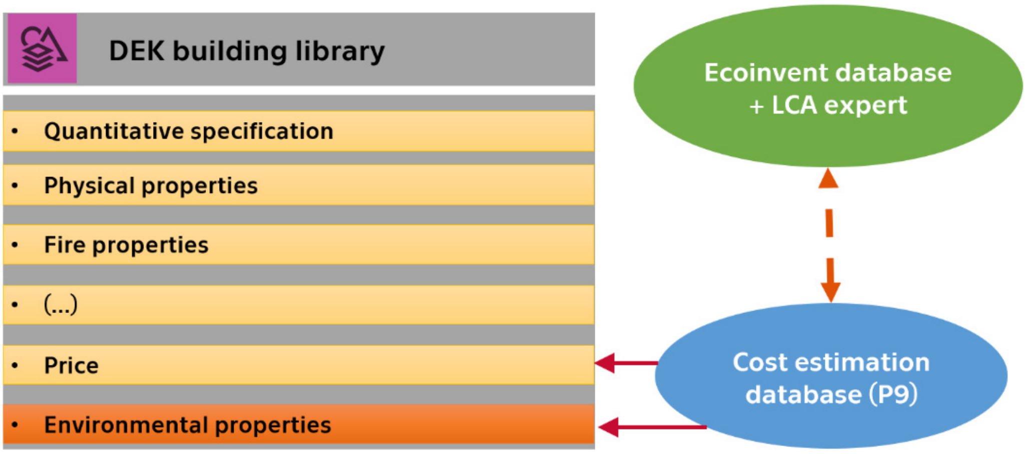

Figure 2. Information about the construction compositions, its linkage with CCED, and its possible linkage with environmental database Ecoinvent.

First, a list of all items of construction works (CCCW) and construction materials (CCM) used in the DEK Building Library was collected from the provider of the library (steps 1, 2, and 3 in Figure 3). The CCCW items are complex—see the structure in Figure 1. Since the cradle-to-gate environmental impacts are tied to materials, it is necessary to obtain information on the individual materials (represented by CCM items) and their quantities represented in each CCCW item. Thanks to the cooperation with the provider of the cost-estimating database, a full list of included materials (CCM items) was generated using the cost-estimating database development software MARVIN in bulk for the entire list of CCCW items (step 4 in Figure 3). The resulting list of 1200 CCM items also included some items belonging to the phase of the construction process, such as the wear and tear of tools, scaffolding, and formwork. These items were left out, and the resulting list was the input database for environmental data matching.

In order to assign environmental data to construction materials (CCM items) in a systematic, automated, and consistent manner, materials need to be classified according to the way in which the environmental data are assigned, modified, or modeled. For this purpose, the Excel tool EnviDataClassifier was developed (step 6 in Figure 3).

The development of environmental data for the DEK Building Library is presented in Figure 3 and described in the following paragraphs:

