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Life-cycle cost estimation of a building structure: An example of partition walls

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Abstract: The growing pressure to optimise construction investment costs from the life-cycle perspective inevitably leads to efforts to seek new solutions that will facilitate informed decision-making in the early stages of the construction project. Awareness of the importance of considering future operation and demolition costs emphasises the shortcomings related to the possibility of making accurate predictions/estimations of such costs, which will become apparent in the future. To address this research gap, an innovative approach of life-cycle cost modelling on the level of individual structures of the building is presented. The model provides users with information on the costs of available technical solutions resulting from the requirements of the investor at a specific stage of the construction project. In this way, it helps investors optimise their building projects and to find the most economical solutions. Specifically, this model is assembled for the purpose of selecting a suitable partition wall and, therefore, it takes into consideration specific characteristics relating to this particular type of structure. The results indicate diversity in partition wall structural design variants at the early stage of the project. Since the ability to influence future costs decreases as the project progresses, the model allows capturing LCC perspective even if only a construction study is available without more detailed technical and economic information. The presented model aims to contribute to the higher performance of construction projects in the planning phase from the perspective of LCC and investors'/owners' point of view.

Keywords: building, construction, estimation, life-cycle costs, maintenance, partition wall, project

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1 Introduction

Increasing costs of utilities, repairs and services force investors to focus more on buildings' life cycle with the aim not only of capturing investment costs but also of considering future operation and maintenance costs. The life-cycle costs (LCC) approach is widely acknowledged by the research community, but its practical implementation is considerably limited because most building systems are designed without proper consideration of LCC (Illankoon and Lu 2019). Although several LCC methods have been developed, one of the major concerns is connected to the cost estimation far into the future as a result of the long service life of buildings (Goh and Sun 2016). The LCC limitations are also connected to other uncertainties such as accurate prediction of inflation rates, setting appropriate discount rates, deviations in material and other costs, and absence of complete data (Wong et al. 2010; Islam et al. 2015).

In order to tackle LCC uncertainties, several solutions have been proposed. Regarding the use of service life data during the design stage, Silva and de Brito (2021) have provided a database of durability and service life of building envelope components. In this connection, it should be emphasised that proper maintenance is an essential requirement to reach the expected service life or even to extend it (Marchini and Patzlaff 2016). Therefore, proper planning alone is not enough and maintenance management should be carried out by means of periodic inspections allowing to analyse the progression of damage and prediction of future impacts (Torres et al. 2019). To support effective maintenance, various tools such as inspection protocols (Torres et al. 2019) or performance degradation models (Flores-Colen and de Brito 2010) have been developed.

The importance of LCC is highlighted by the fact that decisions made in the early stages of the project (e.g. regarding the materials, technology used etc.) will have significant and long term cost effects on the building. Car-Pušić et al. (2020) argue that poor planning at the conceptual stage of the project is one of the core causes of cost overruns. Accordingly, LCC has to be performed in the early stages (i.e. at the conceptual stage, for instance as a part of the feasibility study) in order to facilitate finding cost-efficient solutions (Heralova 2017). Unfortunately, cost underestimation is not rare in the construction industry and is closely followed by failure to meet deadlines (Flyvbjerg 2009). The problems in achieving core project goals thus influence the trust of stakeholders involved in the project (Cerić et al. 2020). In this view, not just costs, but also work schedules should be managed in an advanced manner, for example by using optimisation techniques (Krzemiński 2017).

From the economic perspective, the prediction of implementation costs is quite accurate if detailed project documentation is available and a standard bill of costs can be compiled. If the documentation is processed in the earlier stages of the project, it contains less detailed data and cost predictions become less accurate. To make such cost estimation possible and more accurate, various prediction models have been proposed, for example those based on multiple and stepwise regression, support vector machine, neural networks and fuzzy inference (Xie and Fang 2018; Leśniak et al. 2020; Plebankiewicz and Wieczorek 2020; Fan and Sharma 2021). Special models were developed, for example for refurbishment works on historical buildings (Śladowski et al. 2019) or for accounting for risks (Plebankiewicz et al. 2021).

