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Energy-efficient Optimization of Life-cycle Costs Based on BIM

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Abstract: This article deals with a methodology for the economic development of energy-efficient buildings from an early planning or development phase based on building information modelling (BIM). In this context, both geometrically and energetically relevant parameters of a building are derived from a digital building model, already in the early phase of a project. The subsequent definition of building components for the building envelope and the performance of an energy demand calculation provides the basis for the selection of reference buildings suitable for the respective application. This enables the determination of practical costs, which include both annuity costs and total costs arising in the life cycle of the building for the cost groups of the building structures and the technical building equipment. By taking a holistic view of all costs and focusing specifically on energy efficiency, the methodology presented in this article can be used to identify both ecological and economic advantages for planning in the early stages of a project. By incorporating energy efficiency and economic efficiency, a sustainable and successful project can be achieved.
Keywords: BIM; Life-cycle costs; Energy-efficient buildings; Project development.

1. Introduction

The pressures on the environment resulting from greenhouse gas emissions, energy consumption, and waste are predominantly generated by the global building and construction sector. According to current forecasts, energy consumption and greenhouse gas emissions from buildings are projected to double by 2050 due to population and economic growth. Consequently, it will be imperative to incorporate measures for energy conservation and enhance energy efficiency within building design in the future [1].

Energy efficiency aims to reduce energy consumption while ensuring occupant comfort. In terms of sustainable development, reducing the energy consumption also leads to lower operating costs for building maintenance, decreased environmental impacts, and improved economic performance of the building [2].

There is a growing trend in research to utilize building information modelling (BIM) for enhancing the energy efficiency of buildings. Since 2011, there has been a significant surge in publications and citations in this field, indicating a strong interest in this topic within the scientific community [3].

When contemplating energy-efficient buildings, several fundamental properties emerge that encompass both user requirements, including comfort, and protective functions against cold and frost, heat and solar radiation, air and soil moisture, as well as wind, sound, and fire protection. Furthermore, an energy-efficient building must strive to minimize the consumption of energy raw materials and effectively meet the heat demand. By optimizing these aspects, a building can achieve higher levels of energy efficiency [4].

The application of BIM offers the opportunity to integrate digital building modelling with energy-related parameters and attributes. This allows for the assessment and analysis of energy efficiency across various equipment options and building types, coupled with the estimation of associated life-cycle costs from the early stages of a project. The early consideration of life-cycle costs in project decision-making is crucial, as the building envelope, materials employed, and technical building equipment, in addition to the supporting structure and usage type, are key factors determining costs [5].

Building owners and project developers require prompt and cost-effective design completion. Architects have so far focused their designs on functionality and costs instead of energy consumption and sustainability. The development of software-based cost estimates combined with the determination of energy consumption is considered to have development potential for future BIM tools [3].

For holistic cost planning, both factors from geometric building properties and building services equipment are relevant to costs. These result in high production and utilization costs, especially when considering buildings with a high degree of technical building services [6].

The interoperability between building modelling and energy simulation tools can be categorized into three main areas, as identified by several studies conducted on the subject: data exchange using gbXML, data export using IFC, and API-based data exchange. The gbXML schema has emerged as an industry standard, facilitating interoperability between BIM modelling software (including Autodesk, Trimble, Graphisoft) and energy simulation tools (including EnergyPlus, Ecotect). IFC was developed by buildingSMART as an object-oriented data model to describe and share information throughout the life cycle of buildings. The development of Model View Definitions (MVD) within IFC enables data exchange related to a specific exchange scenario. In this context, MVDs have been developed to facilitate data exchange between BIM and energy simulation tools. With an API-based data exchange, energy simulations can be carried out externally within the respective energy software due to an application programming interface (API) coupled to the modelling programs. Subsequently the results are displayed and further processed in the modelling software [7].

An example of API-based data exchange is Graphisoft ArchiCAD, a modelling software that enables the conversion of existing building models into building energy models (BEM). Based on these models, energy-calculations and analyses are then carried out in various planning phases [8]. Autodesk Revit is the most widely used modelling software for energy analysis. It provides interfaces to energy analysis tools such as Energy Plus, Ecotect and Green Building Studio, among others [3].