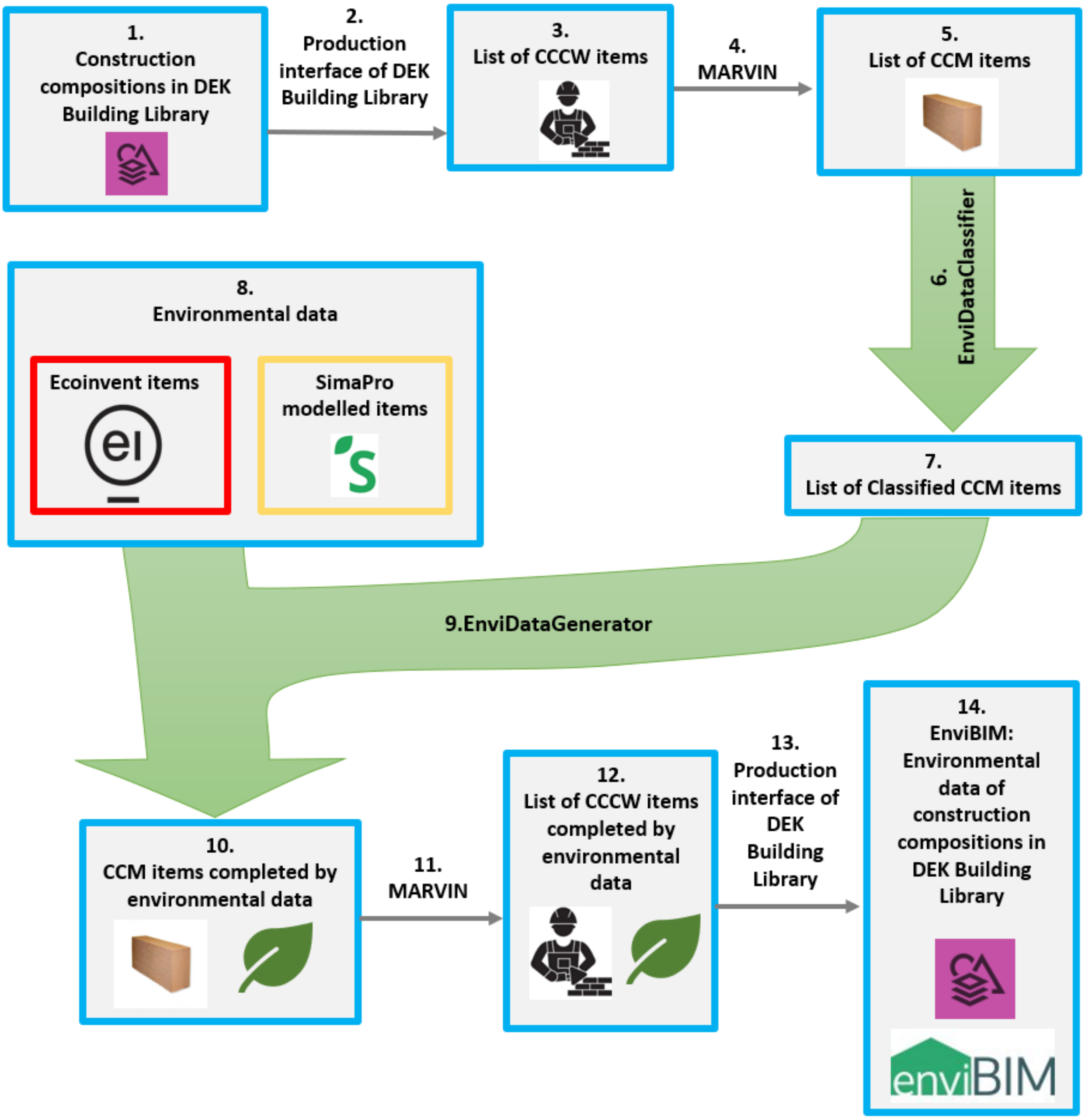

Figure 3. The process of obtaining a list of cost-estimating items, modelling the environmental data, linking them to the cost-estimating items, and implementing these data into the DEK Building Library.

The classified list of CCM items (step 7 in Figure 3) is one of the main inputs into the process of the interconnection of pricing and environmental data. The second main input for this process is a list of required Ecoinvent items and the corresponding unit environmental impacts (step 8 in Figure 3). A total of 140 default Ecoinvent items were used. The list was extended using an additional 30 items of materials for which the corresponding item did not exist in Ecoinvent. These were modeled in SimaPro 8 [43] using Ecoinvent as a combination of material and manufacturing processes (see example in Figure 4). Examples of such items are HDPE film, PVC film, and aluminum foil (all per kg).

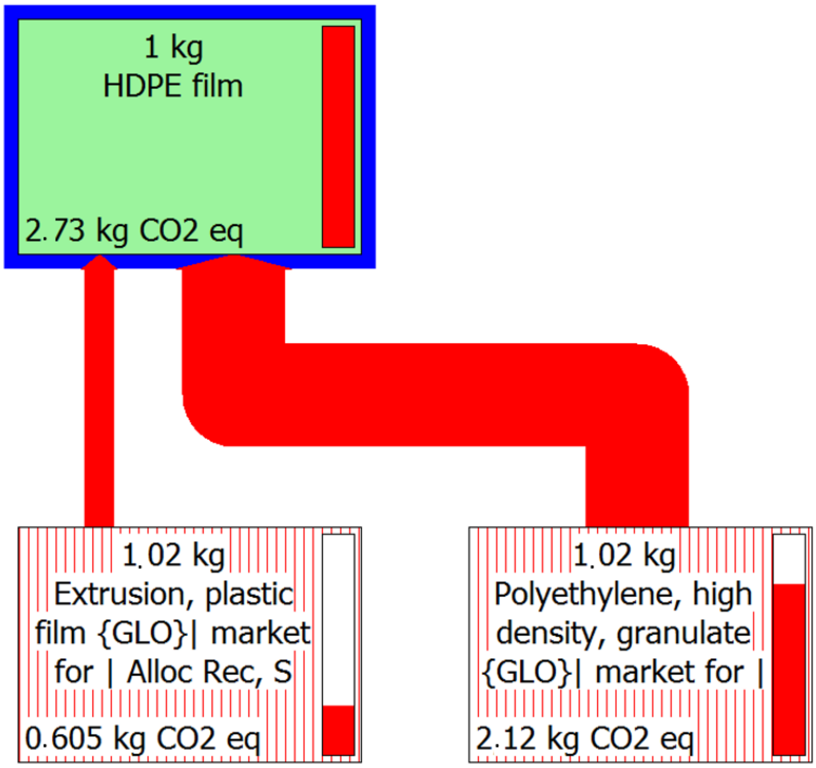

Figure 4. Visualization of how HDPE film is modeled in SimaPro.

An Excel tool called EnviDataGenerator was developed to link environmental data with CCM items (step 9 in Figure 3). This connection is not straightforward. The environmental data need to be modified and combined in various ways to match the CCM items. If a CCM item corresponds to one specific item from Ecoinvent, EnviDataGenerator determines which one it is (how to select it) and provides the necessary data for any unit conversion (e.g., a polystyrene foam slab, which is in CCM in units of m2 and in Ecoinvent in units of kg). Often, it is necessary to combine several different materials or manufacturing processes to match the environmental data to the CCM item. The EnviDataGenerator is designed to provide the most straightforward and automated way to perform these operations. The basic methods on which EnviDataGenerator is based are discussed in [44]. The output of the EnviDataGenerator is then the list of CCM items compiled by the calculated environmental impacts (step 10 in Figure 3).

The output from the EnviDataGenerator, i.e., the list of CCM items completed by environmental data (step 10 in Figure 3), is first processed by the cost-estimating database development software MARVIN, which assigns the environmental data to the CCCW items via quantity calculations (step 11 in Figure 3). The resulting list of CCCW and CCM items (step 12 in Figure 3) is then applied to the DEK Building Library via its production interface (steps 13 and 14 in Figure 3).

2.4. Validation—Case Studies

The resulting environmental module of the DEK Building Library—EnviBIM—displays the cradle-to-gate environmental impacts of building structures and entire buildings (when building library elements are used). In order to verify the general accuracy of the results provided by EnviBIM, case studies were developed. The information models of two different buildings, one of them with two different BIM tools (ArchiCAD and REVIT), i.e., a total of three models, were subjected to automated calculation using EnviBIM and in parallel to a classical manual calculation. The classical manual calculation follows the LCA guidelines defined in SBToolCZ [45], which is the only national LCA methodology at present.The manual calculation uses automatically generated bills of quantities from BIM tools and the Ecoinvent database. It is made using spreadsheets. For the validation of the results obtained from the EnviBIM module, it was sufficient to perform this validation with only one environmental indicator. For this purpose, GWP (carbon footprint) was chosen. In this paper, the case studies are only briefly addressed, as a number of issues arose during their processing, relating to the way the model was processed rather than to the environmental data. Information modeling and the subsequent environmental calculations are, therefore, the subject of ongoing follow-up research.

