2024 European Conference on Computing in Construction
Chania, Crete, Greece
July 15-17, 2024

SINGLE POINT OF CONTACT:
DENSITY AS A MAPPING PARAMETER FOR BUILDING MATERIAL DATABASES

Toivo Säwén*[1], Pierre Estève-Bourrel[23], Isac Mjörnell[1],
Alina Galimshina[12], Guillaume Habert[2], and Alexander Hollberg[1]
*Corresponding author: sawen@chalmers.se
[1]Dept. of Architecture and Civil Engineering, Chalmers University of Technology, Gothenburg, Sweden
[2]Institute of Construction and Infrastructure Management, ETH Zürich, Switzerland
[3]School of Engineering, The University of Edinburgh, UK

Abstract

Integrating building performance analysis and life cycle assessment in design requires accurate material databases interfacing different analysis engines. However, mappings of databases developed for different purposes are missing. We evaluate whether beyond material name or ID, density can be used as a mapping parameter between environmental, energy, daylight, and structural databases in two cases in Switzerland and Sweden. In total, 16 out of 19 materials could be confidently mapped based on the information available. The variability of the mapping parameter, density, was ±15 % for structural materials, and up to 64 % for insulation materials. The lasting contribution of this work is a consistent methodology for mapping between material databases.

Introduction

To deal with the major environmental impact of the construction industry, the life cycle impact of buildings needs to be considered and reduced during their design (Röck et al., 2020). This needs to be done without overlooking the functional performance of the buildings (Khoshnava et al., 2020). This calls for the integration of environmental Life Cycle Assessment (LCA) and functional Building Performance Analysis (BPA), including structural analysis, approaches into holistic assessment workflows (Säwén, 2023). Such workflows should be introduced in early design stages to achieve the maximum benefit to the final performance of the design (Hollberg et al., 2018; Meex et al., 2018).

For this purpose, several tools both for BPA (Säwén et al., 2022a) and LCA (Säwén et al., 2022b) have been developed. These tools are usually adapted for use with specific material databases. For instance, the BPA toolset Ladybug Tools includes the EnergyPlus database for thermal material properties (Sadeghipour Roudsari and Pak, 2013), whereas the parametric LCA tool Bombyx provides access to the Swiss KBOB database (Basic et al., 2019).

However, including a multitude of analysis methods during design processes quickly becomes time consuming for the designer (Purup and Petersen, 2020). First, they need to develop the geometric model for architectural purposes. Then, they need to adapt this model for each specific analysis mode considered. This includes identifying the associated material properties relevant to each analysis mode. In early design stages the extensive semantic information provided by Building Information Modelling (BIM) workflows, including material data, is usually not available (Cavalliere et al., 2019). This means the analysis process often becomes time- and resource-consuming enough that the analysis is entirely left out, or at best, carried out on a qualitative basis (Jusselme et al., 2020).

One avenue to streamline this process of modelling and data collection, is to make available a *single point of contact* in terms of material properties. By this we mean, as shown in Figure 1, that instead of selecting material properties individually for each analysis module, the material of each building component is selected only once in the user interface. Then, the material properties associated to each analysis module provided by the given analysis workflow are directly linked. In the analysis step shown in the figure, the various models necessary can then be generated based on a consistent material selection.

There are three main benefits for the designer with this approach. Firstly, the modelling and analysis process is greatly accelerated by only selecting the material once. Secondly, the risk of operator error in terms of selecting incorrect materials, or making incorrect mappings between similar materials with different properties, are sharply reduced as the number of operation required are reduced. Thirdly, the widespread use of such a consistent database would make the comparison between different studies achievable, a task which is currently difficult even within a specific analysis domain (Emami et al., 2019).

However, for this to be possible, the mapping of databases developed for different purposes is needed. The designer needs to be able to retrieve trustworthy data for a range of widely used building materials. Such a mapping does not currently exist in the market. This gap has been pointed out in number of research efforts. To bridge it, Fenz et al. (2021) developed an ontology for materials used in renovation and adapted it for use with Industry Foundation Classes (IFC), i.e., a BIM workflow (Theißen et al., 2020). Li et al. (2020) similarly define an ontology aimed at the materials design industry. Hong et al. (2019) instead propose that automated web crawling techniques could be applied to collect consistent material data and avoiding duplicated efforts by collecting data at different points in the design process.

