Comparative Analysis of Life-Cycle Assessment Tools (LCA) Using the Example of Different Energy Supply Variants of a Purpose-Built Building

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Abstract

Using a newly planned building as example, the results of three life cycle assessment (LCA) tools, which use different databases, were in this paper compared.

The first research question in this paper was which energy concept can be used to achieve the lowest environmental impact depending of the used LCA tool within the lifecycle of the building.

The second research question of the paper is which tool is most practical for the life cycle assessment of new office and administrative buildings. The evaluated LCA tools were eLCA, SBS, LEGEP and LEGEP precheck, which are using different databases (OEKOBAUDAT 2011, 2013, 2015 and 2016). Corresponding to the same assessment basis, the resulting degree of fulfilment values using Ökobaudat 2015 or 2016 are significantly higher than those using Ökobaudat 2011 or 2013. Both the emission related environmental impact and the energy demand are significantly higher for the final results than for the preliminary results obtained in the pre-planning phase.

Keywords: LCA, eLCA, SBS, LEGEP, LEGEP precheck, life cycle assessment tools, Environmental station, LCA, recycled concrete, eco-concrete, ice storage, daylight utilization

1. Introduction

Life-cycle assessment (LCA) is a technique to assess environmental impacts associated with all the stages of a product's life from raw material extraction through materials processing, manufacture, distribution, use, repair and maintenance, and disposal or recycling. For building assessments in Germany and Europe, a uniform evaluation method is defined by the standard DIN EN 15978:2011. For the certification of sustainable buildings according to BNB ("Bewertungssystem Nachhaltiges Bauen") or DGNB ("Deutsche Gesellschaft Nachhaltiges Bauen") a life cycle assessment according to this standard is required.

Using the example of the new 'Environmental Station' in Würzburg, located in the south of Germany, three life cycle assessment tools – eLCA (eLCA 2018), SBS (SBS 2018) and LEGEP (LEGEP 2018) - are tested and compared. The Environmental Station is an information and education point for the citizens of the City of Würzburg and was planned as an office and administration building. The floor area is approximately 700 m2. It was constructed mostly in reinforced concrete and recycling concrete.

The Environmental Station should serve as a model in terms of environmental impact and energy consumption. Therefore, one main research object was to find an energy supply concept which shows the lowest environmental impact within the lifecycle of the building. In this context, different LCA tools were used to investigate a bunch of possible options for the energy concept.

A life cycle analysis could be a time consuming task. Especially during the planning phase, quick decision about possible design variants must be made and this should be done on a well-defined knowledge basis. There is a need for LCA tools which can be easy handled in the daily use with little time expenditure. Therefore, a second research question of the paper was which LCA tool is most practical for the life cycle assessment buildings during the planning and construction phase.

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2. LC analysis of the Environmental Station

The Environmental Station design was derived by an architecture competition. Part of the concept is to adapt the building to the existing natural environment and to create a connection between architecture and nature (see Figure 1). The entrance floor welcomes the visitor with its generously proportioned entrance foyer. There is plenty of space for temporary exhibitions and terrariums that provide information about the local flora and fauna. An extensive library as well as two media workstations are available to young and old visitors as a source of information. Adjacent to the foyer are the reception office and an office for two further employees. In addition, the ground floor houses the archive and storage rooms as well as the necessary technical rooms. On the upper floor there are two seminar rooms in which lectures and courses for adults and children take place. In addition, there are sufficient offices where interested citizens can obtain advice on topics such as waste, the environment and energy.

Fig. 1: Visualization of the winning design of the planned Environmental Station © balda architekten.

The LCA tools used here are *eLCA*, *SBS*, *LEGEP* and *LEGEP Precheck*.

eLCA is an open source online tool for building-based life cycle assessment. eLCA was introduced at the end of 2015 and addressed to "planners, architects and builders" (BBSR 2015). The development was developed by the German „Bundesinstitut für Bau-, Stadt- und Raumforschung (BBSR)“, supported by the „Bundesministerium für Umwelt, Naturschutz, Bau und Reaktorsicherheit (BMUB)“.

SBS Building Sustainability is a building-related online tool. Constructions with individual layer structures can be created based on Ökobau.dat and other databases (Fraunhofer IBP and PE International 2013). The evaluations show both the LCA values and evaluation points for a DGNB certification.