3. Results

3.1. Results of the Feasibility Study

The results of the feasibility study were described in detail in [33]. Only the main results are summarized here:

- Database interconnection is feasible within cradle-to-gate boundaries.
- Almost all building materials can be included; the only (but significant) excluded group was the HVAC systems. No volumetric or mass cut-off was necessary. Nevertheless, there were likely to be groups of materials with a small mass fraction of the total building mass for which the determination of environmental impacts is disproportionately laborious, so they would not be included in the database interconnection. These were mainly some coatings and adhesives.
- Linking the databases would not be straightforward; the environmental data needed to be adjusted in different ways or new data needed to be modeled. To maintain consistency, a robust method with detailed instructions on how to work with the environmental data needed to be developed.
- The result of the case study developed as part of the feasibility study showed that linking the cost-estimating database with Ecoinvent would provide relevant results for the cradle-to-gate impacts of the building.

3.2. Method for Linking Cost Estimating and Environmental Databases

The method for linking the cost-estimating items used in the DEK construction library with Ecoinvent has two parts: general and specific.

3.2.1. General Part of the Method

The general part was elaborated in writing. The method recommends following, in particular, the standards ČSN EN 15804 + A1 and ČSN EN 15978 when working with environmental data. For more detailed instructions, the EeBGuide [40], or the ILCD Handbook [46], is recommended. Furthermore, the method provides a list of environmental indicators for EnviBIM and the corresponding LCIA methods for their determination (see Appendix A).

The general method further specified the included life cycle phases, which for this application was only the production phase (cradle-to-gate) and the included parts of the building: all the building parts were included, except for HVAC, which was not included. Furthermore, the following types of materials might not be included if it is difficult to obtain environmental data for them: adhesives, coatings, some very small plastic elements (e.g., dowels), and vegetation. HVAC is undoubtedly very important in terms of cradle-to-gate environmental impacts. The reason for its omission in this research was mainly the lack of data in the Ecoinvent database, or rather the different way of working with the data compared to the building materials. Many studies can be found in the literature that use the Ecoinvent database to calculate the environmental impacts of HVAC systems including the material production phase [47,48], and the authors of this paper have also addressed this topic previously [49]. Linking environmental data with budgeting data for HVAC systems is realistic, but the methods will be very different from those for building materials and will be addressed in future research.

The general method established Ecoinvent as the single and default environmental database for systematic and, as much as possible, automated linking of environmental and cost-estimating items. The method also specified which datasets to select from Ecoinvent in terms of their location and type of models. However, it is questionable how accurate the data from the Ecoinvent database is for the Czech construction industry. The biggest inaccuracies occurred due to the localization; in Ecoinvent, the data was not localized for the Czech Republic, and the energy mixes used in the items, which fundamentally influence the results, were often quite different from the Czech ones. It would, therefore, be advisable to consider the possibility of using EPDs for those products for which EPDs with Czech localization are available. This was also confirmed by various similar studies, where the authors preferred to use specific data (e.g., Eleftheriadis et al. [26]), but in many studies, the Ecoinvent database was perceived as an adequate data source (e.g., Yang et al. [25] use it to complete data missing in the Chinese national database; Freire-Guerrero et al. [32] use Ecoinvent as the only data source for his tool that links construction cost estimation with environmental calculations).

3.2.2. Specific Part of the Method

The specific method provides clear guidelines for the development of environmental data for the CCM items of the cost-estimating database. It took the form of two algorithms in MS Excel, namely, EnviDataClassifier and EnviDataGenerator.

The EnviDataClassifier allows any item from the CCM to be classified according to the way the environmental data are determined and treated. Based on this classification, it is then possible to either add the item from the CCM to a specific data group in EnviDataGenerator and calculate the environmental impacts using instructions and predefined algorithms, or, if a corresponding group or subgroup does not exist, create the group in EnviDataGenerator and then calculate the impacts. For each material, EnviDataClassifier obligatorily defines its belonging to one of the main categories (eCAT) and optionally to subcategories 1 and 2 (eSCAT1 and eSCAT2). The eCAT category indicates mainly the type of material, and for further data processing, it signifies which Ecoinvent items are relevant for this category (included in the next part describing EnviDataGenerator). The eSCAT1 and eSCAT2 subcategories then specify the calculation method within that group. Every material must have an eCAT category, but subcategories are not always relevant. An example of several categories is provided in Table 1.

Table 1. Example of categories and two levels of subcategories in EnviDataClassifier.

eCAT	eSCAT1	eSCAT2
Bitumen	Liquid Mastic asphalt Bitumen membranes	- - m^2 m
Concrete	Cast Blocks	m^3 Solid Aerated
Bentonite	-	-
Mineral wool	Stone wool Glass wool	Board (m^2) Other (m^3) Board (m^2) Other (m^3)
EPS	Boards (m^2) Other (m^3)	- -
Foam glass	Boards (m^2) Other (m^3)	- -

Table 1. *Cont.*

eCAT	eSCAT1	eSCAT2
Wooden products	Solid wood	m^3 m^2
	Other than solid	m^3 m^2
Woodfibre	Boards (m^2)	High density Medium density Low density
	Other (m^3)	Low density
Aluminum products	Products of Al sheet (template1)	-
	Extruded Al product (template 2)	-
	AlMg sheet	-
	Al cast product	-
	Aluminum foil	-

The EnviDataGenerator contains a sheet of Ecoinvent data and their unit impacts, a sheet with a list of CCM items to which the calculated environmental data are automatically assigned, and 33 sheets for different material groups (eCAT in EnviDataClassifier) with more or less automated algorithms for adjusting the environmental data from the Ecoinvent sheet (conversion of units, modeling of complex materials, etc.)