While these studies provide useful starting point for a consistent ontology for material properties, and consistent

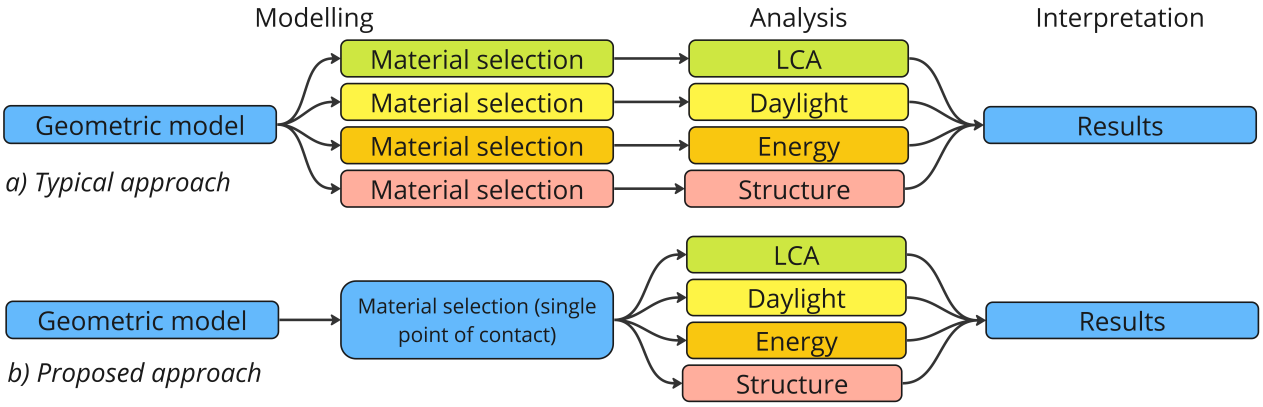

Figure 1: Typical and proposed methods of adding material data to a geometric model.

methodologies for collecting them, no studies known to the authors provide a hands-on approach for actually combining specific databases for LCA and BPA data relevant in the early design stages. We approach this by posing the following research question: *how can material databases developed for different analysis purposes be mapped using material names or IDs and density as mapping parameters?* This question is investigated through two cases, the addition of BPA data to the generic Swedish Klimatdatabas, and the holistic evaluation of an earthen house in Switzerland using KBOB, EnergyPlus, and Eurocode databases for LCA, energy, and structural analysis.

Methods and materials

The overarching method was collecting material data from a variety of sources and intended for different analysis methods, and mapping the data for each material using the density, ρ [$\mathrm{kg\,m^{-3}}$] as a mapping parameter. Both of the case studies are included in an overarching project to study the possibility of developing globally relevant databases for life cycle building performance data as compared to using locally defined databases. The specifics of each case study are described below.

Case study 1: Climate database in Sweden

The aim of the case study carried out in the Swedish context is to create a database which supports a parametric life cycle building performance assessment workflow. This workflow should contain LCA modules as well as BPA modules implemented in the parametric framework Grasshopper® (GH) (Robert McNeel & Associates, 2022).

The workflow is visualised in Figure 2. After geometry is modelled, material data is collected in a single point of contact within the GH interface. Data is collected for the three analysis modules, the analysis is carried out, and the results displayed and exported in the GH interface.

The database used for the climate assessment is the climate database (Klimatdatabas) of the Swedish National Board of Housing, Building and Planning (Boverket) (Boverket, 2023), which is available in Swedish and English. It includes the environmental impact I_{KDB} for the LCA modules A1-A5 [$\mathrm{kg\,CO_2\,eq.\,kg^{-1}}$] (Hollberg, 2016), which is mapped to geometry using the conversion factor density ρ [$\mathrm{kg\,m^{-3}}$] to transform volume of material first to mass of material and then finally to global warming potential. The data included refers to generic materials, not specific products.

There are no standardised databases for energy and daylight material information in Sweden. Instead, data was collected from a variety of sources. The following parameters were collected:

- Thermal conductivity λ [$\mathrm{W\,m^{-1}\,K^{-1}}$]
- Density ρ [$\mathrm{kg\,m^{-3}}$]
- Specific heat c [$\mathrm{J\,kg^{-1}\,K^{-1}}$]
- Roughness [-]
- Thermal absorptance α_t [-]
- Solar absorptance α_s [-]
- Visible absorptance α_v [-]

For the purposes of this article, the thermal conductivity λ and solar absorptance α_s are used for demonstration.

