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Early Design Stage Building LCA using the LCAbyg tool: Comparing Cases for Early Stage and Detailed LCA Approaches

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Abstract. Life Cycle Assessment (LCA) is used and accepted as a method to assess environmental impacts and resource use of buildings. In practice, LCA is typically used in stages where the design of the building is already finalized. However, LCA-calculations from early design stages can be used actively in design and optimization of the building. One of the obstacles to early stage LCA is that extensive data input on precise material types and amounts is needed, which is limited in early design stages. The simplifications needed for a designer in an early design LCA is addressed in a research project, where an extensive library of predefined building components and installations were developed and integrated into the existing Danish LCAbyg tool. The library assists the user in establishing a full building inventory by simple inputs of geometry of the building and a selection from the library of building element layers. However, the simplified approach to LCA of a building at early design stages inevitably affects results compared with results of a calculation made at later design stages where more, specific data is available. This paper presents an evaluation of building cases, modelled with the same background database and life cycle stages, using the simplified early design LCA approach and a detailed LCA approach. The evaluation includes testing of how well the predefined components in the early design approach fit with the case buildings and comparisons of the total material input and precision of the final LCA results.

1. Introduction

1.1. Early design LCA for buildings

Life Cycle Assessment (LCA) is an established and widely used method for assessing and documenting the environmental impact and resource use for products and services.

Conducting a full scope and detailed building model LCA requires both qualifications and large amounts of documentation. Full scope LCA's on buildings are thus rarely made [1,2]. The LCA scope is typically adjusted to a more simplified LCA approach that includes less processes, for instance by reducing the number of life cycle stages, which is also the recommended approach in the sustainability initiatives from the European Commission's Joint Research Centre Level(s) and EeBGuide [3][4]]. But even with these simplifications, the work going into a building LCA is still very large: For instance, it requires inputs of quantity and product type for all the materials used.

In the early design phases of the building project it is an even larger challenge to quantify and specify building products because final dimensions are not known and several design options may need to be compared. However, the early design phases are the phases when informed decisions can be made. The LCA-task should therefore be easy and fast in early design phases.

Approaches for early design tools for LCA include simplifying the method even further with a selective approach; by only including elements that have the greatest relevance to the results [5]. Another approach is to use predefined elements from a library which is also a recommended approach for early design environmental assessment tools [6]. This is the approach used in the new LCAbyg tool

1.2. LCAbyg tool – Early design functions in version 4.0 Beta

In the new version of LCAbyg (version 4.0 beta), a library-based simplification approach has been used [7]. LCAbyg is a free tool from Denmark for performing LCA on buildings [8,9]. The predefined component library in version 4.0 beta contains building products that are bundled together in typical or conservative dimensions. For estimating quantities, the tool introduces a "guided inventory input". The tool is designed to be used in all stages of the building project, and it is therefore possible to adjust dimension in the component library, as more knowledge becomes available in the project.

LCAbyg 4.0 Beta differs from the existing LCAbyg version 3.2 only by introducing the above mentioned functions. The calculations are based on the same selected life cycle stages and LCIA data.

1.3. Evaluating early design approach

When using an early design approach with a library of building components, the results will naturally vary from the detailed LCA approach. Testing the performance of the early design tool compared to a more detailed LCA is therefore relevant for estimating if the tool gives a true representation of the building's environmental performance. This can be evaluated by testing the early design approach against a more detailed approach.

A similar evaluation has previously been done in the library based (and simplified geometry) early design tool, LCAP [10], where the performance of the early design tool is tested against a more detailed LCA approach [11]. The result is 4-19% lower in global warming potential (GWP) for the buildings where the early design tool was used. The reduced impact is mainly due to the exclusion of some building elements in the early design tool, including building services and internal doors.

In LCAbyg 4.0 Beta, the early design approach has a comprehensive component library, that also includes several building services and the completeness of the inventory is high. The component library uses conservative estimates in terms of material use and LCIA data. Contrary to the LCAP-tool, the impact from the materials in the early design approach should therefore give higher impacts than a detailed approach because the catalogue is conservative and completeness is higher than a typical LCA on building.