Two examples of categories with automated modeling are as follows. Table 2 provides the names and brief descriptions of the two categories (eCAT), and a description of the work with the environmental data in that group of materials. The Ecoinvent items relevant to the group are also listed, as well as a more detailed description of these Ecoinvent items to facilitate further work.

Table 2. A structured description of the formation of environmental data for two categories (eCAT) of construction materials.

Category and Its Description	Method of Adjusting/Modelling Data	Corresponding Ecoinvent Items	Description of Ecoinvent Item (If Needed)
Bitumen membranes Waterproofing and vapor barrier sheets made of bitumen and modified bitumen.	Selection from a range of Ecoinvent items. Default Ecoinvent items provide the four most used types of bitumen membranes. For each cost-estimating database item, the one that best matches its material composition shall be chosen. The new item shall be modeled in SimaPro and included in the menu if an environmentally significant material would otherwise be omitted.	*Bitumen seal*, *V60 {RER}*, kg	Considered as the most common and average item, it has a fiberglass textile insert, sprinkles, and a combustible PE film.
		Bitumen seal, *polymer EP4 flame retardant {RER}*, kg	Bitumen is modified with polymers (e.g., SBS) via polyester grid reinforcement
		Bitumen seal, *VA4 {RER}*, kg	Aluminum is sprayed on PE foil, which is part of the bitumen membrane.
		Bitumen seal, *Alu80 {RER}*, kg	Similar to the V60, there is an aluminum foil instead of a glass textile.
		Bitumen seal, *SBS*, *alu + polyester*, kg *(modeled in SimaPro)*	Sheet modified with SBS, and reinforced with aluminum foil in addition to polyester.

Table 2. *Cont.*

Category and Its Description	Method of Adjusting/Modelling Data	Corresponding Ecoinvent Items	Description of Ecoinvent Item (If Needed)
Aluminum products This group contains all aluminum products.	For each item, its weight must be determined, most often by looking up information from the manufacturer, or by calculating from dimensions and volume weight. The weight and material of the coating (PVC, PES, etc.) must also be determined. It is also necessary to determine whether the product is formed by extrusion, sheet bending or otherwise, and select the appropriate items accordingly. EnviDataGenerator provides templates for the two most common types of aluminum products: the aluminum sheet product and the extruded product. In both cases, the weight can be entered either directly, or via thickness and area. Next, the material for the coating, if applicable, and the weight of the coating are selected from a drop-down list. After entering these data, the environmental parameters are calculated automatically.	*Aluminum, wrought alloy {GLO}∣market*, kg	
		Impact extrusion of aluminum, 3-stroke {RER}∣processing, kg	
		Aluminum sheet, kg *(modeled in SimaPro)*	
		Aluminum foil, kg *(modeled in SimaPro)*	
		Polyester resin, unsaturated {RER}∣production, kg	
		Polyvinylchloride, bulk polymerized {RER}∣polyvinylchloride production, bulk polymerization, kg	

The principles used to link cost-estimating data with environmental data are very different for different categories of materials, and some of the most common are described and illustrated in Figures 5–7:

- Once the cost-estimating item has been classified into the main category, it can be added to the appropriate sheet in the EnviDataGenerator (see the blue box in Figure 5).
- On this sheet, it is often necessary to select a relevant Ecoinvent database item from the drop-down list (see yellow box in Figures 5 and 7). However, sometimes, only one item from the Ecoinvent database is relevant for an entire category (e.g., the category extruded polystyrene).
- In addition, it is usually necessary to manually enter the information for unit conversion (purple boxes in Figures 5 and 7), possibly additional information and drawings of the element (grey box in Figure 7), so that the values for conversion are well supported and sourced.
- For some groups, where many different ways of modifying environmental data are applied, there is a range of templates to choose from, depending on the method of calculation (which can be specified by classifying the material into subcategories). An example is shown in Figure 6, where a calculation template for an aluminum element produced by extrusion or a template for an element made of the sheet can be selected (and more templates will be added). With the templates, the corresponding Ecoinvent items are then selected automatically. Within the template, the options then branch further; for example, the weight of the element can be specified either directly or via the thickness and area of the sheet metal.
- The environmental impacts are then calculated automatically based on the data entered—see the green boxes in Figures 5 and 7.

When linking environmental and cost-estimating data, this work focuses on the EnviDataGenerator, which is a software that should guide the environmental data preparer through the process of selecting and adjusting environmental data for cost-estimating items so as to minimize any uncertainty. However, the software has to be continuously extended because new groups of materials (but also new materials within existing groups) may require new calculation methods and algorithms. MS Excel seems to be suitable for the prototyping of computational algorithms, which is a job for an LCA expert who has a detailed insight into the whole process of linking environmental and cost-estimating data. However, due to the complexity of the algorithms, the amount of budgeting data (up to 38,000 items in the future), and the need to create a user interface, MS Excel seems to be an inadequate tool. It would be advisable for the algorithms to be prototyped by an LCA expert in MS Excel and then converted by a programmer into a suitable programming language to produce a true software.