The climate database under consideration currently contains 171 opaque materials. Based on being representative, 10 materials from a variety of categories were selected for evaluation in this study. The mapping process, exemplified in Figure 3 for the case of ”Structural steel, all sorts, primary material” in Klimatdatabas, was performed in two steps:

- Mapping of material names or IDs
- Mapping using parameter value (ρ [$\mathrm{kg\,m^{-3}}$])

The mapping of material name or IDs was done manually, by finding identical or near-identical labels for the materials included in the compared databases. When several candidate materials were present, for instance steel materials

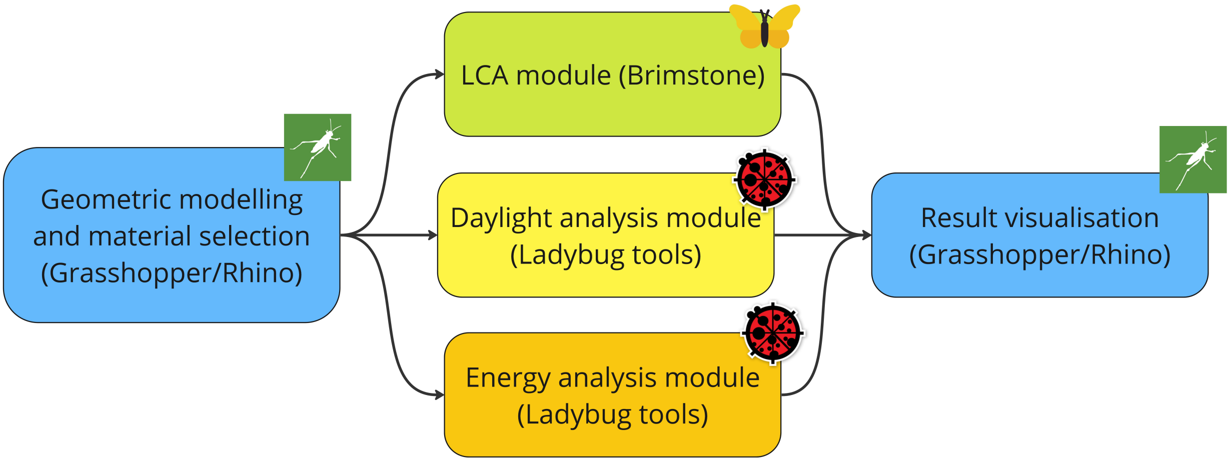

Figure 2: Workflow for parametric life cycle building performance assessment.

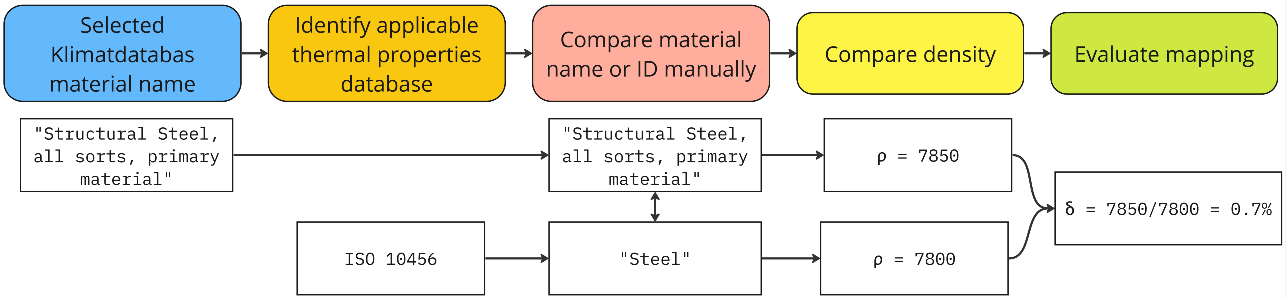

Figure 3: Example of mapping process for material "Structural steel, all sorts, primary material" in Klimatdatabas (Boverket, 2023) to thermal properties database (Pinterić, 2021).

with different structural performance, the material with the closest density was selected. Once the mapping was made, parameter values were collected and the precision of the mapping evaluated using the name or ID and density as comparative parameters to make sure that consistent data was collected.