This paper evaluates building cases where a detailed LCA has been performed with an early design component library-based LCA approach using two generations of the tool, LCAbyg (version 3.2 and 4.0 beta). The evaluation will consider the inventory of cases with a detailed LCA approach compared with component library in early stage approach, and the mass and impact in GWP of the two approaches. Lastly the precision of the early design approach will be estimated.

2. Method

2.1. Study samples

The case samples presented in table 1 consists of three residential buildings that have been certified with the Danish version of DGNB certification system for sustainable buildings [12]. The buildings are completed between 2016 and 2018. The cases are selected because they represent different

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material compositions: One with wooden-frames, one in Cross Laminated Timber (CLT), and the final with concrete walls and wooden roof.

Table 1. Case buildings

	Building type	Description
Case A	Residential, Terraced house	*Foundation and ground floor slab*: concrete, EPS insulation *Walls and slabs/roof:* prefab wood elements, mineral wool insulation *Surfaces:* paint on internal surfaces, externally plaster on ventilated facade and roofing felt on roof.
Case B	Residential, Multi-family building	*Foundation and ground floor slab*: concrete, EPS insulation *Walls and slabs/roof:* CLT wall elements with columns and beams in steel and wood, slabs in concrete/CLT-hybrid, truss roof, mineral wool and cellulose insulation *Surfaces* in wood and roofing felt on roof.
Case C	Residential, Terraced house	*Foundation and ground floor slab*: concrete, EPS insulation *Walls and slabs/roof:* concrete walls with roof in wood and CLT. Mineral wool insulation. Structure with steel and wood beams and columns. *Surfaces:* paint on internal surfaces, externally brick and roofing felt on roof.

2.2. Scenarios

The early design approach for LCA is evaluated through three modeling scenarios listed in table 2. BL scenario has been calculated using LCAbyg 3.2, while LCAbyg 4.0 is used for scenarios ED1 and 2 in order to make use of the new component library.

Table 2. Scenarios

Abbr.	Scenario	Inventory
BL	Baseline (detailed approach)	**Specific inventory** taken from DGNB-certified cases. Example (wall): Actual wall area with material type and dimension according to inventory from DGNB.
ED1	Early design 1	**Component library.** A combination of predefined components from library and specific element areas from DGNB-certified cases. Example (wall): Actual wall area, but material type and dimension according to the closest match available in the component library.
ED2	Early design 2	**Adjusted component library.** Same as ED1, but with adjustments of materials type and dimensions. Example (wall): Actual wall area with material type and dimension according to inventory from DGNB, however, without removing extra library elements such as paint, connecters etc. (which may not be included in BL).

BL is the life cycle inventory taken from cases, which have been DGNB certified. The inventory elements from the three cases can be seen in table 3.

ED1 uses the component library to match material type and dimensions of the building elements in the cases as good as possible.

ED2 follows ED1, however, dimensions and material type for major elements in the building structure and insulation have been adjusted where needed according to the original case inventory. Table 3 shows all adjustments and their nature, may it be changes in material property or quantity.

Scenarios ED1 and ED2 include all the element layers listed in table 3 (if applicable), thus making the building inventory more complete than the detailed approach (BL). For estimating quantities in the element layers that are not included in the DGNB cases (and therefore no data is available); the “guided inventory input” from LCAbyg 4.0 Beta is used. The guided inventory input uses basic building information including gross and heated floor area, floor height, no. of floors etc. for estimating quantities. In this study only the technical installations have been estimated, if they are not already given in the DGNB cases.

Table 3. Inventory scheme. Level of completeness and adjustments are given for all cases and scenarios. Columns BL show the as-is state of completeness in the DGNB cases. Columns ED2 show the adjustments made. Scenario ED1 uses library material choice and detailing for all element layers and is not shown.