LEGEP (abbreviation for "Lebenszyklus-Gebäude-Planung” (Pelzeter 2006) is a commercial calculation tool for "integral planning of sustainable buildings". It is the oldest tool among the three solutions and was originally developed in 2000 by a research project of the University of Karlsruhe (Pelzeter 2006). The tool is maintained by LEGEP Software GmbH (LEGEP 2018). LEGEP consists of different modules. Based on a proprietary method, which provides a step-by-step detailed presentation, lifecycle costs, production costs and energy requirements can be calculated in addition to life cycle assessment (Pelzeter 2006). The ecological and economic parameters can be used for the assessment according to the BNB or DGNB certification system (ZAE 2016). A special feature of this program is that product declarations EPD that are not yet included in the eco-budget can be included in the program.

LEGEP Precheck is a simplified tool used for preliminary estimations according to DGNB. It is based on typical benchmark values for the construction and final energy demand of the building (ZAE 2016).

The LCA-tools base on records contained in the associated LCA-database (latest version is Ökobaudat 2018). Older versions Ökobaudat 2011, 2013, 2015 and 2016 were obtained from different LCA software tools - eLCA, SBS and LEGEP. Furthermore a comparing analysis of the combination of the variants of the insulation standard with the various building techniques was performed. Subsequently, the variants of the energy standard of the building envelope were combined with the various technical building systems resulting in 24 variations generated from four LCA-Tools. The emissions-related environmental impacts global warming potential (GWP), acidification potentials (AP), ozone depletion potential (ODP), photochemical ozone creation potential (POCP) and the eutrophication potential (EP) and furthermore the non-renewable primary energy demand and the total primary energy demand were calculated. Additionally, a plausibility analysis was carried out to determine incorrectly entered data.

For comparison of the variations the evaluation system of the DGNB NBV15 (DGNB, 2015) was applied. Finally, a degree of fulfillment according to DGNB was determined. This degree of fulfilment is a measure of the ecological quality of the building. It is based on two parts, the emission-related environmental impact and the primary energy demand of the building. From these values a dimensionless property in the range from zero to 111.7 is calculated, a higher value means a better ecological quality of the building. For a new office and administration building a degree of fulfillment above about 80 is an excellent value.

Further boundary conditions were:

- In the preliminary planning / design planning, it was still unclear which heating technology was to be used. Therefore, an ecological calculation was carried out with different heat supply variants: pellet heating, an air-water heat pump or a water-water heat pump with ice storage.
- A planned large PV system was not taken into account when calculating the LCA according to DGNB. Calculations with PV (estimated output 28.000 kWh per year) showed that an extremely good result in the LCA of the DGNB near the maximum score could be achieved. In this case the properties of the building structure itself has no more significant influence on the results of the LCA.

Three different variants for the energy concept were investigated. All variations are for the energy PLUS house insulation standard (even better than passive house standard).

3. Results

3.1 Comparison of SBS, eLCA and LEGEP

Table 1, table 2 and table 3 show the comparison of the degree of fulfillment for different variations of the building analyzed with different LCA-tools The first variation in table 1 is for pellet heating (pellet), table 2 is for heat pump (HP) and table 3 is for heat pump with ice-storage (HP + icestorage) as heat supply system. The results are (whereby a degree of fulfillment of 80 is considered very well according to the DGNB classification system):

- Using the tool eLCA, the fulfillment levels are between 73.8 and 85.4, which is relatively high. The best building variant is the “Plus building envelope with pellet heating” variant.
- Using the tool SBS the fulfillment levels are between 75.7 and 89.3, which is relatively high, too. The best variant is again the “Plus building envelope with pellet heating”.
- With LEGEP, compliance levels are between 86.4 and 106.8, close to the full score, which is significantly higher than using the eLCA and SBS tools. In contrast to the other tools, however, the best variant is the “Plus building envelope with heat pump (WP) and ice storage”. During this project, LEGEP was used with three different databases: Ökobaudat 2011, Ökobaudat 2015 and Ökobaudat 2016.
- LEGEP Precheck is a simplified procedure in LEGEP, which shows the complete building construction with average values according to the LCA of the DGNB. It should help the user to get an initial, easy and quick ecological estimate for the building. Required for the entry is only the energy consumption of

the planned building and the corresponding reference building calculated according to EnEV (EnEV 2018). Consequently, the user can save a lot of time using Precheck. The fulfillment degrees calculated with LEGEP Precheck are between 97.9 and 103.1 points, which are also similar than the results obtained with LEGEP, but much better results than the results obtained with eLCA and SBS tools for the best variant. On the other hand, the big advantage of LEGEP Precheck is that the data input takes only a couple of minutes.