At present, the software-integrated modules and interfaces discussed earlier do not provide a methodology for integrating the results of energy simulations with the costing of the building envelope and building services equipment. However, in the following sections, the author introduces a newly developed method that addresses this gap by considering both the energy-efficient development of buildings and the associated life-cycle costs. The aim of this methodology is to optimize both the energy efficiency of planned buildings and the resulting life-cycle costs by considering different equipment variants and building types. This results in the creation of an energetically and economically optimized planning solution that can be provided from an early planning phase.

2. Materials and methods

As significant cost factors of a property, the operating costs exceed the investment costs after approximately ten years. These costs can still be influenced by up to 80 % in the early planning phase. In later project phases, these costs can only be marginally adjusted [9]. In this context, a definition of the thermal building envelope in combination with the resulting requirements for the building services is relevant to be able to control the impact of these essential cost components on life-cycle costs at an early stage.

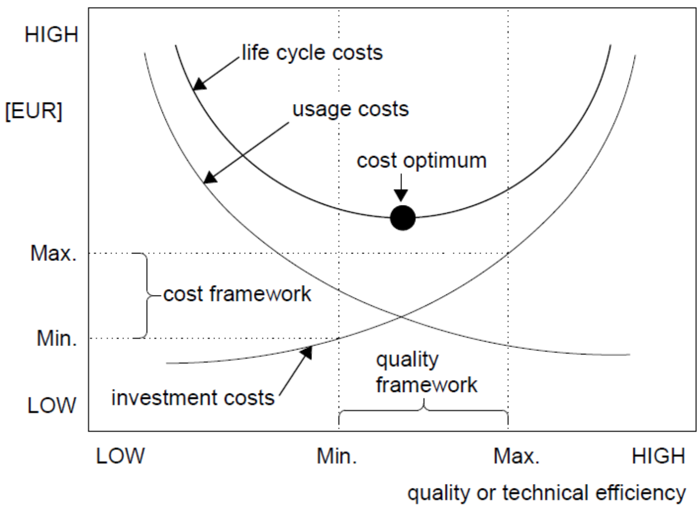

Figure 1. Cost optimum quality and technical efficiency (own representation based on [10])

The influencing parameters for optimizing life-cycle costs in the energy-relevant areas are illustrated in Figure 1. In this figure the minimum of all costs incurred over the life cycle is described by the economic optimum in relation to technical efficiency. Technical efficiency is defined as quality, which requires the definition of the cost and quality framework as project goals in the planning [10].

The methodology presented in this article enables the determination of the "economic optimum" as the minimum of all costs incurred over the life cycle in relation to quality and technical efficiency of a project. The optimization of the parameters relevant for the energy demand calculation in the building model by considering variants of different component combinations and equipment of the building services allows the examination of economic advantages of certain energy saving measures, e.g. by changing insulation types and thicknesses.

The results of this analysis are information on the effects of energy-saving measures on both energy parameters and the associated life-cycle costs. In this way, the factors influencing the construction and follow-up costs are determined, dependencies for detecting the economic optimum are analysed and the economic advantages of individual energy-saving measures are shown.

Energy-efficient optimization of life-cycle costs is achieved through a combination of three influencing factors, as shown in Figure 2:

1) The first factor is the determination of the usage demand. The use within the building is usually recorded in an area classification according to the standard. For including the areas of use in an energy analysis, the energy reference area in the building is determined.

2) The second factor is the determination of the building's demand. On the one hand, this includes the determination of the components of the thermal building envelope and, on the other hand, the calculation of the essential energy parameters such as final energy demand and heating load.

3) The determination of the demand for both factors, use and building, makes it possible to determine the coverage of demand by the building technology as a third factor. This determination is made by selecting components suitable for this purpose.

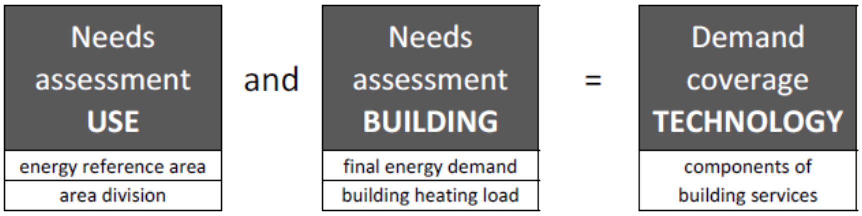

Figure 2. Factors of the energy-efficient cost consideration

In compliance with this basic principle, the author developed a methodology for optimizing the factors shown in Figure 2, which is independent of the modelling software. This requires the transfer of the modelling data into a spreadsheet using the IFC interface. The procedure of the methodology is shown in a flow chart in Figure 3.