Building element	Element layers	Case A		Case B		Case C	
		BL	ED2	BL	ED2	BL	ED2
Foundations	Foundations	x		x		(x)	
Ground floor slab	Flooring	x		x		x	
	Load-bearing system	x	m	x	q	x	q
	Insulation and underlay	(x)	q	(x)		x	q
External walls	Inside finishing	(x)		n/a		x	
	Load-bearing and insulating system	x	q, m	x	q, m	x	q
	Façade system	x		x	m	x	
Internal walls	Finishing	x		x		x	
	Load-bearing	x	q, m	x	q, m	x	q
	Finishing	x		n/a		x	
Floor deck	Flooring	x		x		x	
	Load-bearing and insulating system	x	q	x	q	x	q, m
	Ceiling	(x)		x		x	
Columns and beams	Columns and beams	n/a		x		n/a	
	Finishing	n/a		-		n/a	
Balconies	Platform	x	q	n/a		n/a	
	Mounting	-		n/a		n/a	
	Balustrates and handrails	x		n/a		n/a	
Roof	Roof cladding	x		x		x	
	Load-bearing and insulating system	x	q, m	x	q, m	x	q, m
	Ceiling	x		x		x	
Windows, doors, glazing systems	Profiles	x		x		x	q
	Panes	x		x		x	
	Doors	x		-		x	
Drainage	Soil pipe	-		-		-	
	Down comer	x		-		-	
Drinking water	Hot water tank	-		-		x	
	Piping	x		-		-	
Space heating	Supply	x		-		-	
	Piping	n/a		-		-	
	Radiator / floor heating	x		x		-	
Ventilation and cooling	Supply	-		x		-	
	Ductwork	x		-		-	
Electrical units	PV-panels	x		n/a		x	

BL: [x] complete or including main elements. [(x)] poor completeness within the element layer. [-] not included. [n/a]: not relevant to case.
ED2: [q] quantity adjustments. [m] material adjustments.

2.3. *Life cycle assessment*

The LCA is conducted in compliance with the standards ISO 14040-44 and [13,14] EN 15978 standard [15] for LCA on buildings. The functional equivalent is set to 1 m^2 residential gross floor area. The LCA includes the following life cycle stages: A1-A3 production of building products, B4 replacement of building products in use stage, C3-C4 waste treatment and disposal of building products at End of Life (EoL). Operational energy consumption (stage B6) is not included in the LCA, due to the study's focus on impacts related to embodied materials. The LCA uses a reference study period of 100 years following the Danish guidelines on building's service life [16]. This report also provide service lives for building products, which are used for estimating the number of replacements of building products in the use stage (B4).

The modelling is carried out in two generations of the Danish LCAbyg tool. Both tools use the same LCIA database, which consists of mainly extracts of Ökobau generic database from version 2016. In the Ökobau database the life cycle impact assessment is done with characterisation method

CML-IA baseline version 4.1. The study only reports on the impact category Global Warming Potential (GWP), for simplicity reasons.

3. Results

3.1. Impacts from early design scenarios

Impacts for GWP can be seen in figure 1 for the three scenarios. Using the early design tool (scenario ED1) gives a higher impact of 18-42% for the whole building compared to the detailed LCA approach. This is due to the additional building elements, the conservative materials estimation and the completeness of inventory from the early design approach.

The library material estimates are adjusted to the specific case in scenario ED2; here the impacts in GWP for the building cases are still higher than BL, but for cases B and C the GWP has decreased from 42% down to 31% and from 27% to 21% above BL. However, case A has an increase in GWP from 18% to 33% higher than BL. One of the reasons case A increases is that the insulation quantity is underestimated in ED1. This is because case A is a low energy building and the house is more insulated than a house that only complies with operational energy demands from the Danish Building Code. Another reason is that the type of insulation material used some places in case A, has a substantially higher impact than the insulation in the case building, such as rigid mineral wool.

Insulation material also gives inaccurate results in case B, where the external walls in ED1, gives an impact three times that of BL and ED2, as shown in Figure 1. This is mainly due to use of cellulose insulation in the case building, which is not an option in the component library, see table 4. Furthermore the CLT dimensions is highly overestimated in the library layer because this is designed as a load carrying element, while the case element is not. A better option would have been to choose the frame construction in library, which has the opportunity to choose cellulose insulation. While most building elements have a higher impact in the early design scenarios, this is not the case for the foundation. For all cases; the impacts from foundation are smaller in early design scenarios, due to a smaller amount of materials used for the scenarios. Overall, however, figure 1 shows that on a building element level, the impacts from the early design approach in ED1 gives a good representation of the adjusted scenario impacts in ED2.