However, further plausibility analysis yielded that the reason for the good results of the variants with heat pump (WP) calculated with LEGEP and Precheck was that the auxiliary energy for heat pump was not considered (software bug in LEGEP).

In summary, the results from eLCA and SBS are relatively consistent, and LEGEP and LEGEP Precheck are relatively consistent as well but at a higher degree of fulfillment.

Tab. 1: Comparison of all tools for the Energy PLUS-house standard with pellet heating as energy supply according to the DGNB (German Sustainable Building Council) degree of fulfillment. Implausible results are marked with red digits.

		PLUS + Pellet					
	Tool	**SBS**	**eLCA**	**LEGEP**	**LEGEP**	**LEGEP**	**precheck**
	Ökobaudat	**2013**	**2011**	**2011**	**2015 with phase C/D**	**2015 separate phase C and D**	**2015**
emission-related enviromental impact	Global Warming Potential / $kg_{CO2\text{-}equiv.}/(m^2_{NRA} \cdot a)$	8.55	38.96	37.38	37.53	35.60	30.14
	Acidification Potential / $kg_{SO2\text{-}equiv.}/(m^2_{NRA} \cdot a)$	0.1064	0.1144	0.1120	0.0990	0.0905	0.0990
	Photochemical Ozone Creation Potential / $kg_{C2H4\text{-}equiv.}/(m^2_{NRA} \cdot a)$	0.0093	0.0108	0.0114	0.0092	0.0088	0.0066
	Eutrophication Potential / $kg_{PO4\text{-}equiv.}/(m^2_{NRA} \cdot a)$	0.0144	0.0134	0.0131	0.0153	0.0144	0.0104
	Ozone Depleting Potential / $\cdot 10^{-8}\ kg_{R11\text{-}equiv.}/(m^2_{NRA} \cdot a)$	16.8	29.7	36.0	6.0	– 4.4	53.0
Primary Energy	total Primary Energy demand PE_{total} / MJ	1002.0	984.1	980.8	687.7	656.6	490.6
	non-renewable Primary Energy demand $PE_{non\text{-}re}$ / MJ	525.9	538.5	523.8	450.5	419.8	333.7
	PE_{re}/PE_{total} PE_{re} : renewable Primary Energy demand	0.48	0.45	0.47	0.34	0.36	0.32
DGNB Evalu. NBV15	Points "emission-related environmental effects"	91.1	84.2	85.2	90.7	95.8	96.3
	Points "Life Cycle Assesment - Primary Energy"	86.8	87.1	88.0	100.0	100.0	100.0
	Degree of Fulfilment "LCA"	**89.3**	**85.4**	**86.4**	**94.6**	**97.5**	**97.9**

Table 1 shows a very good agreement with regard to the individual values and the overall result "degree of fulfillment LCA" between LEGEP and eLCA with the Ökobaudat 2011. The results with SBS and the Ökobaudat 2013 were slightly higher in the degree of fulfillment than the evaluations with SBS and LEGEP 2011.

The evaluations with the Ökobaudat 2015 in LEGEP showed a clear improvement. Taking into account the separate phases C (dismantling) and D (recycling) according to DIN EN 15804 using LEGEP 2015, the result improves significantly. Detailed evaluations have shown that LEGEP 2015 with common phase C / D completely disregarded the recycling credits in phase D. Consequently, the result of LEGEP 2015 with separate phase C and D is more accurate than the evaluation LEGEP 2015 with joint phase C / D.

A detailed evaluation of the use phase of the building within 50 years shows that the global warming potential calculated with SBS and the Ökobaudat 2013 results in implausible values. Within the project it was not possible to determine the reason for that.