In a first step, a spatial model is created within a modelling program suitable for BIM. This should enable an initial abstract representation of the planning ideas using a digital building model from the project development phase onwards with little input effort. Since a room model only contains rooms and no boundary components (including walls, ceilings, floors), the rooms are modelled as "gross room elements”. In this case, room elements also contain a part of the bounding components. The resulting boundary surfaces between the individual rooms of the room model must touch each other. This forms the prerequisite for the evaluation of "virtual" boundary surfaces in the building. These provide a basis for the early evaluation of the individual building component masses for calculating the factors for energy efficiency. The energy reference area and the component masses of the thermal building envelope, among other things, serve as the basis for determining the characteristic energy values required within the methodology.

The thermal building envelope includes the boundary surfaces (including walls, roof and floor structure of the lowest floor) between the heated rooms and the unheated environment (unheated rooms or outdoor space). The energy reference area includes the usable areas within the thermal building envelope. However, there are rooms which only have 60% of their area added to the energy reference area, such as cellars and ancillary rooms. The areas of staircases, lifts and shafts are not counted for this purpose [11].

Based on this, the component structures are determined regarding to the areas for the thermal building envelope evaluated from the room model. Based on this definition, component-specific factors such as the U-value can be determined as well as follow-up measures for the maintenance and repair of the components in the life cycle of the building. The U-value typically refers to the thermal transmittance of a material, building component, or an entire building assembly as a measurement of how effectively heat is transferred through a particular structure (e.g., walls, windows). To estimate the costs for the selected building components, the construction costs according to DIN 276 [12] and follow-up costs according to DIN 18960 [13] are determined and defined using suitable cost parameters.

The energy parameters required for an energy-efficient cost analysis are determined using the methodology of the PHPP (Passive House Planning Package, Version 9). The PHPP is a planning tool for optimizing the energy consumption of buildings. This enables the determination of the energy demand using renewable energy sources as well as the evaluation of the future overall efficiency of a building [14].