3.2. Impact related to inventory completeness

The impact from added inventory elements shown above the dotted line in figure 1 (these are the elements layers from table 3 that were not included in BL) contribute with between 3% and 20% of the building's total GWP, depending on case building and scenario. Case B has the smallest inclusion of building elements in BL, and consequently this is where we see the largest contribution when elements are added. The added impacts from building services and doors contribute notably in case B. Case A shows the lowest impact from only adding a number of elements in building services.

If we exclude the added elements from the early design inventory, thereby only including element layers that exist in BL, we get a clearer picture of the library's difference from BL when it comes to completeness and conservative estimates. These differences can be seen in the case results for scenario ED1, and shows that GWP is 14%, 21% and 19% above BL. When adjustments have been made in scenario ED2, the results provides an understanding of just the difference in completeness between early design approach and BL; the GWP is 29% higher for case A and only 9% and 12% higher for cases B and C than baseline.

The difference in completeness for Case A is substantially higher due to impacts from finishes on internal walls and from floors and ceiling on floor deck, roof and ground floor slab as illustrated in figure 1. The higher completeness comes from including the structure in floors and ceiling, and amounts of paint to cover all internal as well as inside parts of external walls, which was not adequate in the BL scenarios for case A.

For case B and C; the higher GWP also stems from finishes on walls and floor and ceilings, and for case B; the windows were missing materials for frame.