In a new program version of LEGEP (published during this project), it was possible to investigate the separation of phases C and D according to DIN EN 15804. LEGEP and the according Ökobaudat 2015 with separate phase C and D show an even better result with 97.5 points. The earlier program version of LEGEP has ignored recycling (phase D). If, as in the new LEGEP versions, phase C (dismantling) and phase D are considered separately, the result in almost all ecological values changed once again for the better. This is caused by the credits in the recycling phase. Detailed evaluations confirmed that previously LEGEP did not consider phase D.

However, the result of the ozone depletion potential (marked in red in table 1) as a negative value is implausible. Further research found that this was due to unrealistically high Phase D credits. Considering phase D, significantly better ecological results are expected in the future. Thus, ecological calculations from different software versions are definitely not comparable.

Tab. 2: Comparison of all LCA tools for the Energy PLUS insulation standard with heat pump (HP) according to the DGNB degree of fulfillment. Implausible values are again marked red.

		PLUS + HP					
	Tool	**SBS**	**eLCA**	**LEGEP**	**LEGEP**	**LEGEP**	**precheck**
	Ökobaudat	**2013**	**2011**	**2011**	**2015 with phase C/D**	**2015 separate phase C and D**	**2015**
emission-related enviromental impact	Global Warming Potential / $kg_{CO2\text{-}equiv.}/(m^2_{NRA} \cdot a)$	48.17	43.65	30.84	33.11	37.72	27.49
	Acidification Potential / $kg_{SO2\text{-}equiv.}/(m^2_{NRA} \cdot a)$	0.0907	0.0943	0.0700	0.067	0.0711	0.0650
	Photochemical Ozone Creation Potential / $kg_{C2H4\text{-}equiv.}/(m^2_{NRA} \cdot a)$	0.0079	0.0095	0.0076	0.0065	0.0067	0.0063
	Eutrophication Potential / $kg_{PO4\text{-}equiv.}/(m^2_{NRA} \cdot a)$	0.0102	0.0097	0.0073	0.0088	0.0100	0.0092
	Ozone Depleting Potential / $\cdot 10^{-8}$ $kg_{R11\text{-}equiv.}/(m^2_{NRA} \cdot a)$	30.8	46.1	34.0	6.0	-3.5	53.0
Primary Energy	total Primary Energy demand PE_{total} / MJ	1016.7	809.3	528.2	555.9	707.8	525.7
	non-renewable Primary Energy demand $PE_{non\text{-}re}$ / MJ	669.4	710.8	445.5	394.0	477.9	366.1
	PE_{re}/PE_{total} PE_{re} : renewable Primary Energy demand	0.34	0.12	0.16	0.29	0.32	0.30
DGNB Evalu. NBV15	Points "emission-related environmental effects"	80.1	77.2	109.0	108.3	99.4	102.4
	Points "Life Cycle Assesment - Primary Energy"	69.4	69.1	100.0	100.0	97.6	100.0
	Degree of Fulfilment "LCA"	**75.7**	**73.8**	**105.3**	**104.8**	**98.6**	**101.4**

Table 2 shows, that the difference between the variants is sometimes very large, especially using Ökobaudat 2015. However, this was also the case for the building variant with pellet heating (see Table 1 and Table 3).

In a detailed analysis we were able to determine that some results in LEGEP resulted in erroneous results due to a program error according to the heat pump (values marked red in Tab. 2). In the program version "LEGEP 2015 separate Phase C and D" (penultimate column), an implausible negative value in the ozone depleting potential is highlighted in red. However, this influences the degree of fulfillment only slightly. The software error causing this was localized in a detailed study in phase D.

Tab. 3: Comparison of all LCA tools for the Energy PLUS insulation standard with heat pump (HP) and icestorage system. Values are according to the DGNB (German Sustainable Building Council) degree of fulfillment.