Investors often require more economic information for decision-making, which is why, for example, LCC and net present value (NPV) calculations can be combined (Spickova and Myskova 2015). Furthermore, also the payback period, internal rate of return (IRR) or savings to investment ratio can be used (Oduyemi et al. 2018). Both NPV and IRR belong to the dynamic methods considering the time value of money. These indicators are often used for example to evaluate the economic efficiency of energy savings measures on buildings. In this way, it is possible to identify optimal insulation thickness for a building (Nematchoua et al. 2015). Several researchers also propose the use of the whole life cost indicator in order to include various costs and benefits associated with the building from both internal and external perspectives (Korytarova and Hromadka 2010; Goh and Sun 2016).

A new dimension to LCC planning is connected with the recent use of modern information technology, mostly of Building Information Management (BIM). Mésároš et al. (2021) have discussed benefits of using information and communications technology in the LCC management; however, significant limitations still exist, for example in relation to the interconnection between life-cycle assessment (LCA), LCC and BIM (Santos et al. 2020) or Enterprise Resource Planning (ERP) and BIM (Venkrbec et al. 2012) platforms, for example in the form of data compatibility and transferability.

Furthermore, it is worth mentioning that artificial intelligence can be applied diversely for cost estimation issues, for example in relation to macro-BIM cost estimates of floor structural frames (Juszczyk 2018), or by using principal component data compression in artificial neural network supported cost estimation (juszczyk 2016). As concluded by a recent study by Bottero et al. (2021), advanced approaches such as BIM and multicriteria analysis are gaining importance in relation to sustainable view and life-cycle perspective of the projects.

For construction projects, one of the most important factors is the cost, or the estimated cost, of acquisition and the LCC. The problem arises in determining these at different stages of the design process. The available literature points to outstanding difficulties in the application of the LCC approach in the early stages of the buildings' project life cycle. On the one hand, there is a need to make early informed decisions, and on the other hand, the available data are typically insufficient to predict and manage economic aspects adequately.

Despite the clear definition of LCC calculation specified on the European Union level (European Commission, 'Life-cycle costing.'), LCC calculation tools have been developed for example for vending machines and computers, but not for buildings as a whole. Such tools are available only for selected relatively simple systems (indoor and outdoor lighting). The creation of an entire LCC concept on the level of buildings becomes very difficult due to the high complexity of construction projects (Qazi et al. 2016), their long service life and the uniqueness of each building that limits the accuracy of predictions and complicates the creation of the necessary databases that would be compatible across different countries and/or software solutions. As a result, attempts are being made to create the necessary procedures at a high level of detail at least for selected structures or functional parts of buildings.

This study aims to propose an innovative model supporting managerial decisions made in the selection of suitable partition wall structures from the LCC perspective at an early stage of the construction project. In order to achieve the objective, the subsequent parts of the paper present the development of the model, as well as its application on selected design variants of partition walls. The forthcoming sections of the paper provide results, discussion, conclusions, limitations and future research directions.

2 Model development

Designers aim to design a building that will correspond to the expected costs determined by the investor at the beginning of the project and to avoid excessive changes in the expected costs during the design of the building project. In the initial design of the building at the study stage, only limited information is known about the individual structures that will make up the building. In most cases, however, the architect should know what properties each particular structure should have. Subsequently, in the later stages of the building project (see Figure 1), refinements of the properties should be made until a specific product is selected or defined.

The conceptual model presented here builds on the basics of the previous solution for the external thermal insulation composite system (Biolek and Hanák 2019). This solution is aimed at ascertaining the most suitable solution from the building's LCC perspective, based on the same or better properties of the specific solution required by the investor, which corresponds to the construction implementation stage (CID). The ambition of the new model is to develop a solution within the project life cycle so that it can establish more credible LCCs for individual structures already at the construction study stage (COS), with only partial later refinements of the LCCs (i.e. during the preparation of the more detailed planning permit documents [PPD] and construction permit documents [CPD]). This new proposal is designed to be applied to partitions as a building structure.