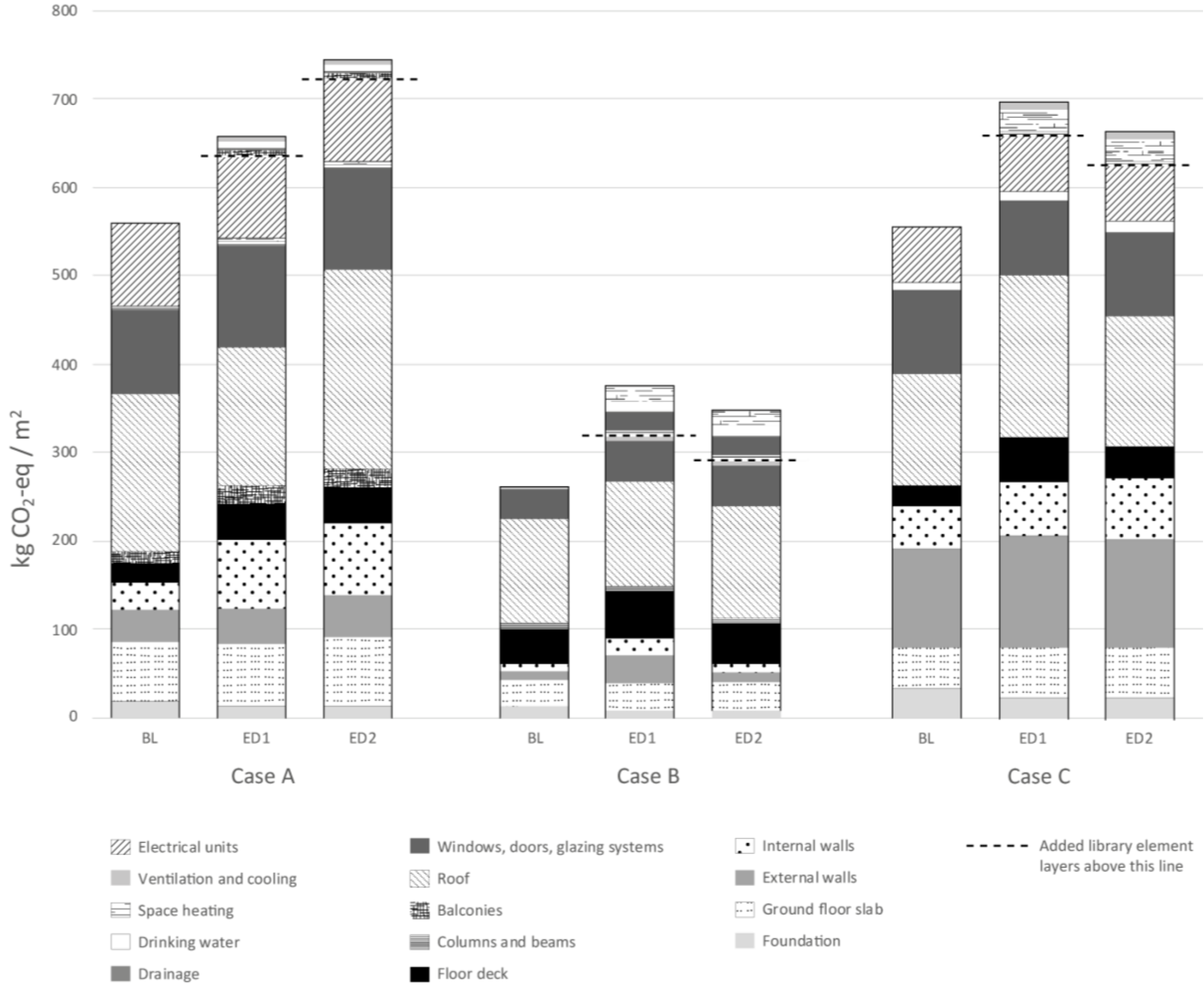

Figure 1. GWP impacts for building elements in the three case buildings for the different scenarios: Detailed approach (BL), early design (ED1), early design with adjustements of material and dimension (ED2). Included life cycle stages are A1-A3, B4 and C3-C4.

Table 4. Materials use of 1 m^2 external wall in case building B. The element has a notable difference in GWP for the three scenarios, mainly due to a different insulation type in the component library used in ED1.

BL		ED1		ED2	
260 mm	Cellulose fibre	300 mm	Mineral wool	*260* mm	Cellulose fibre
40 mm	CLT	100 mm	CLT	*40* mm	CLT
-	-	0.38 kg	Wood protection	-	-
30 mm	Pine wood	30 mm	Pine wood	30 mm	Pine wood
-	-	150 g	Screws, nails, fittings in galvanized steel	150 g	Screws, nails, fittings in galvanized steel
150 g	Aluminum profile	2 mm	Wood lists	2 mm	Wood lists
1 pcs	Plaster board, wind barrier	1 pcs	Plaster board, wind barrier	1 pcs	Plaster board, wind barrier

3.3. Correlation of mass and impact for early design scenarios

In early design scenarios both material mass and GWP is increased compared to BL scenario, the relation to BL on mass and GWP can be seen in Figure 2. For cases B and C, the GWP has increased substantially more than the mass, implying that the extra material included in the component library has a large impact on GWP compared to the existing mass. A specific example of this is the internal walls in case B: In scenario B2 the increase in mass is 7 %, while the increase in GWP is 54%. This is due to adding material elements such as paint and membrane conjoining wet rooms, which are materials with high impact in GWP per mass.

Case A shows the opposite trend with a higher added mass, and lower GWP. This is mainly due to the gravel below the ground floor slab, which was not included in BL. Gravel has relatively low GWP per mass, which explains the results. If gravel is removed from the assessment; case A will have a mass compared to BL of 116%, which is similar to the trend for case B and C (103% and 113%). The reduced GWP from removing gravel is only from 133% to 132%, thereby showing a similar trend in case A; of higher increase in GWP than in mass when using ED-scenarios.