		PLUS + HP + Ice storage						
	Tool	**SBS**	**eLCA**	**LEGEP**	**LEGEP**	**LEGEP**	**LEGEP**	**precheck**
	Ökobaudat	**2013**	**2011**	**2011**	**2015 with phase C/D**	**2015 separate phase C and D**	**2016 separate phase C and D**	**2015**
emission-related enviromental impact	Global Warming Potential / $kg_{CO2\text{-}equiv.}/(m^2_{NRA} \cdot a)$	45,94	41,53	28,69	31,32	35,93	39,57	25,24
	Acidification Potential / $kg_{SO2\text{-}equiv.}/(m^2_{NRA} \cdot a)$	0,0871	0,0901	0,0660	0,064	0,0685	0,0780	0,0610
	Photochemical Ozone Creation Potential / $kg_{C2H4\text{-}equiv.}/(m^2_{NRA} \cdot a)$	0,0076	0,0092	0,0073	0,0063	0,0065	0,0072	0,0060
	Eutrophication Potential / $kg_{PO4\text{-}equiv.}/(m^2_{NRA} \cdot a)$	0,0099	0,0093	0,0070	0,0083	0,0095	0,0081	0,0086
	Ozone Depleting Potential / $\cdot 10^{-8}$ $kg_{R11\text{-}equiv.}/(m^2_{NRA} \cdot a)$	29,6	45,7	33,0	6,0	-3,5	20,5	53,0
Primary Energy	total Primary Energy demand PE_{total} / MJ	976,9	765,0	483,2	512,6	625,1	592,2	479,2
	non-renewable Primary Energy demand $PE_{non\text{-}re}$ / MJ	635,6	673,3	407,2	366,7	424,9	493,8	335,9
	PE_{re}/PE_{total} PE_{re} : renewable Primary Energy demand	0,35	0,12	0,16	0,28	0,32	0,17	0,30
DGNB Evalu. NBV15	Points "emission-related environmental effects"	84,4	82,4	111,7	111,5	103,2	99,3	105,3
	Points "Life Cycle Assesment - Primary Energy"	74,3	75,8	100,0	100,0	100,0	100,0	100,0
	Degree of Fulfilment "LCA"	**80,2**	**79,6**	**106,8**	**106,7**	**101,9**	**99,6**	**103,1**

In Table 3 are implausible values again marked in red digits. The reason for the wrong values are the same as explained at table 2. In addition, the results of a newer version of the program are shown in the penultimate column "LEGEP 2016 separate phase C and D". This gives a flawless result with a degree of fulfillment "LCA" of 99.6. The reason for this was again a software error: the heat demand calculated according to EnEV was used instead of heat for the heat pump.

3.2. Comparison of all degrees of fulfilment

Table 4 shows the degree of fulfilment using different software tools and databases for all three variants of the energy supply system. Results from the software tool LEGEP for variants including a heat pump are wrong or implausible (marked red) because of an error in the software version used here.

Tab. 4: Comparison of all tools and variants according to the DGNB degree of fulfillment. Implausible or wrong values are marked red.

	Ökobaudat	Pellet	HP	HP + Icestorage
SBS	2013	89.3	75.7	80.2
eLCA	2011	85.4	73.8	79.6
LEGEP	2011	86.4	105.3	106.8
LEGEP - with phase C/D	2015	93.9	104.8	106.7
LEGEP - separate phase C and D - 1. Correction	2015	97.5	98.6	101.9
LEGEP - separate phase C and D - 2. Correction	2016	–	–	99.6
precheck	2015	97.9	101.4	103.1

Fig. 2 shows the values from Tab. 4 as a bar chart. In each case, the results are grouped by the used software. The results show that with the same assessment basis, the resulting degree of fulfilment values using Ökobaudat 2015 or 2016 are significantly higher than those using Ökobaudat 2011 or 2013.