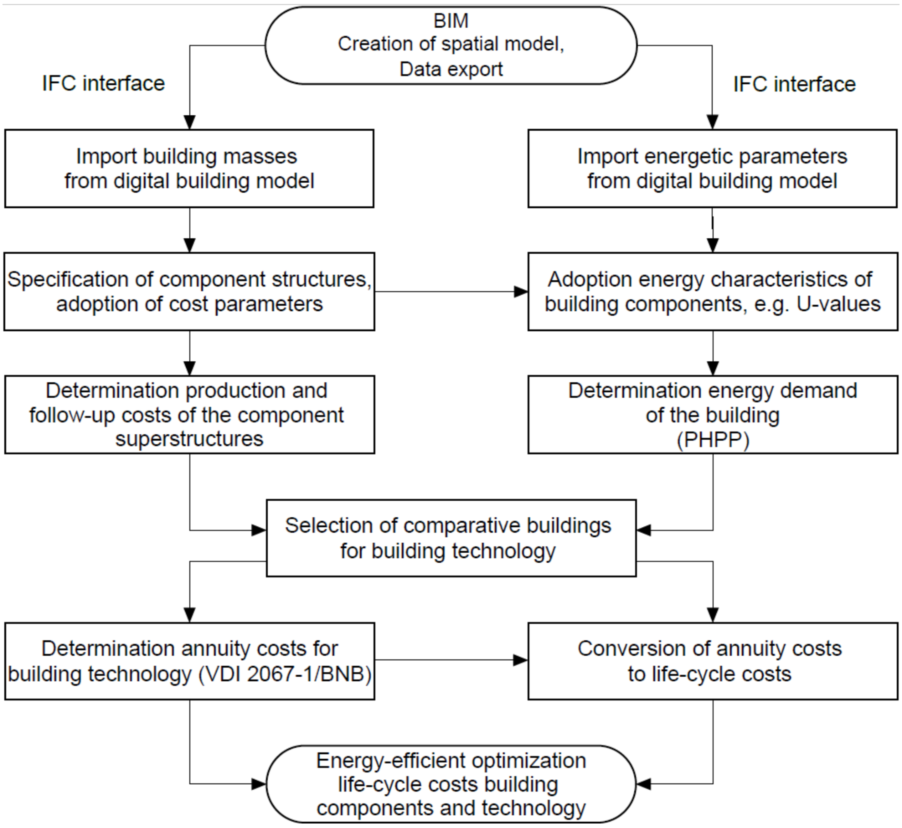

Figure 3. Flowchart energy-efficient costing

For the application of the PHPP, the factors required for the calculation, including heat generators, ventilation systems and climate data, are defined within the methodology presented in this article. Since no glazing areas are represented in the room model, a WWR (window to wall ratio) must also be defined, which defines the ratio of glazed to opaque wall areas. Based on the results of these calculations, the following energy parameters are used for an energy-efficient cost analysis: standard building heating load, final energy demand and compactness.

The standard building heating load is considered the decisive variable for the design of the heat generation system in combination with the planning of fuel storage rooms and heating systems. This is the sum of transmission heat loss and ventilation heat loss [15]. The standard heating load is usually calculated according to ÖNORM H 12831 [16].

The final energy demand serves as a monetary classification for end users by identifying all heating and cooling systems and other required energy (e. g. hot water demand). Therefore, the final energy demand (and not the primary energy demand) is used for the economic efficiency assessment [17]. Corresponding consumption parameters for final energy of the heating energy and electricity demand can be derived from VDI 3087 / Sheet 2. This gives guideline values for different types of buildings [18].

The compactness of a building is the ratio of the surface area of the thermal building envelope divided by the heated volume. This means that the building is more energy-efficient if there is a smaller value for the compactness of a building.

The processes described so far in this section enable the needs assessment of the use and requirements of the building described at the beginning of this section. In the following, possibilities for deriving suitable equipment for the building services are presented.

The basis for the selection of building services equipment in the context of an energy-efficient cost analysis is provided by information from corresponding reference buildings. These must contain both energy parameters and information on the components of the thermal building envelope as well as cost parameters for construction costs according to DIN 276 [12] cost group (KG) 400 (2nd level). As selection criteria for the suitability of a reference building, both comparative energy values (standard building heating load, final energy demand and compactness) and matching criteria within the building type and the building size are used.

The cost parameters used for the follow-up costs of the building services equipment are characteristic values of the Sustainable Building Assessment System (BNB), which was published in 2015 by the German Federal Ministry for the Environment, Nature Conservation, Building and Nuclear Safety in cooperation with the German Sustainable Building Council (DGNB). As a scientifically founded and planning-based assessment system for sustainable buildings, the BNB consists of a catalogue of criteria for the holistic consideration and assessment of sustainability aspects and the consideration of the entire life cycle of buildings [19]. Within the BNB, both useful lives for technical building systems and cost shares for maintenance, inspection and repair are specified in % of the production costs per year.

As a basis for determining the construction and follow-up costs of the building services equipment, the methodology according to guideline VDI 2067 / Part 1 [20] is applied, which enables the calculation of the economic efficiency of building services equipment for all types of buildings. The results obtained enable the comparison of different system concepts [20]. As basic data for the cost representation, the following characteristics are taken from a reference building: type of building, gross room volume, gross floor area, cost data for KG 400 (level 1 and 2 according to DIN 276 [12]), cost basis (year of cost data). Within the methodology according to VDI 2067 / Part 1 [20], the costs are divided into the following components [20]:

1) capital-linked costs: Investment costs
2) demand-related costs: fuel costs for the final energy demand
3) operation-related costs: heating operation costs, operating costs
4) other costs: calculated as a percentage of the investment costs
5) revenues: income from the sale of energy to external energy sources

The result of the methodology according to VDI 2067 / Part 1 [20] is an annuity list of both the construction costs and the follow-up costs of the technical building equipment. Subsequently, this cost listing according to the annuity method is converted into a life-cycle related cost listing based on the net present value method. In this way, the construction costs of the building services according to DIN 276 [12] KG 400 (2nd level) and the cost groups of the follow-up costs according to DIN 18960 [13] can be added to the list of life-cycle costs.