2.1 Specification of technical parameters of partitions

When designing buildings, it is usually necessary to divide the interior space into rooms or other functional parts. Internal partitions are used for this purpose. There are no special load-bearing capacity requirements for partitions – they should be able to bear their own weight or that of objects placed on them. The main requirements for partitions are sound insulation (soundproofing) and, where applicable, fire resistance if these partitions separate fire compartments inside the building. As partitions are regarded as internal structures, they encroach on the surface area of rooms; consequently, the less the thickness of the partition, the greater the surface area of the room. This is important in terms of selling or renting spaces, where more area means a better price, but also due to the fact that the requirements for room sizes and the distances of, for example, furnishings from walls, are important in terms of healthy surroundings. If the partition separates a damp room or is directly located in this room (toilets,

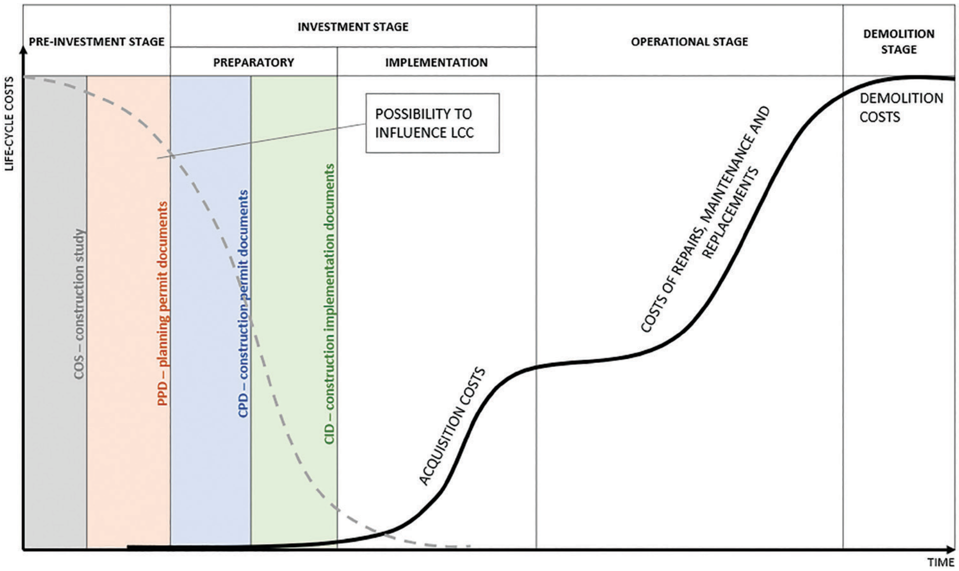


Fig. 1: Chart showing the dependence of LCC and possibilities to influence it at various stages of the building's life cycle and types of documentation (own work based on the researches of Tillmann [1997] and Prostějovská [2008]). CID, construction implementation stage; COS, construction study stage; CPD, construction permit documents; LCC, life-cycle costs; PPD, planning permit documents.

bathrooms, etc.), damp conditions resistance requirements must also be met.

The following parameters are considered within the proposed model:

- Type of partition and the associated acquisition costs
- Type of plaster and the associated acquisition costs (in case of masonry partitions)
- Repair and maintenance costs
- Demolition costs
- Laboratory weighted soundproofing
- Fire resistance
- Suitability for damp conditions
- Partition thickness

2.2 Types of partitions implemented in the model

There are many categories and types of partitions, and thus the model will be designed to take into account the commonly used types of non-load-bearing partitions, namely masonry and prefabricated ones. Masonry partitions are classified as heavy. These are made of bricks or blocks of various materials that are built using a mortar or adhesive bond to achieve a basic load-bearing capacity. With the exception of decorative surfaces, brick partitions must be fully plastered. This is because in most cases the declared soundproofing or fire resistance relies on plastered masonry (Příčky zděné [těžké]).