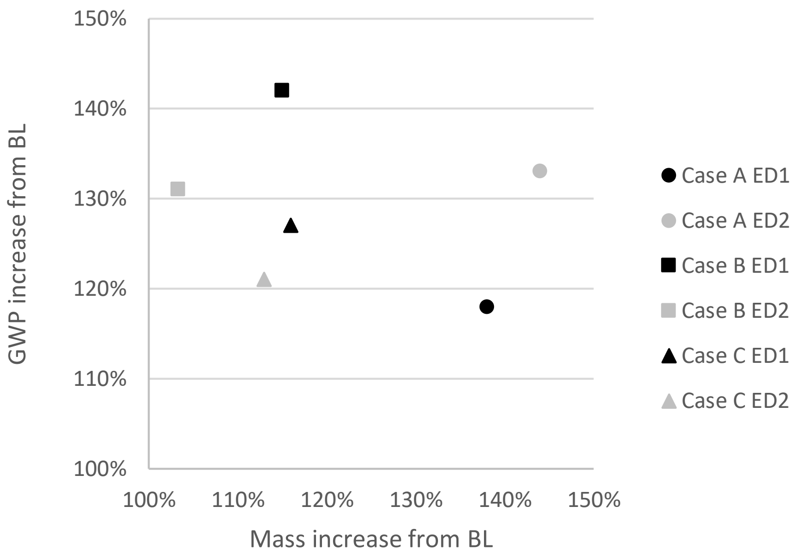

Figure 2. Mass and GWP of building cases for the two scenarios (ED1 and ED2) seen in relation to BL scenario (100 %).

4. Discussion

4.1. Component library

Differences in inventory completeness across the scenarios have shown to have a large impact on the results. The BL inventory both lack entire building elements and components or building products in the original cases. These additional materials included in the early design scenarios even shows to have a large impact on GWP when seen in relation to the building mass, making them an important part of the LCA.

The component library is conservative in estimating materials, especially insulating materials. The insulating materials is dimensioned to comply with building regulations in terms of thermal conductivity, where only the insulating material is used to dimension the thermal conductivity (without taking the remaining layers in the building element into account) [7]. However, special circumstances such as low energy buildings will likely surpass the dimension of insulating material in the component library, as was the case for case A. For low energy buildings and buildings that have special demands, the LCA practitioner must take it into account by adjusting dimensions of the insulating material first and foremost (this will likely be a natural process, because the practitioner, typically an architect or engineer, is aware of all elements that are not standard throughout designing). This will apply for all cases with special designs that are likely to make material use greater than the norm.

The same approach should apply to the material type used to insulation materials. Some of the notable differences in impacts in the component library estimates stem from the type of insulation material. The LCIA data used for rigid mineral wool has a much higher impact in GWP than normal mineral wool, and cellulose insulation, on the other hand, performs much better. When there is no cellulose to choose in the library, the results of the assessment will give a higher impact and thus a conservative estimation, which is as expected. However, when the rigid mineral wool cannot be chosen in the library, this can have a large impact on the results, giving the assumption that the building performs better than it actually does. In the component library of LCAbyg 4.0 Beta it is possible to choose elements with rigid insulation, just not for the particular structure used in Case A. A solution could be to include more types of insulation materials in the catalogue, however, a value of the catalogue is also that it is not too large.

4.2. Precision of results

The early design tool is evaluated by comparing with a detailed LCA, however, in material completeness, the early design tool can be considered even more 'detailed', than the detailed approach. Evaluating precision by comparing to the detailed approach would therefore be misleading.

The estimates on material and dimensions made in the component library, however, can be evaluated for GWP by looking at the two early design scenarios and the deviation in results from using the library (ED1) compared to the scenario where the library has been adjusted (ED2). For cases A, B and C the library shows a deviation in results of -12%, 11% and 6%, (not including the added library elements, which will only make the difference smaller). The precision of the component library can therefore be considered to be within a deviation of 12% of result, which is considered good for early design. Case A is negative due to the wrong type and quantity of insulation from the library. However, Case B and C are conservative in the estimated impact, which is typically considered a quality in early design, especially if the goal is to gain a certain amount of points for i.e. green certifications.

Only GWP was investigated in this study, however, other impact categories will be necessary for a broader approach to environmental performance.

5. Conclusion

As expected; the ED-tool gives a higher GWP impact overall than the detailed LCA. This is because the early design approach is more conservative in estimating materials and has a higher completeness in material use: both by including more of the typical building elements such as building systems and by providing a more complete bill of materials for the defined element layers, for instance by including finishes of elements such as paint as well as membranes, fastenings and structures for build-up floor, ceilings etc. These added elements in the early design approach contributed to a high increase in GWP compared to their mass contribution, which hints to the importance of including these elements for a better understanding of impacts from buildings.

The component library used in the early design approach overall gives a good representation of the building, however, in some cases it is important to the result, to specify material type and dimensions, especially for insulating materials. However, without specification, the precision of estimates made on material type and dimension in the component library is within a deviation of 12% of the result, which is considered good for early design.

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