To illustrate the methodology described in this section, chapter 3 describes an exemplary task in the project development phase consisting of a comparison of three office building types. The three variants consist of the same gross floor area (GFA) of 1925 m², their building typology is different. The following three building types are distinguished:

1) Square building with inner courtyard (type V1)
2) Rectangular building (type V2)
3) Square building (type V3)

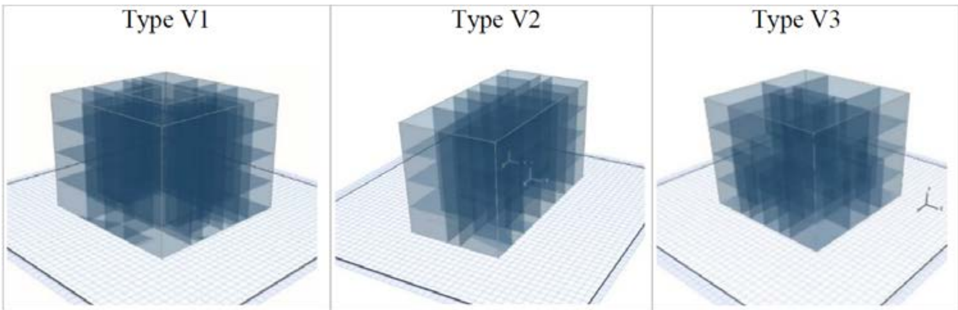

Figure 4. Building types V1, V2 and V3 (modelled with Graphisoft ArchiCAD, Version 25)

The building types considered are shown in Figure 4. A direct comparison of the effects of the different building typologies on both the building component costs (KG 300, see section 3.1) and the building services equipment (KG 400, see section 3.2) is made possible due to the same size of the gross floor area of all three variants.

In relation to these three building types, two equipment variants A and B are also considered. Equipment variant A consists of a conventional construction method according to the building regulations (see Table 1). Equipment variant B describes a low-energy construction method (see Table 2). Both variants contain different specifications for the thermal building envelope and technical building equipment. To complete the expected costs in KG 300, the same interior components were considered for the equipment variants A and B according to Table 3.

3. Results and discussion

An energy-efficient cost analysis according to the methodology presented in this article includes the determination and optimization of life-cycle costs within KG 300 and KG 400 according to DIN 276 [12] and follow-up costs according to DIN 18960 [13]. The focus of this analysis is the detailed preparation of cost scenarios for both the thermal building envelope and the building services equipment. The costs of these areas usually form significant components of the total costs.

In this section, the new construction of an office building in the project development phase is considered as an application example. The aim of this exemplary building task is to determine the effects of different building typologies both on energy parameters and on the life-cycle costs within KG 300 and KG 400 according to DIN 276 [12] and the follow-up costs according to DIN 18960 [13]. The observation period for determining the life-cycle costs is set at 30 years. The building description of the building types is integrated at the end of chapter 2. Table 4 shows the component masses of the three types determined from the building model. Due to the same gross floor area in all three variants, there are only differences in the comparison of the vertical component masses of the three types.

Table 1. Equipment variant A: conventional construction

component	sector	structure
Exterior wall	Outside	External thermal insulation composite system (14 cm)
against air	Inside	Reinforced concrete walls (20 cm), thin plaster, dispersion
External wall	Outside	Thermal insulation XPS (12 cm), waterproofing
against ground	Inside	Reinforced concrete walls (25 cm), dispersion
Roof	Outside	Bituminous waterproofing, thermal insulation (20 cm)
	Inside	Reinforced concrete ceiling (18 cm), dispersion
Base plate	Outside	Reinforced concrete foundation slab B25 (25 cm),
	Inside	Waterproofing, thermal insulation (10 cm), screed, linoleum
Technical	Heat	District heating from combined heat and power
building	Cooling	Concrete core activation with water system
equipment	Ventilation	Window ventilation, partly automatic Ventilation/ deaeration

Table 2. Equipment variant B: low-energy construction

component	sector	structure
Exterior wall	Outside	Fibre cement panels
against air	Inside	Wooden stud wall/mineral wool insulation (30 cm), plasterboard
External wall	Outside	Thermal insulation XPS (30 cm), waterproofing
against ground	Inside	Reinforced concrete walls (25 cm), dispersion
Roof	Outside	Plastic waterproofing
	Inside	Wooden construction/foam glass insulation (30 cm), plasterboard
Base plate	Outside	Reinforced concrete foundation slab C 20/25 (25 cm),
	Inside	Waterproofing, thermal insulation XPS (20 cm), screed, laminate
Technical	Heat	Gas supply, heat pump system and condensing boiler
building	Cooling	Concrete core activation and refrigerating machine
equipment	Ventilation	Ventilation system