For the purpose of model development, the ÚRS price database (ÚRS, a.s.) is used, which contains most of the masonry partitions used in the Czech Republic. The database contains 63 masonry partition options divided into eight categories (see Table 1). As mentioned above, in order to ensure the declared properties, the partition walls must be plastered. The ÚRS price database contains four basic types of interior plasters and three types of special plaster. Special plasters are those that have a specific area of application and are not commonly used. In the model presented in this paper, only one layer of plaster is taken into consideration, with no final stuccos or painting. When plastering masonry, the masonry surface must be correctly primed so that the plaster sufficiently bonds to the wall. Variants of base coat preparation according to the ÚRS price database are also provided in Table 1. All cost information regarding acquisition costs and demolition costs that can be found in this article are taken from the ÚRS price database.

Base coat preparation differs depending on the type of plaster material. Therefore, a schematic was created based on the available base coats for combinations of masonry–base coat–plaster that are possible in the construction of a masonry partition wall, separately for standard (see Table 2) and special plasters (Table 3).

In the case of prefabricated partitions, these are classified as lightweight. They are a combination of a frame (most often thin-walled steel sheet) and a thin board material (most often plasterboard or gypsum fibreboard). Thermal insulation can be placed in the frame, which forms a cavity, to improve the properties of the partition wall, or it can be a suitable place for wiring. The boards can have different thicknesses, in the range of 10–15 mm, as well as different properties, namely standard, impregnated for damp environments, fire-resistant, acoustic, or a combination thereof. To improve the properties, the boarding can be doubled or tripled. A primer must be applied to the prefabricated wall before the final layer is applied. For the purposes of calculations in the model, prefabricated partitions are divided into gypsum plasterboard and fibreboard.

Prefabricated partitions do not require plaster, and thus there is no need to consider the relationship between the partition and the plaster. Thin-layer plastering or replastering is only used for aesthetic reasons where the emphasis is on the same wall structure in the room or when a perfect appearance is necessary. Such cases were disregarded for the purposes of this research.

Tab. 1: List of examined types of masonry partitions, plasters and base coat preparation (own work, based on ÚRS, a.s.)

Types of masonry partitions	Types of plaster	Types of base coat preparation
Partitions made of burnt bricks	Lime plaster	Polymer-cement adhesive primer
Partitions made of unburnt bricks	Lime-cement plaster	Clay primer
Partitions made of concrete blocks	Cement plaster	Acrylic-silicone primer
Partitions made of ceramic blocks	Gypsum plaster	Clay spraying
Calcium-silicate partitions	Clay plaster (special)	Lime spray
Cellular concrete partitions	Thermal insulation plaster (special)	Cement spray
Concrete partitions for plasterless masonry	Barite plaster (special)	
Gypsum partitions for plasterless masonry		

Tab. 2: A schematic of possible combinations of masonry–base layer–standard plaster (own work, based on Cemix [wall systém])

Base layer / masonry	Lime plaster						Lime-cement plaster						Cement plaster						Gypsum plaster					
	Polymer-cement adhesive primer	Clay primer	Acrylic-silicone primer	Clay spraying	Lime spray	Cement spray	Polymer-cement adhesive primer	Clay primer	Acrylic-silicone primer	Clay spraying	Lime spray	Cement spray	Polymer-cement adhesive primer	Clay primer	Acrylic-silicone primer	Clay spraying	Lime spray	Cement spray	Polymer-cement adhesive primer	Clay primer	Acrylic-silicone primer	Clay spraying	Lime spray	Cement spray
Burnt brick partitions	–	–	X	–	X	–	–	–	X	–	–	X	–	–	X	–	–	X	–	–	X	–	–	–
Unburnt brick partitions	–	–	X	–	X	–	–	–	X	–	–	X	–	–	X	–	–	X	–	–	X	–	–	–
Concrete block partitions	X	–	X	–	X	–	X	–	X	–	–	X	X	–	X	–	–	X	X	–	X	–	–	–
Ceramic block partitions	–	–	X	–	X	–	–	–	X	–	–	X	–	–	X	–	–	X	–	–	X	–	–	–
Calcium-silicate partitions	–	–	X	–	X	–	–	–	X	–	–	X	–	–	X	–	–	X	–	–	X	–	–	–
Cellular concrete partitions	–	–	X	–	X	–	–	–	X	–	–	X	–	–	X	–	–	X	–	–	X	–	–	–