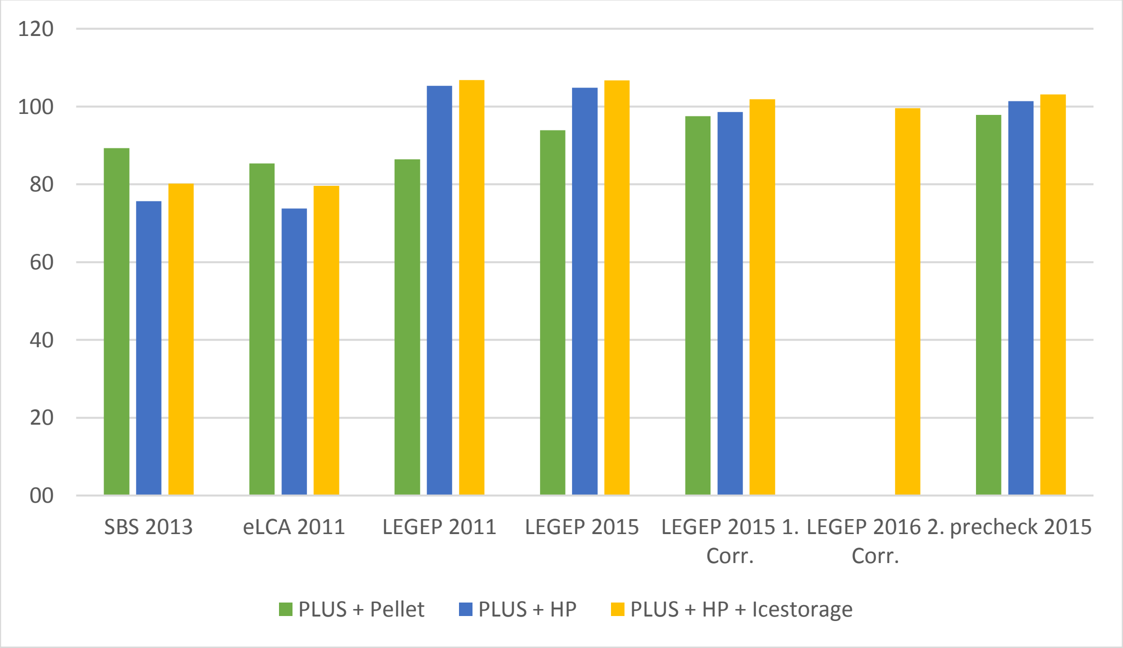

Fig. 2: Comparison of the degree of fulfilment of all LCA-Tools for the three different heat supplies, SBS 2013 takes ökobaudat from 2013 into account, eLCA 2011 the ökobaudat 2011, LEGEP 2015 and precheck 2015 the ökobaudat from 2015.

3.3. Comparison of Preliminary Planning and Detailed Design

In the detailed analysis of the building after the end of the bidding phase, the over 2400 bill of lading positions to be built were examined, of which about 630 positions were taken over in LEGEP. The large difference between the bidding phase positions and the actual inserted positions in LEGEP is mainly due to many small parts without any ecological material data in the database.

Table 5 takes only the phases A1 to A3 into account, corresponding to the current construction progress of the environmental station. Phase B would be identical for both program versions, phase C and D would depend on the future maintenance of the building within 50 years. Maintenance is currently also not reproducible in LEGEP.

Tab. 5: Comparison of LEGEP 2015 (Ökobaudat 2015) for the preliminary planning and LEGEP 2016 (Ökobaudat 2016) for the detailed design (Energy PLUS insulation standard) with heat pump and ice storage according to the DGNB degree of fulfillment; the calculation in the preliminary planning was done with elements and for the detailed design with performance positions. The last column shows the ratio of the preliminary results (LEGEP 2015) to the final results (LEGEP 2016).

	Construction phase A1-A3	PLUS + HP + Icestorage		
		preliminary planning LEGEP 2015 without PV moduls	detailed design LEGEP 2016 without PV moduls	quotient preliminary/detailed in %
emission-related enviromental impact	Global Warming Potential / $kg_{CO2\text{-}equiv.}/(m^2_{NRA} \cdot a)$	11.70	13.10	89%
	Acidification Potential / $kg_{SO2\text{-}equiv.}/(m^2_{NRA} \cdot a)$	0.0330	0.0392	84%
	Photochemical Ozone Creation Potential / $kg_{C2H4\text{-}equiv.}/(m^2_{NRA} \cdot a)$	0.0029	0.0046	62%
	Eutrophication Potential / $kg_{PO4\text{-}equiv.}/(m^2_{NRA} \cdot a)$	0.0037	0.0040	91%
	Ozone Depleting Potential / $\cdot 10^{-8}$ $kg_{R11\text{-}equiv.}/(m^2_{NRA} \cdot a)$	5.1	52.3	10%
Primary Energy	total Primary Energy demand PE_{total} / MJ	161.3	184.9	87%
	non-renewable Primary Energy demand $PE_{non\text{-}re}$ / MJ	125.6	147.4	85%
	PE_{re}/PE_{total} PE_{re} : renewable Primary Energy demand	0.22	0.20	109%

The ratio of preliminary results to final results from Tab 5 are shown in Figure 3, normalized to 100%. Both the emission related environmental impact and the energy demand is higher for the final results than for the preliminary results obtained in the pre-planning phase.