Table 3. Interior components

component	sector	structure
Ceiling superstructures	Inside	Dispersion, plaster, reinforced concrete ceilings C 20/25 (20 cm), impact sound insulation, cement screed, linoleum flooring
Interior walls load-bearing	Inside	Dispersion, synthetic resin plaster, reinforced concrete walls (20 cm)
Interior walls non load bearing	Inside	Metal stud frame with mineral wool filling, drywall cladding (2 x 1.25 cm), dispersion

Table 4. Component mass, types V1 - V3

	type V1 [m²]	type V2 [m²]	type V3 [m²]
base plate	385	385	385
soffit	1925	1925	1925
roof	385	385	385
interior walls load bearing	280	332	410
interior walls non load bearing	2120	2112	1835
external wall surfaces	2223	1619	1530
window areas	602	438	414

The biggest difference relates to the comparison of the external wall areas. These are approx. 27% higher for type V1 compared to type V2 and approx. 31% higher compared to type V3. This difference is an important "indicator" both for the subsequent energy comparison and for the resulting component costs.

3.1 Construction costs for building components

This section compares the construction costs for the building structures (=cost group (KG) 300 according to DIN 276 [12]) of the three development variants type V1, V2 and V3.

Table 5 shows the costs of the building components (KG 300) of all three construction variants of equipment variant A "conventional construction method" as well as the respective percentages of these costs of the total construction costs according to DIN 276 [12].

Table 5. Equipment variant A: total costs KG 300 according to DIN 276 [12]

type V1-A		**type V2-A**		**type V3-A**	
1,80 M €	57%	1,59 M €	54%	1,55 M €	53%

The comparison of the three variants shows that the construction costs for type V1 (square building with inner courtyard) are 13% higher than for type V2 (rectangular building) and 16% higher than for type V3 (square building). Consequently, type V1 results in a higher share of building component costs (KG 300) in the total construction costs compared to the other two variants.

Table 6. Equipment variant B: total costs KG 300 according to DIN 276 [12]

type V1-B		**type V2-B**		**type V3-B**	
1,87 M €	60%	1,65 M €	57%	1,61 M €	56%

Table 6 shows in analogy to Table 5 the equipment variant B "low-energy construction". The comparison of the three building types shows the same percentage cost differences between the three types as for equipment variant A. However, a comparison of the two equipment variants A and B shows that for all three development types, the building component costs for equipment variant B are approx. 3.5% higher than those for equipment variant A.

Table 7. Equipment variant A: construction costs KG 320 – 360

Cost group	**type V1**		**type V2**		**type V3**	
320 foundations	70 T€	2,2%	70 T€	2,4%	70 T€	2,4%
330 exterior walls	820 T€	26,0%	596 T€	20,2%	571 T€	19,6%
340 interior walls	196 T€	6,2%	204 T€	6,9%	198 T€	6,8%
350 ceilings	440 T€	13,9%	442 T€	15,0%	440 T€	15,1%
360 roofs	131 T€	4,1%	134 T€	4,6%	131 T€	4,5%

Table 7 shows KG 320 - 360 according to DIN 276 [12] for equipment variant A. This includes cost data (in thousands of euros) and % data (=ratio to total costs according to DIN 276 [12]) of all horizontal and vertical components.

There are only minor cost differences within the horizontal building components (KG 320/350/360) when comparing the three variants, despite the different building types due to the same gross floor area. In KG 340 (interior walls), there are also only minor cost differences of up to a maximum of 4% in the comparison of the three building types.

Within KG 330 (external walls), which includes the vertical components of the thermal building envelope in terms of energy, there are greater differences of up to a maximum of 30% additional costs in the comparison of type V1 with type V3. In addition, KG 330 (external walls) accounts for the largest share of the total costs of KG 300 for all three types, followed by KG 350 (ceilings) and KG 340 (internal walls). Table 7 shows that the influence of different building types with the same gross floor area and building height on the building costs (KG 300) primarily affects the exterior walls (KG 330).

3.1.1 Energy parameters

Based on the selected components of the thermal envelope, the energy parameters required as a basis for determining the equipment of the building services are determined by using the methodology of the PHPP [14], as shown in section 2. These are shown in Table 8 for all three building types and both equipment variants A and B.

Table 8 shows that the compactness of the buildings has a direct influence on both the area-specific heating load and the final energy demand. These values are the lower (and therefore better) if the value for the compactness of an example building is lower.