‘X’ denotes usability and ‘–’ absence of use or non-usability.

Tab. 3: A schematic of possible combinations of masonry–base layer–special plaster (own work, based on Cemix [wall systém])

Base layer / masonry	Clay plaster						Thermal insulation plaster						Barite plaster					
	Polymer-cement adhesive primer	Clay primer	Acrylic-silicone primer	Clay spraying	Lime spray	Cement spray	Polymer-cement adhesive primer	Clay primer	Acrylic-silicone primer	Clay spraying	Lime spray	Cement spray	Polymer-cement adhesive primer	Clay primer	Acrylic-silicone primer	Clay spraying	Lime spray	Cement spray
Burnt brick partitions	–	X	–	X	–	–	–	–	–	–	–	X	–	–	–	–	–	X
Unburnt brick partitions	O	O	O	O	O	O	–	–	–	–	–	X	–	–	–	–	–	X
Concrete block partitions	X	–	–	–	–	X	X	–	–	–	–	X	X	–	–	–	–	X
Ceramic block partitions	–	X	–	X	–	–	–	–	–	–	–	X	–	–	–	–	–	X
Calcium-silicate partitions	X	–	–	–	–	X	–	–	–	–	–	X	–	–	–	–	–	X
Cellular concrete partitions	–	X	–	X	–	–	–	–	–	–	–	X	–	–	–	–	–	X

‘X’ denotes usability, ‘O’ that the base layer is not necessary and ‘–’ absence of use or non-usability.

2.3 Creation of a database of the examined variants

From the above information on partition types, a database of specific partition options was created, both for masonry with plaster and prefabricated partitions. For each partition option, information was added based on the information available from the manufacturers on:

- the weighted laboratory soundproofing measured in dB (with plaster on both sides of a masonry partition);
- fire resistance (with plaster on both sides of a masonry partition);
- thickness with surface plaster; and
- information on suitability for damp conditions.

In addition to this information, the database contains information on:

- unit purchase price in EUR;
- unit weight in tonnes to determine the weight of the material to be transported and the weight of the rubble; and
- the unit workload in man-hours (MH) to determine the time requirements and to facilitate creating a time schedule.

In total, the database contains 828 brick and prefabricated partition design variants. An example of a masonry partition wall specification is shown in Table 4; an example of a precast partition specification is provided in Table 5.

Tab. 4: Sample of masonry partition from the database (own work, based on ÚRS, a.s., and Cemix [wall systém])

Description	**Simple partitions made of classic perforated bricks, tongue and groove joints with M5 mortar, brick strength up to P15, partition thickness 115 mm + 20 mm plaster thickness**
Partition type	Masonry
Material type	Brick partition
Type of plaster	Lime-cement plaster
Base layer type	Acrylic-silicone primer
UoM	m^2
Acquisition costs	43.4 EUR/m^2
Costs per one repair (according to Tab. 8)	14.3 EUR/m^2 (undiscounted)
Demolition costs	11.7 EUR/m^2 (undiscounted)
Total weight	0.14331 tonne
MH total	1.3 MH/m^2
Laboratory weighted soundproofing (Rw)	46 dB
Fire resistance	EI 180
Suitability for damp conditions	Yes
Partition thickness	135 mm

The MH is representative of the standardised time required to perform a specific work (i.e. the norm of time).
MH, man-hours; EI, fire shutters to prevent fire.