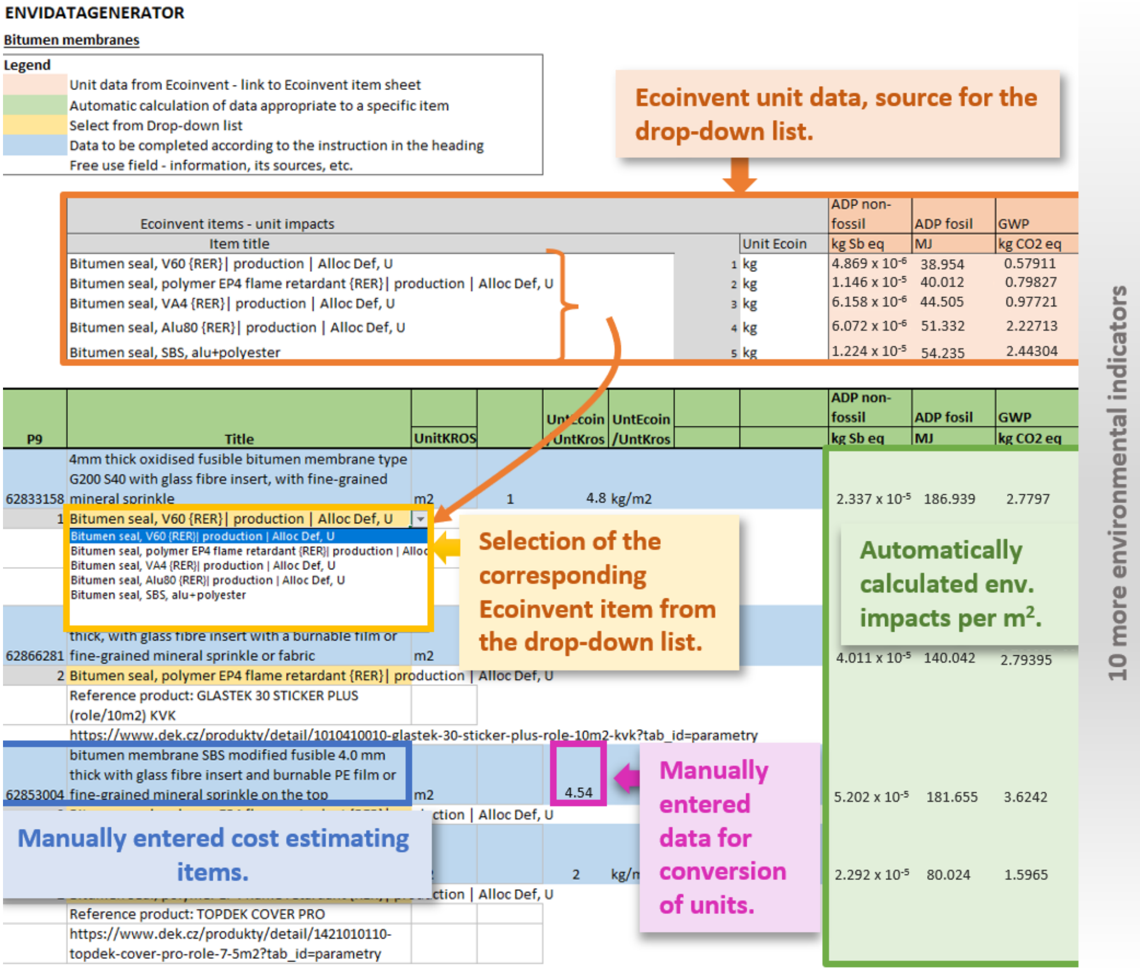

Figure 5. Automatic calculation of environmental impacts of bitumen membranes in EnviDataGenerator.

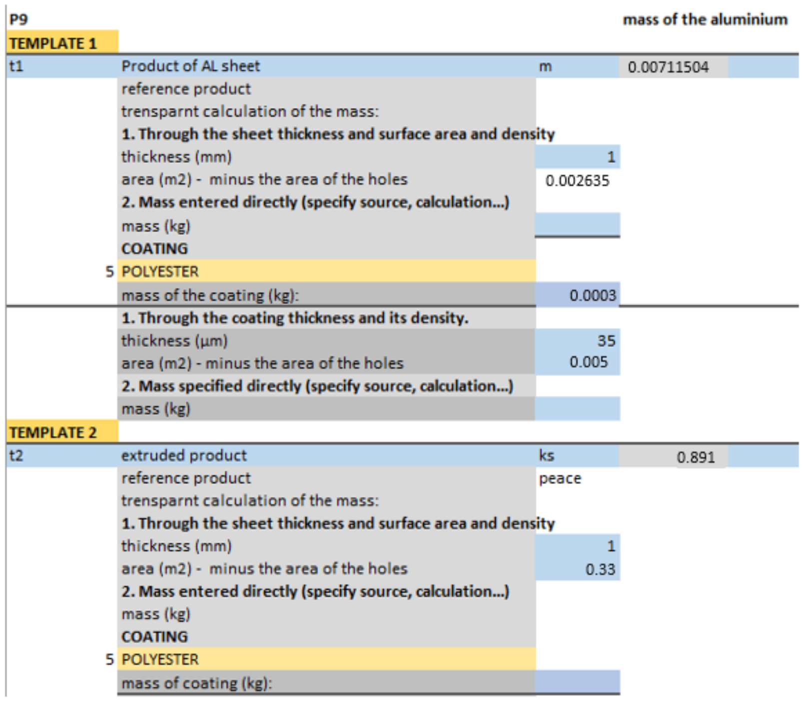

Figure 6. Templates for automatic calculation of environmental impacts of the two most common types of aluminum products: aluminum sheet product and extruded product.