This shows that type V1, with the highest value for compactness compared to the other two variants, also has higher consumption data in terms of heating load (difference approx. 25-30%) and final energy demand (difference approx. 13-15%) compared to the other two variants. The energy characteristics of type V2 as a rectangular building and type V3 as a square building show only minor difference to each other.

Table 8. Energy parameters

	area-specific heating load [W/m2]	final energy demand [kWh/(m²y)]	Compactness (A/V ratio)
type V1-A	30,5	84,7	0,52
type V1-B	27,0	75,4	0,52
type V2-A	22,8	73,5	0,42
type V2-B	19,7	65,4	0,42
type V3-A	21,8	72,3	0,40
type V3-B	18,9	64,6	0,40

3.2 Production and follow-up costs for building technology

In the following, the production and follow-up costs for the building services are given in relation to the three building variants. For comparability of the variants, the reference building selected for equipment variants A and B is considered for all three building types within the respective equipment variant in this example, despite the different energy parameters of the building variants (see Table 8). As described in Section 2 the methodology of VDI 2067 / Part 1 [20] was used to determine the annual costs for building services. This enables the economic efficiency of technical building systems to be determined, differentiated according to capital-related, demand-related, operational, and other costs.

Table 9 shows that the capital-linked, operational costs and other costs reach approximately the same value irrespective of type, both within equipment variant A (left) and within equipment variant B (right). It is also noticeable that the demand-based costs, which refer to the fuel requirements of a building, are approx. 15% higher for type V1 in both equipment variants than for types V2 and V3. This shows that despite the different building types, only the demand-based costs (for the fuel demand) differ according to the respective building types for the same gross floor area.

Table 9. Equipment variants A and B: annuity costs for building services

cost type	V1-A	V2-A	V3-A	V1-B	V2-B	V3-B
capital-linked	55 T€	55 T€	55 T€	55 T€	55 T€	55 T€
demand-based	22 T€	19 T€	19 T€	20 T€	17 T€	17 T€
operational	22 T€	22 T€	22 T€	23 T€	23 T€	23 T€
other costs	2 T€	2 T€	2 T€	2 T€	2 T€	2 T€
total	**101 T€**	**98 T€**	**98 T€**	**100 T€**	**97 T€**	**97 T€**

Table 10. Equipment variants A and B: production costs KG 400

V1-V3-A	V1-A	V2-A	V3-A	V1-V3-B	V1-B	V2-B	V3-B
0,88 M €	28,0%	30,0%	30,4%	0,79 M €	25,3%	27,2%	27,6%

Table 10 shows the costs for the building services (KG 400 of the construction costs according to DIN 276 [12]) and their share of the total production costs of all three building variants on the left for equipment variant A "conventional construction" and on the right for equipment variant B "low-energy construction". These costs were converted to the costs of KG 400 according to DIN 276 [12] for the period under consideration of the building (=30 years) using the net present value method based on the annuity costs shown in Table 9.

It is striking that the production costs for building services for the "conventional construction method" (equipment variant A) exceed those for the "low-energy construction method" (equipment variant B) by approx. 11%. In addition, the production costs of equipment variant A account for a larger share of total costs than the production costs of equipment variant B.

Table 11. Equipment variant B: production costs KG 410 – 430

cost group	V1-V3 [€]	V1 [%]	V2 [%]	V3 [%]
410 sewage, water, gas systems	85 T€	2,7%	2,9%	2,9%
420 heat supply systems	144 T€	4,6%	4,9%	5,0%
430 ventilation systems	110 T€	3,5%	3,8%	3,8%

Table 11 shows the costs (each in thousands of euros) and the ratio to the respective total costs according to DIN 276 [12] of KG 410 - 430 of the building types exemplary for equipment variant B. Due to the same gross floor area of the building types, the same cost values result for types V1, V2 and V3. When comparing the cost groups, the largest costs of 144 T€ are incurred for KG 420 (heat supply systems). These are approx. 24% higher than the costs of the following KG 430 (ventilation systems) and approx. 41% higher than the costs of KG 410 (sewage, water, gas systems).

3.3 Follow-up costs for building structures / building services engineering

In this section, the relevant cost groups according to DIN 18960 [13] for the follow-up costs of the building structures and building services are considered regarding the presented methodology.