2.4 LCC calculation

The LCC indicator is calculated based on the formula indicated in the European ISO 15686-5:2017 (ISO 15686-5:2017) standard, which is based on the discounting of future costs in the examined period (the discounted cash flow [DFC] model). LCC is calculated according to the following formula:

$$\mathrm{LCC} = \Sigma_{t=0}^{T} \frac{C_t}{(1+r)^t}$$

where C_t indicates all costs as equivalent cash flows in year t; r the discount rate; t the analysed year (t = 0, 1, 2..., T); and T the length of the life cycle in years.

Tab. 5: Sample of prefabricated partition from the database (own work, based on ÚRS, a.s., and Heluz katalog)

Description	**Gypsum plasterboard partition with supporting structure made of simple steel profiles UW, CW simply sheathed with standard A board 12.5 mm thick, partition thickness 75 mm, profile 50, with insulation, EI 30, Rw up to 45 dB**
Partition type	Prefabricated
Material type	Plasterboard partition
Board type	A 1 × 12.5 mm
UoM	m^2
Acquisition costs	33.0 EUR/m^2
Costs per one repair (according to Tab. 8)	19.4 EUR/m^2 (undiscounted)
Demolition costs	5.1 EUR/m^2 (undiscounted)
Total weight	0.02493 tonne
MH total	0.02476 MH/m^2
Laboratory weighted soundproofing (Rw)	45 dB
Fire resistance	EI 30
Suitability for damp conditions	No
Partition thickness	100 mm

MH, man-hours; EI, fire shutters to prevent fire.

Other types of LLC models work on the principle of different discounting of regular and irregular costs (see e.g. Bromilow and Pawsey [1987] or Sobanjo [1999]), but this approach is not used in our proposed methodology. Instead, DFC model is used for the purpose of this research.

The demolition costs are included in the analysis; however, it must be noted that due to the long building life span and applied discount rate, the NPV of a demolition cost becomes negligible (Galimshina et al. 2020). For this reason, selected undiscounted LCC values are also presented here.

2.5 LCC modelling using the proposed model

From the above description of the partition function and requirements laid on it, the information to be considered in the design process can be identified. At each stage of the project, only certain elements of information are known or only certain properties of the partition can be determined. The designer can choose a range of values for a given characteristic or a specific value based on the information known to him about the building at different stages of preparing the necessary documents. The working principle of the model and the links between the data are shown in Figure 2.

According to ČSN 73 0532, the weighted laboratory soundproofing must be corrected based on the type of structure and the structures surrounding it. The specific corrections for research purposes are given in Table 6.

The scope of requirements for the individual properties of partitions is given in Table 7.

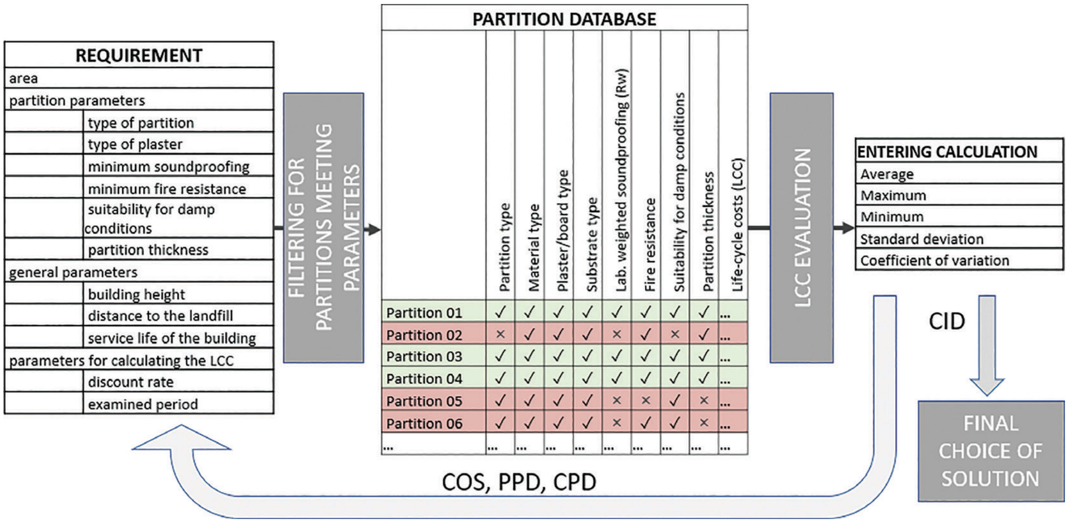
The designer can also limit the specific properties of the structures according to the investor's requirements, for example, as to whether the partition should be brick or prefabricated or whether only certain materials should be filtered for. It all depends on the experience of the designer and other constraints, such as statics, labour input, etc.