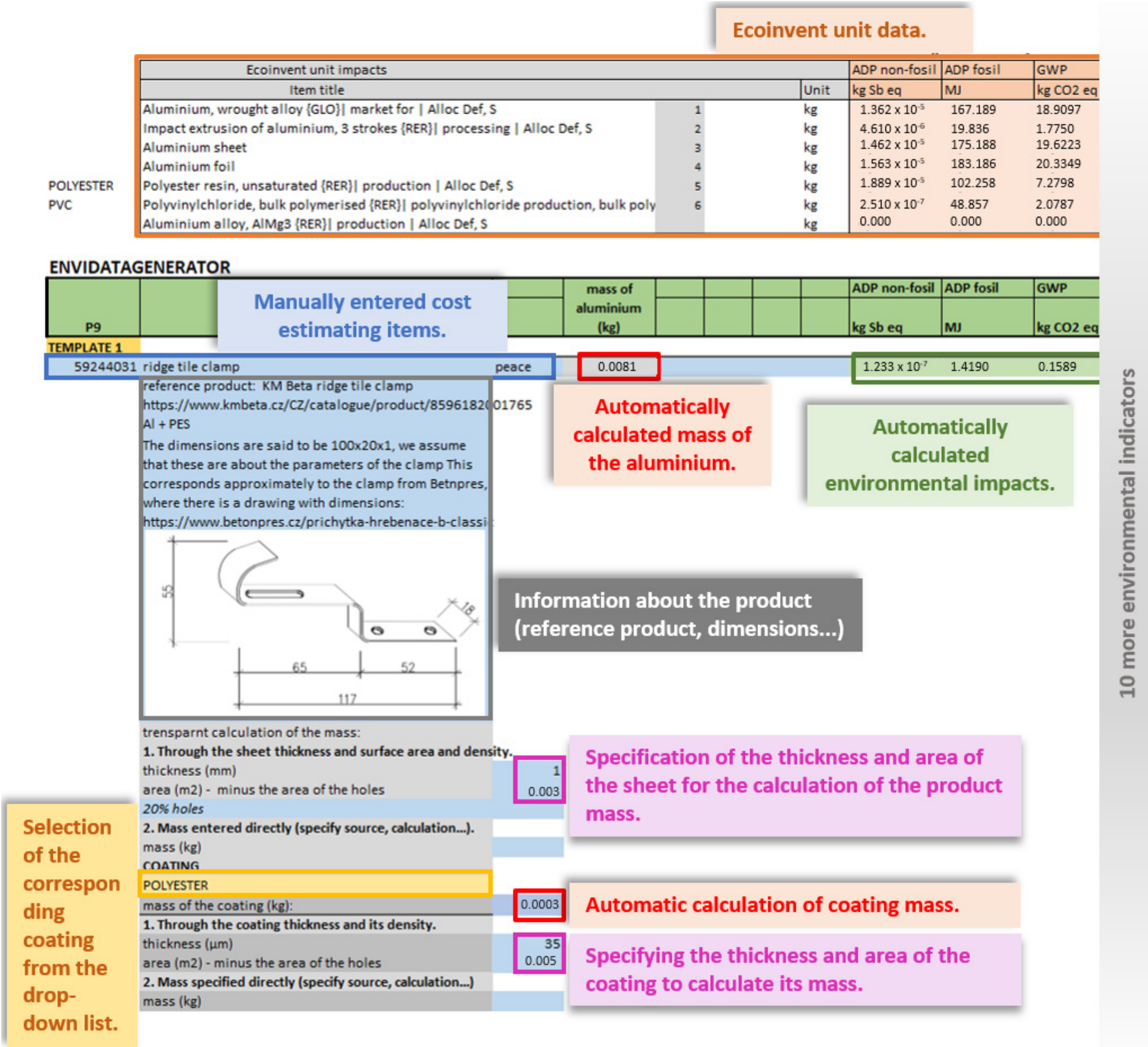

Figure 7. Use of template 1 (aluminum product eCAT) for automatic calculation of the environmental impact of ridge tile clamp.

The cost estimating database is updated twice a year, mainly for price reasons. On that occasion, however, titles, compositions, and therefore IDs of some items are also changed in order to improve the database. The operator of the cost-estimating database provides information on the changes so that the EnviDataenerator can be updated accordingly every six months, but it would be desirable to systematize this process.

3.3. Environmental Module for the Building Library

The applied result of the research described in this paper was EnviBIM—a new environmental module of the DEK Building Library. The data developed in EnviDataGenerator were imported into the DEK Building Library. The user of the building library can view the embodied environmental impacts of the entire construction composition (not individual materials), as shown in Figure 8. EnviBIM can be used either on the web interface or as a plugin to the REVIT and ArchiCAD BIM tools. The plugin allows the use of construction compositions from the DEK Building Library to build a model, and it is possible to view the environmental impacts of individual construction compositions.