Case study 2: Earth building in Switzerland

The aim of the Swiss case study is to combine database for an unconventional construction technique: using earthen materials. Earthen materials can be used in a variety of techniques, such as earth bricks or rammed earth, as shown in Figure 4, where rammed earth was used to build a school in the centre of Zurich. In addition to the LCA and BPA modules, the workflow of this case study integrates a Finite Element Modelling (FEM) module in GH, based on the Karamba plugin (Preisinger, 2013).

The FEM database for structural analysis is based on Eurocode materials, such as EN 1992-1-1 (European Committee for Standardisation, 2014) for concrete or EN 338 (European Committee for Standardisation, 2016) for timber. The mechanical properties of the materials are matched to the LCA and BPS database using the conversion factor density ρ [$\mathrm{kg\,m^{-3}}$]. Although earthen materials are missing from the FEM database, the workflow in GH provides the ability to create bespoke isotropic or orthotropic materials. Assuming isotropic linear behaviour,

Figure 4: Umbau Schulpavillon Allenmoos II: school with rammed earth walls in Zurich © Boltshauser Architekten

the mechanical properties of the earthen materials are derived from the average values given in the RILEM State of the Art report (RILEM TC 274-TCE, 2022). The following parameters were collected:

- Young's modulus E [MPa]
- In-plane shear modulus G_a [MPa]
- Transverse shear modulus G_t [MPa]
- Density ρ [$\mathrm{kg\,m^{-3}}$]
- Tensile strength σ_t [MPa]

- Compressive strength σ_c [MPa]
- Coefficient of thermal expansion α [°C^{-1}]
- Strength Hypothesis: Mises, Rankine or Tresca

The LCA database used for the Swiss context is provided by the Swiss Federal Conference of Public Project Owners for the Coordination of Construction and Building Services (KBOB, 2023). This database, available in German and French, provides information on materials, building services and systems, and transport. The Life Cycle Impact Assessment (LCIA) methodology calculates the Global Warming Potential (GWP) of materials, including manufacturing (A1-3) and disposal (C3-4). Energy consumption is assessed according to the Swiss standards SIA 2032 (Société suisse des Ingénieurs et des Architectes (SIA), 2020) for energy efficiency and embodied energy of buildings. This LCA database includes earth materials such as rammed earth, earth bricks or earth plaster. Rammed earth is taken as a reference for earth materials in the KBOB database.

The BPS database follows the EnergyPlus data developed by the US Department of Energy's Building Technologies Office (US DOE BTO, 2023). Although there is a mud material in the database suitable for modelling soils, a bespoke earth material is created against a monitored earth building (Estève-Bourrel et al., 2023).

Once the custom materials have been created and integrated into their respective database, and material names or IDs translated from French and German to English, the mapping procedure is carried out in the same way as in case study 1, using a single contact point in GH. In addition to earth materials, conventional materials such as concrete for the slab or timber for the roof are also considered.

Results

Case study 1: Climate database in Sweden

As seen in Table 1, all the materials presented were possible to map to materials in relevant databases for thermal properties, whereas consistent databases for data relevant for lighting simulations are harder to find. As seen in Figure 5, the mapping using the density ρ as a mapping parameter was generally successful, with a divergence of ± 15 % for most materials, notwithstanding EPS with a divergence of 36 %.

It should be noted that when collecting the data, no single database could be identified which collected all the relevant information. Instead, data was collected from varyingly from ISO standards (Pinterić, 2021), online resources (The Engineering ToolBox, 2009; Svenskt trä, 2003), and material manufacturers (Vitro Glazings, 2020; Eco Merchant, nd).

Case study 2: Earth building in Switzerland

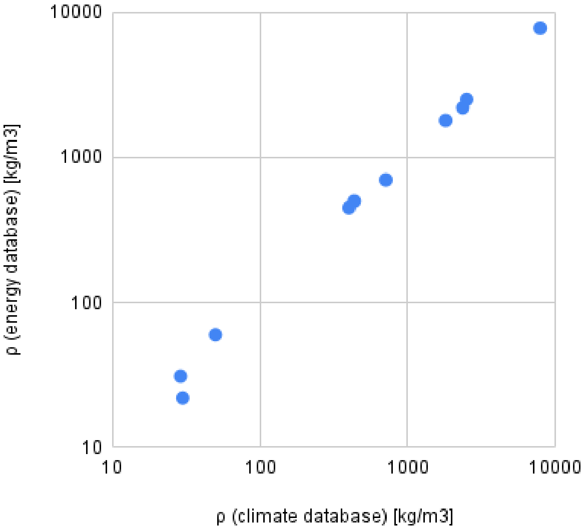

Figure 5: Overlap of parameters in baseline database and comparison database in case study 1 (Swedish climate database). X axis shows the density in the climate database for all materials, and Y axis shows the density in the respective energy databases.