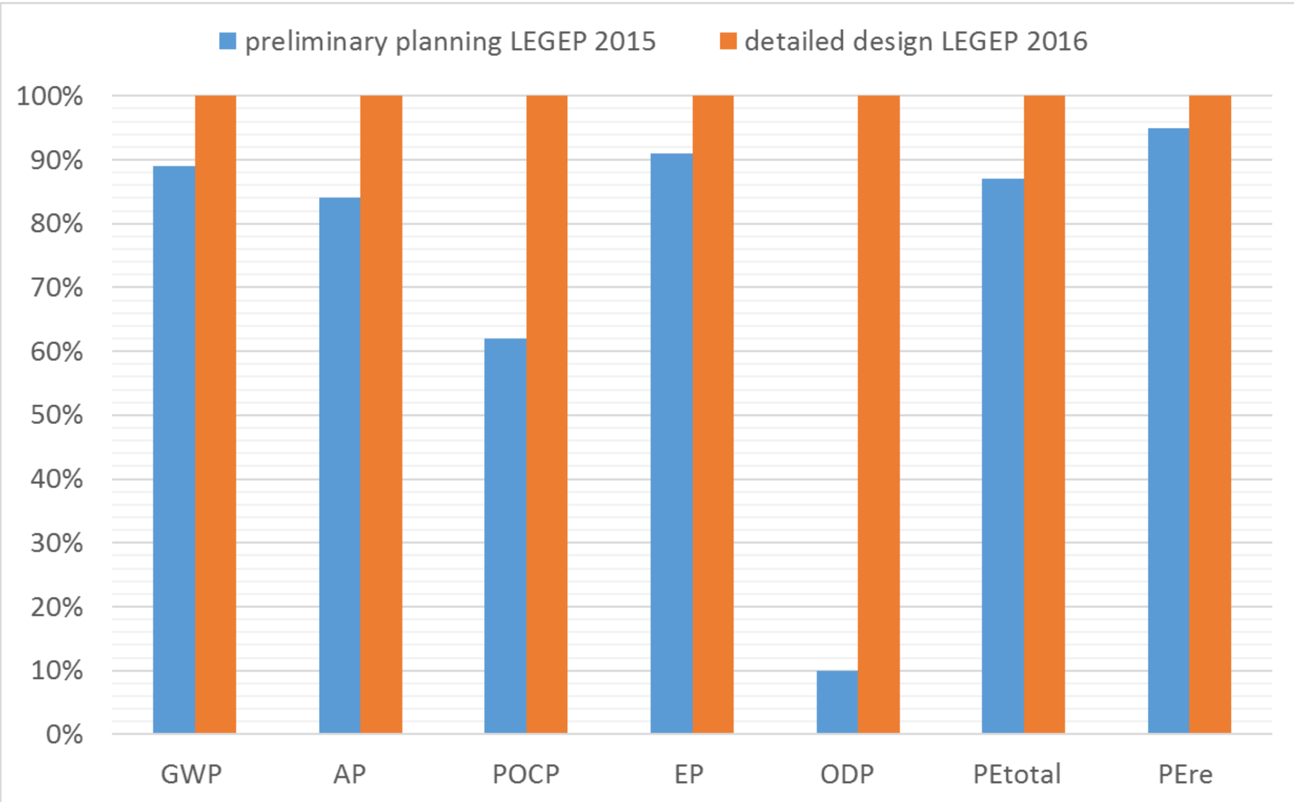

Fig. 3: Comparison of the preliminary planning and the detailed design for the construction phase A1-A3

4. Conclusion

The evaluation methodology of the DGNB can be used to answer the question of which energy concept achieves a certain degree of fulfillment over the life cycle of the building.

The detailed analysis using the environmental station in Würzburg as an example shows that the values calculated during the pre-planning phase lead to an excessive degree of fulfillment of the life cycle assessment because the individual ecological indicators result in values that are too low.

The accurate and detailed comparison of the results using different LCA tools in this project brought out a lot of software bugs causing implausible values. Most of these bugs were removed during this project by the makers of the software packages.

Therefore, there is still a considerable need for research in order to better forecast the LCA in the preliminary planning phase. Additionally, there is further need for research to harmonize the results using different LCA tools with different databases. Actually, the results from different tools are in some points not comparable.

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