Table 12. Equipment variants A and B: follow-up costs KG 350, 410, 420

cost group	V1-A	V2-A	V3-A	V1-B	V2-B	V3-B
350 operation, inspection, maintenance	340 T€	336 T€	336 T€	358 T€	354 T€	353 T€
410 repairs of the building structures	241 T€	222 T€	210 T€	168 T€	157 T€	149 T€
420 repairs of the technical installations	198 T€	198 T€	198 T€	246 T€	246 T€	246 T€

Table 12 shows the resulting follow-up costs for the building structures and building services for both equipment variants A (left) and B (right). These consist of KG 350 (operation, inspection and maintenance), KG 410 (repairs of the building structures) and KG 420 (repairs of the technical installations). It is evident that cost differences between the three types within both equipment variants are similar.

The maintenance costs of the building structures (KG 410) are 30% higher for all three building types in equipment variant A than in equipment variant B. Within the construction costs (KG 300 according to DIN 276 [12]), the cost level of equipment variant B is only 4% higher than the cost level of equipment variant A (see Table 5 and Table 6). This means that the initially higher construction costs of the building structures for equipment variant B result in a clear cost advantage over equipment variant A in the operating phase.

Regarding the maintenance costs of the technical installations (KG 420), the costs for equipment variant B are approx. 20% more expensive than for equipment variant A for all three building types. The construction costs (KG 400 according to DIN 276 [12]) of equipment variant A are about 10% higher than for equipment variant B (see Table 10).

In the costs for operation, inspection and maintenance (KG 350), the costs for all three building types within equipment variant B are approx. 5% higher than those for equipment variant A. It can be deduced that the higher degree of mechanization of the building services equipment of equipment variant B causes higher maintenance costs.

4. Conclusions

The construction and follow-up costs of the building structures and building services engineering form a significant proportion of the life-cycle costs. Therefore, an early estimation of these cost components based on a consideration of the associated energy efficiency of buildings is essential. The analysis of different combinations of building components of the thermal envelope as well as of the building services components serve as a prerequisite for this. Subsequently, energy-efficient measures can be defined at an early stage of the project in combination with the estimation of the associated costs in the construction and operation phases. The methodology presented in this article offers a way to determine the influencing factors and effects of energy-saving measures on the life-cycle costs of a building. The example given in section 3 provides an insight into the possibilities for early derivation of results on both costs and energy efficiency factors. Some of the findings are summarized below.

A direct influence of the compactness of the buildings on the area-specific heating load and the final energy demand can be seen when looking at the determined energy parameters of the example building types V1, V2 and V3. Regarding to the costs for the fuel demand of a building (= demand-based costs according to VDI 2067 / Part 1 [20]), the building variant with the highest value for compactness (type V1) also has higher consumption costs than type V2 and type V3. Within the component masses, the comparison of the external wall areas of the three building types shows that type V1 has a higher amount of area compared to the other two building types (up to 31%), which also means that the construction costs of the building structures (KG 300 according to DIN 276 [12]) of type V1 are higher compared to the other two variants (up to 16%). In a more detailed cost analysis, KG 330 (external walls) has the largest share of the total costs of KG 300. Within the construction costs of the building services equipment (KG 400 according to DIN 276 [12]), KG 420 (heat supply systems) has the largest share of the total costs of KG 400 for all three types.

A comparison of the cost group for the building structures (KG 300) within the construction costs (according to DIN 276 [12]) shows higher costs for equipment variant B compared to equipment variant A (approx. 3.5%). This shows that the low-energy construction method considered in the example contains a higher-quality (and more expensive) equipment compared to the conventional construction method.

Within the follow-up costs, regarding to all three building types, the maintenance costs of the building structure (KG 410) are higher for equipment variant A than for equipment variant B (approx. 30%). Thus, despite the higher construction costs of equipment variant B compared to equipment variant A, equipment variant B has a cost advantage in the operating phase. Within the follow-up costs according to DIN 18960 [13], the maintenance costs of the technical installations (KG 420) are higher in equipment variant B than in equipment variant A (approx. 20%) for all three building types. The higher degree of mechanization of the building services equipment in equipment variant B also results in higher maintenance costs (KG 350 according to DIN 18960 [13]) than in equipment variant A.

In conclusion, this article presents a methodology that allows for the early optimization of energy efficiency in buildings, starting from the project development or early planning phase using the information available from a digital building model.

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