In the case study 2, the earth building, the densities of the materials considered have a variability of less than 10%. The KBOB LCA database suggests a range in the density of mineral wool and cellulose fibres, with values ranging from 32 to 160 $\mathrm{kg\,m^{-3}}$ and 35 to 60 $\mathrm{kg\,m^{-3}}$ respectively, which can create a greater disparity in the correct matching of densities, see Figure 6. The fact that the materials are also matched on the basis of their names or IDs confirms that they match correctly.

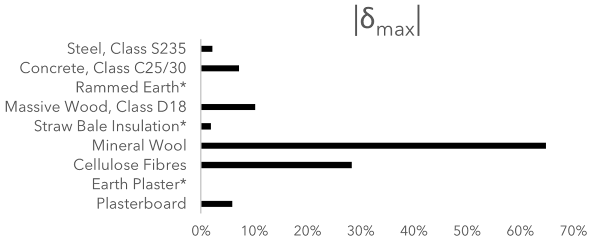

*Figure 6: Maximum absolute difference $|\delta_{max}|$ between the densities of the materials considered for the three studied databases (KBOB, EnergyPlus and Eurocodes). *bespoke material*

It is worth noting that the non-conventional construction materials chosen for this case study, shown in Table 2 such as rammed earth, straw bale or earth plaster, are included in the KBOB LCA database, but are absent from the EnergyPlus and Eurocode databases. The creation of these bespoke data is therefore based on scientific literature. The RILEM State of the Art book (RILEM TC 274-TCE, 2022) provides mechanical and thermal values for earth materials, including density matching the value in the KBOB database. The thermal characteristics were then checked against a monitored earth building. The thermal properties of straw bale were derived from experimental tests (Czajkowski et al., 2022).

Table 1: Excerpt of material mapping in case study 1 (Swedish climate database). I_{KDB} is the environmental impact (A1-A5 modules), λ is the thermal conductivity, and α_s is the solar absorptance. ρ_c is the density defined in the climate database, ρ_e is the density defined in the energy database, and ρ_d is the density defined in the reference data used for daylight material data. δ refers to the difference (in percent) between the ρ_c and ρ_e.

Material ID	I_{KDB}	ρ_c	λ	ρ_e	α_s	ρ_d	δ
Structural steel, all sorts, primary material	3.4	7850	50	7800[a]	0.65	7820	0.7
Floatglass (FG)	1.8	2500	0.94	2510[b]	0.14	2510	-0.4
Ready-mix made concrete, buildings C20/25	0.13	2350	1.65	2200[a]	0.6	2200	6.8
Bricks	0.38	1800	0.8	1800[a]	0.68	1900	0
Gypsum, standard plasterboard	0.34	710	0.21	700[a]	0.35	800	1.4
Glulam, u 12 %, spruce	0.18	434	0.13	500[c]	-	-	-13
Autoclaved Aerated Concrete, (AAC)	0.65	400	0.1	450[d]	-	-	-11
Wood fibre insulation, bats	0.43	50	0.036	60[e]	-	-	-17
EPS, expanded polystyrene	4.3	30	0.035	22[a]	-	-	36
Stone wool, bats and rolls	1.7	29	0.035	31[a]	-	-	-6.5

[a] Pinterić (2021)
[b] Vitro Glazings (2020)
[c] Svenskt trä (2003)
[d] The Engineering ToolBox (2009)
[e] Eco Merchant (nd)

Discussion

Compared to creating different models for each analysis mode, the creation of a single model which interfaces with several analysis engine would speed up the analysis process by greatly reducing the time needed for modelling and data collection. However, this hinges on the use of one database which can be used to define material properties for a variety of analysis methods. The currently available databases with life cycle impact data generally only include this data as well as conversion factors such as density to be able to map it to geometric data. This is true also in the case for the two climate databases considered in the present study: the Swedish Klimatdatabas, and the Swiss KBOB.

This means data needs to be collected from other resources to add the information needed for holistic life cycle building performance analysis including energy, daylight, and structural analyses, etc. We investigated the extent to which these resources could be mapped to the climate databases using the density as a quantitative and the resource name or ID as a qualitative parameter.