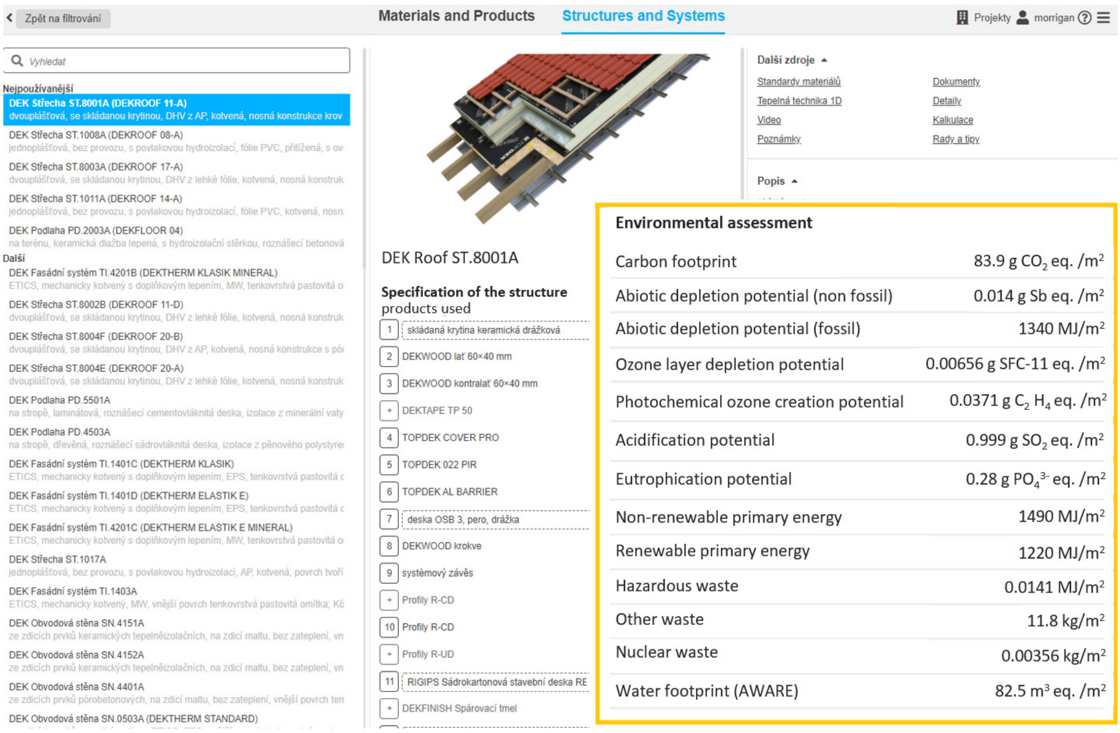

Figure 8. Environmental impacts of the roof composition displayed in the web interface of the DEK Building Library.

Users who do not use BIM tools can use the BIM platform provided by DEK to display the model and, among other things, the environmental parameters of the construction compositions. On the BIM platform, it is possible to compare construction variants, in terms of their environmental performance, to view a detailed quantification of the embodied environmental impacts, or to display their sum for the entire building (see Figure 9).

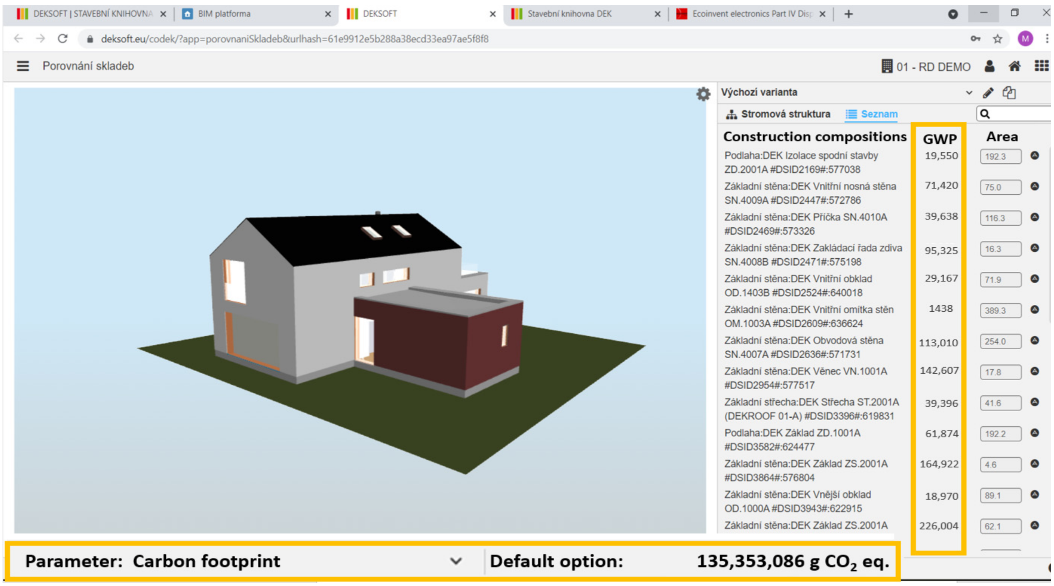

Figure 9. Carbon footprint of the construction compositions and of the whole building is displayed using the BIM platform.

A library for BIM tools that provides such a wide range of information for designers, including environmental impacts, is unique in the Czech construction industry. The environmental data are processed very precisely on a single-source basis (Ecoinvent), ensuring the comparability of design variants. There is also a transparent methodology behind it. A major limitation, however, is that environmental data are so far only available for those items owned directly by DEK. The library contains elements and compositions of other manufacturers in the Czech construction industry. The issue of publishing environmental data for these other elements of the construction library is the subject of future negotiations with these companies. This is of course related to the question of the use of EPD data, which some material manufacturers have processed, and can undoubtedly be considered better quality data than generic Ecoinvent data, but the compatibility of specific EPD data and generic Ecoinvent data is questionable.

3.4. Results of Validation by Case Studies

The aim of the comparison between the resulting carbon footprints obtained automatically from EnviBIM in REVIT and ArchiCAD programs and the manual calculation was to verify that EnviBIM was working correctly. Since the structure of the EnviBIM calculation and the manual calculation is different—EnviBIM shows the results by individual components, and the manual calculation by individual materials—only the resulting carbon footprint of the whole building was compared, but it must be noted that the actual carbon footprint would be higher. This is because the calculation did not cover elements that are not yet included in the building library (windows, doors, etc.).

Figure 10 shows the results of all three case studies—the embodied carbon footprint (GWP in kg CO_2 eq.) related to 1 m^2 of net floor area. For the residential dwelling, the carbon footprint is slightly higher when calculated automatically using EnviBIM than when calculated manually. This is a predictable result: thanks to the product modeling in SimaPro, EnviBIM works with almost no cut-off criteria, even very small elements are included. The manual calculation, on the other hand, neglected some minor elements. However, it was very surprising that for a family house, the result was the reverse—the carbon footprint calculated by EnviBIM was lower than the result of the manual calculation. The problem turned out to be caused by large discrepancies in the automatically generated bill of quantities from Revit and ArchiCAD, which was used for the manual calculation. The fault was, therefore, on the side of how the BIM model is processed rather than on the side of the environmental calculation.