We found that the mapping to publicly available databases for energy analysis could be done based on the name or ID for most typical construction materials like concrete and steel. However, there was a variation in density ranging between ±15% for most structural materials, and up to 64 % for insulation materials. This means there is an uncertainty in terms of how well the material properties are actually matched. Future work could delve into explaining these discrepancies in a deeper examination of the databases, or alternatively, evaluate what kind of uncertainties are acceptable when making design decisions based on the analysis results. It would also be relevant to study the impact of the need for translation between databases defined using different languages.

Further, we found that some important materials in the sustainable transition are missing even in widespread material databases like the ones offered by ISO (ISO 10456 regarding the hygrothermal properties of building materials and products (Pinterić, 2021)) and EnergyPlus (US DOE BTO, 2023). This includes wood materials like glulam and earthen materials like rammed earth and earth plaster, data for which instead needs to be collected from specific material manufacturers, which risks a bias. We also found that while energy data is accessible for most materials, data necessary for daylight analyses like reflectances/absorptances are more obscure and also require the use of data from specific manufacturers.

The method of using the density as a mapping parameter in addition to the name or ID of the specific resource appears useful based on our study, but it adds a layer of uncertainty to an already highly uncertain situation in the early design stages. This situation could be improved through a collective effort to improve climate databases by adding information needed also for other analysis modes. Alternatively, databases for structural, energy, and daylight analyses could be updated to also include climate information relevant to the local context. However, the constant evolution of life cycle data as more ecological approaches are adopted, and life cycle assessments are carried out in greater detail, mean that any such database needs to be in constant flux and requires regular update as new life cycle information is retrieved.

One limitation of our study is of course that only a few materials were selected for analysis. In future work, a wider overview of materials, in different national contexts, could be provided. In such an overview, the deeper analysis of the risk for false positives would be beneficial, especially if transitioning from manual to automatic mapping meth-

Table 2: Mapping of materials in case study 2 (earth building in Switzerland). I_{KBOB} is the environmental impact (A1-3; C3-4 modules), C^{bio}_{KBOB} is the biogenic carbon in the material, ρ_{KBOB} is the density defined in the climate (KBOB) database, ρ_{E+} is the density defined in the energy (EnergyPlus) database, ρ_{EU} is the density defined in the structure (Eurocode) database. $|\delta_{max}|$ refers to the absolute difference (in percent) between ρ_{KBOB}, ρ_{E+} and ρ_{EU}.

Material ID	I_{KBOB}	C^{bio}_{KBOB}	ρ_{KBOB}	ρ_{E+}	ρ_{EU}	$\|\delta_{max}\|$
Steel, Class S235	0.736	0	7850	7680	7800	2.2
Concrete, Class C25/30	0.177	0	2500	2322	2500	7.1
Rammed Earth	0.019	0	2000	2000[a]	2000[a]	0
Massive Wood, Class D18	0.129	0.413	485	540	500	10
Straw Bale Insulation	0.096	0.368	215	211[b]	-	0
Mineral Wool	1.19	0	32/160	91	-	64
Cellulose Fibres	0.280	0.404	35/60	43	-	28
Earth Plaster	0.032	0	1800	1800[a]	-	0
Plasterboard	0.301	0.018	850	800	-	5.9

[a] RILEM TC 274-TCE (2022)
[b] Czajkowski et al. (2022)

ods. Another important future work is cross-referencing of a number of available databases for improved robustness. Further, it should be noted that different parameters were collected in the different case studies based on their respective purpose. The overlap of the case studies is the evaluation of name or ID and density as mapping parameters.

Since the only parameters mapped were the name or ID and the density, there is a great risk of misidentifying some materials, leading to incorrect data mappings. One potential way of overcoming this would be comparing further data attached to each resource, such as the material description commonly provided. To investigate such qualitative parameters, natural language processing (NLP) methods could be applied to compare great amounts of textual data.

We acknowledge that the proposed method only resolves the issue of selecting consistent material data for an existing geometric model for use with a variety of simulation tools. Further work is needed to streamline the workflows which generate each necessary analysis model from this single geometric model with added material data.

Conclusion

In the present study, the mapping of life cycle data from the Swedish Klimatdatabas and the Swiss KBOB database to databases for energy, daylight, and structural material properties was investigated. This was done by comparing the names or IDs and densities of materials to check whether the materials could be mapped.

A divergence of ±15 % was detected for structural materials, whereas the divergence of up to 64 % was detected for insulation materials. This indicates that while the mapping using the proposed methodology is possible, it introduces a great uncertainty in terms of the material properties.

We propose the development of robust, nationally and internationally relevant material databases including life cycle information along with energy, daylight, and structural material properties. The mapping of materials used when developing such databases could include the material name or ID, the density, and other parameters. These databases need to be periodically updated and revised as the life cycle impact of materials is improved through the sustainable transition of the production industry. The benefit of the use of such a holistic database is reducing modelling and analysis time, avoiding user errors, and allowing direct comparison between analyses, by only selecting material information once as shown in Figure 1.

In future work, we propose that the applied methodology of matching materials through resource name or ID and density is further tested by comparing several available databases, and by testing it in different national contexts.

Acknowledgements

The research presented in this paper was partly funded by the Swedish Energy Agency, project number 51715-1.

References

Basic, S., Hollberg, A., Galimshina, A., and Habert, G. (2019). A design integrated parametric tool for realtime life cycle assessment – bombyx project. IOP conference series: earth and environmental science, 323:012112. Publisher: IOP Publishing.

Boverket (2023). About Boverket. Online: https://www.boverket.se/en/start/about/about-bover ket/(accessed 2023-12-12).

Cavalliere, C., Habert, G., Dell'Osso, G. R., and Hollberg, A. (2019). Continuous BIM-based assessment of embodied environmental impacts throughout the design process. Journal of Cleaner Production, 211:941–952.

Czajkowski, L., Kocewicz, R., Weres, J., and Olek, W. (2022). Estimation of thermal properties of straw-based insulating panels. Materials, 15:1073. `https://www.ncbi.nlm.nih.gov/pmc/articles/PMC8838588/`.

Eco Merchant (n.d.). Steico flex 036 wood fibre insulation batts (100mm x 375mm wide). Online: `https://www.ecomerchant.co.uk/interior/insulation/steico-flex/steico-flex-wood-fibre-insulation-375mm.html` (accessed 2023-12-13).

Emami, N., Heinonen, J., Marteinsson, B., Säynäjoki, A., Junnonen, J.-M., Laine, J., and Junnila, S. (2019). A life cycle assessment of two residential buildings using two different LCA database-software combinations: Recognizing uniformities and inconsistencies. Buildings, 9(1).

Estève-Bourrel, P., Beckett, C., Bosché, F., and Habert, G. (2023). How load-bearing earth construction can meet today's energy demands? In International Conference on Biobased Building Materials 2023, Vienna. `https://www.researchgate.net/publication/374000156_How_load-bearing_earth_construction_can_meet_today%27s_energy_demands`.

European Committee for Standardisation (2014). EN-1992-1-1:2004+A1:2014 - Eurocode 2: Design of concrete structures. Part 1-1: General rules - Rules for buildings, bridges and civil engineering structures. `https://eurocodes.jrc.ec.europa.eu/EN-Eurocodes/eurocode-2-design-concrete-structures`.

European Committee for Standardisation (2016). EN 338:2016 - Structural timber. Strength classes. `https://www.en-standard.eu/csn-en-338-structural-timber-strength-classes/`.

Fenz, S., Bergmayr, J., Plattner, N., Chávez-Feria, S., Poveda-Villalón, M., and Giannakis, G. (2021). Integration of building material databases for IFC-based building performance analysis. In Proceedings of the International Symposium on Automation and Robotics in Construction, volume 2021-November, pages 182–189. ISSN: 2413-5844.

Hollberg, A. (2016). Parametric Life Cycle Assessment: Introducing a time-efficient method for environmental building design optimization. PhD thesis, Bauhaus-Universität, Weimar.

Hollberg, A., Lichtenheld, T., Klüber, N., and Ruth, J. (2018). Parametric real-time energy analysis in early design stages: a method for residential buildings in Germany. Energy, Ecology and Environment, 3(1):13–23.

Hong, S.-H., Lee, S.-K., and Yu, J.-H. (2019). Automated management of green building material information using web crawling and ontology. Automation in Construction, 102:230–244.

Jusselme, T., Rey, E., and Andersen, M. (2020). Surveying the environmental life-cycle performance assessments: Practice and context at early building design stages. Sustainable Cities and Society, 52:101879.