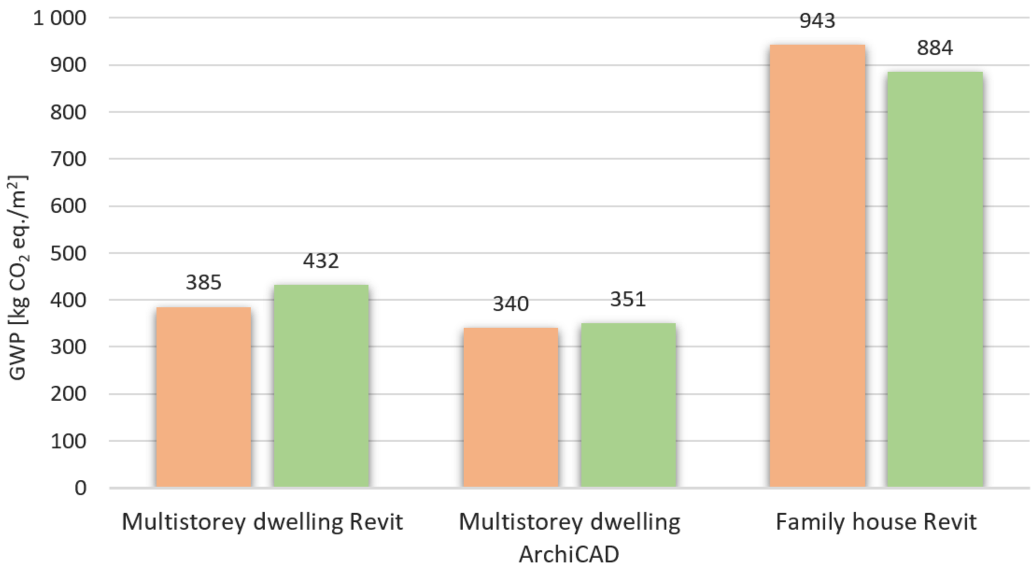

Figure 10. Comparison of the embodied carbon footprint of the three information models calculated both manually and automatically using EnviBIM.

The differences between the results were 10.9%, 3.1%, and 6.3%, which was considered a successful validation, considering that EnviBIM provides relevant information on the environmental impacts of building structures.

Another challenge of a proposed BIM-LCA workflow is the precision of the model itself, which is, as with any other model, a simplification of reality. Therefore, it highly depends on the project phase and the quality of the model developer. The Level of Development (LOD) must be at least 300; otherwise, there is a lack of detail (e.g., missing materials or elements). The volume of basic building elements, such as walls, floors, roofs, columns, and foundations, are calculated correctly, but there are specific details that must be considered: (1) missing elements (e.g., bracing, joints, and materials in the air cavities); (2) openings and other user-made elements are often simplified (e.g., one layer of glazing instead of three and a full profile in the façade elements). Therefore, it is necessary to calculate the volume of those elements carefully; otherwise, the level of uncertainty of the proposed assessment increases. The mentioned requirements of the model should be covered in the BIM Execution Plan (BEP), a document used for a detailed specification of the model.

4. Conclusions and Future Research

This research has shown that extending the Czech cost-estimating database with cradle-to-gate environmental parameters is possible and very useful.

For this extension, a methodology was developed to establish a process for matching LCA data to items in the ÚRS cost-estimating database. This linking involved 1200 cost-estimating items and 160 LCA datasets, and a semi-automated tool EnviDataGenerator was developed in MS Excel to complete it.

The next step was the development of a publicly accessible web interface and plugin for BIM tools called EnviBIM, linked to the DEK Building Library program, which is widely used in Czech construction practice.

The functionality of EnviBIM was verified and validated using three case studies of buildings that were modelled in ArchiCAD and REVIT and also assessed manually. The difference in the results ranged from 3.1 to 10.9%, and the validation was, therefore, considered successful.

However, the analysis of the results of the case studies highlighted the issue of the readiness of common building information models to be used, for example, for LCA. When the bill of quantities from the BIM is used also for an environmental assessment, it is important to have a model of the best possible quality. Therefore, research clearly confirmed the importance of properly defined requirements to the models described in a BEP document. It should be addressed to the industry and BEPs updated accordingly.

Further research should aim to apply these methods to the entire cost-estimating database. Here, the first major question is whether to simply extend KROS—the existing software for utilizing the budgeting database—with an environmental module, or whether to develop completely new software that would include this new environmental functionality and would also be linked to BIM.

Another issue for further research is the search for, or preferably the creation of, environmental data localized for the Czech Republic and compatible with the EPDs.

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Appendix A

Table A1. Environmental indicators for EnviBIM and the corresponding LCIA methods for their determination.

	Indicator	Unit	LCIA Method
1	Abiotic depletion potential for non-fossil resources (ADP—minerals and metals)	kg Sb eq.	CML 2001 [50]
2	Abiotic depletion for fossil resources potential (ADP-fossil)	MJ, net calorific value	CML 2001 [50]
3	Acidification potential of land and water (AP)	kg SO_2 eq.	CML 2001 [50]
4	Ozone depleting potential (ODP)	kg CFC 11 eq.	CML 2001 [50]
5	Global warming potential (GWP)	kg CO_2 eq.	CML 2001 [50]
6	Eutrophication potential (EP)	kg $(PO_4)^{3-}$ eq.	CML 2001 [50]
7	Photochemical ozone creation potentials (POCP)	kg Ethene eq.	CML 2001 [50]
8	Total use of renewable primary energy resources (primary energy and primary energy resources used as raw materials)	MJ, calorific value	CED [51]
9	Total use of non-renewable primary energy resources (primary energy and primary energy resources used as raw materials)	MJ, calorific value	CED [51]
10	Water (user) deprivation potential, deprivation-weighted water consumption (WDP)	m^3 eq.	AWARE [52]
11	Hazardous waste disposed	kg	EDIP2003 [53]
12	Non-hazardous waste disposed	kg	EDIP2003 [53]
13	Radioactive waste disposed	kg	EDIP2003 [53]

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