KBOB (2023). Données écobilans dans la construction. Online: `https://www.kbob.admin.ch/kbob/fr/home/themen-leistungen/nachhaltiges-bauen/oekobilanzdaten_baubereich.html` (accessed 2023-12-13).

Khoshnava, S. M., Rostami, R., Mohamad Zin, R., Štreimikienė, D., Mardani, A., and Ismail, M. (2020). The Role of Green Building Materials in Reducing Environmental and Human Health Impacts. International Journal of Environmental Research and Public Health, 17(7):2589. Number: 7 Publisher: Multidisciplinary Digital Publishing Institute.

Li, H., Armiento, R., and Lambrix, P. (2020). An ontology for the materials design domain. Lecture Notes in Computer Science (including subseries Lecture Notes in Artificial Intelligence and Lecture Notes in Bioinformatics), 12507 LNCS:212–227. ISBN: 9783030624651.

Meex, E., Hollberg, A., Knapen, E., Hildebrand, L., and Verbeeck, G. (2018). Requirements for applying LCA-based environmental impact assessment tools in the early stages of building design. Building and Environment, 133:228–236.

Pinterić, M. (2021). Building Physics: From physical principles to international standards. Springer International Publishing.

Preisinger, C. (2013). Linking structure and parametric geometry. Architectural Design, 83:110–113.

Purup, P. B. and Petersen, S. (2020). Requirement analysis for building performance simulation tools conformed to fit design practice. Automation in Construction, 116:103226.

RILEM TC 274-TCE (2022). Testing and Characterisation of Earth-based Building Materials and Elements: State-of-the-Art Report. `https://link.springer.com/10.1007/978-3-030-83297-1`.

Robert McNeel & Associates (2022). Rhinoceros 3D. Online: `https://www.rhino3d.com/` (accessed 2023-12-12).

Röck, M., Saade, M. R. M., Balouktsi, M., Rasmussen, F. N., Birgisdottir, H., Frischknecht, R., Habert, G., Lützkendorf, T., and Passer, A. (2020). Embodied GHG emissions of buildings – the hidden challenge for effective climate change mitigation. Applied Energy, 258:114107.

Sadeghipour Roudsari, M. and Pak, M. (2013). Ladybug: A parametric environmental plugin for grasshopper to help designers create an environmentally-conscious design. In Proceedings of BS 2013: 13th Conference of the International Building Performance Simulation Association, pages 3128–3135.

Société suisse des Ingénieurs et des Architectes (SIA) (2020). SIA 2032:2020 - L'énergie grise – Établissement du bilan écologique pour la construction de bâtiments. `http://shop.sia.ch/collection%20des%20normes/architecte/sia%202032/f/2020/F/Product`.

Svenskt trä (2003). Värmeegenskaper. Online: `https://www.traguiden.se/om-tra/materialet-tra/traets-egenskaper-och-kvalitet/termiska-egenskaper1/varmeegenskaper/` (accessed 2023-12-13).

Säwén, T. (2023). Early stage architectural design practice perspectives on life cycle building performance assessment. Licentiate thesis, Chalmers University of Technology, Gothenburg, Sweden.

Säwén, T., Magnusson, E., Sasic Kalagasidis, A., and Hollberg, A. (2022a). A characterisation framework for parametric building performance simulation tools. In Proceedings of BuildSim Nordic 2022, volume 362. E3S Web of Conferences.

Säwén, T., Magnusson, E., Sasic Kalagasidis, A., and Hollberg, A. (2022b). Tool characterisation framework for parametric building LCA. In IOP Conference Series: Earth and Environmental Science, volume 1078, page 012090.

The Engineering ToolBox (2009). Solids - densities. Online: `https://www.engineeringtoolbox.com/density-solids-d_1265.html` (accessed 2023-12-13).

Theißen, S., Höper, J., Wimmer, R., Zibell, M., Meins-Becker, A., Rössig, S., Goitowski, S., and Lambertz, M. (2020). BIM integrated automation of whole building life cycle assessment using german LCA data base ÖKOBAUDAT and industry foundation classes. In IOP Conference Series: Earth and Environmental Science, volume 588. ISSN: 1755-1307 Issue: 3.

US DOE BTO (2023). Energyplus. Online: `https://www.energyplus.net/` (accessed 2023-12-13).

Vitro Glazings (2020). Clear technical product data. Online: `https://www.vitroglazings.com/media/rnff0xlj/vitro-clear-technical-pds.pdf` (accessed 2023-12-13).