To calculate the LCC it is necessary to define the service life, scope and frequency of repairs. Since the definition excludes painting, tiling and stuccos as parts of the partition for the purposes of this research, it is not necessary to consider the associated maintenance. The proposed structure of the information concerning repairs and service life (IRL) (see Table 8) is based on the available literature (Marková 2011).

According to the input information in the IRL database, LCC is calculated for each partition variant according to formula presented in Eq. (1). The price for each IRL and the demolition costs are based on the ÚRS price database (ÚRS, a.s.).

2.6 Application of the model

To demonstrate the functionality of the model, a partition separating living space from a corridor designated as a protected escape route (PER) was selected. According to the ČSN 73 0532:2020 standard, the partition must meet the following parameters: minimum sound insulation of 42 dB and minimum fire resistance (due to PER requirements) of EI 45.



PARTITION DATABASE	Partition type	Material type	Plaster/board type	Substrate type	Lab. weighted soundproofing (Rw)	Fire resistance	Suitability for damp conditions	Partition thickness	Life-cycle costs (LCC)
Partition 01	✓	✓	✓	✓	✓	✓	✓	✓	...
Partition 02	×	✓	✓	✓	×	✓	×	✓	...
Partition 03	✓	✓	✓	✓	✓	✓	✓	✓	...
Partition 04	✓	✓	✓	✓	✓	✓	✓	✓	...
Partition 05	✓	✓	✓	✓	×	×	✓	×	...
Partition 06	✓	✓	✓	✓	×	✓	✓	×	...
...	...	...	...	...	...	...	...	...	...

Fig. 2: Schematic of LCC modelling (own work). CID, construction implementation stage; COS, construction study stage; CPD, construction permit documents; LCC, life-cycle costs; PPD, planning permit documents.

Tab. 6: Correction of the weighted laboratory soundproofing according to ČSN 73 0532 (ČSN 73 0532 [730532])

Dividing element	Side structure	Correction (dB)
Masonry wall	4× heavy	2
	3× heavy, 1× light	3
	2× heavy, 2× light	4
	1× heavy, 3× light	5
	Masonry skeleton	≥4
Prefabricated partition R_w ≤55 dB	4× heavy	5
	3× heavy, 1× light	6
	2× heavy, 2× light	8
Prefabricated partition R_w ≥55 dB	4× heavy	6
	3× heavy, 1× light	7
	2× heavy, 2× light	≥8

Tab. 7: The scope of requirements for the individual properties of non-load-bearing partitions (own work)

Soundproofing R_w (dB)	35–74 - correction
Fire resistance	EI 15–EI 180 or N/A
Suitability for damp conditions	Yes/no
Partition thickness (mm)	70–290

Tab. 8: Database of the service life and scopes and frequencies of repairs for masonry and prefabricated partitions (own work, and based on Marková's study [2011])

Masonry partitions	Lifetime (years)	Repairs	
		Scope in percentage (%)	Frequency (years)
Masonry partitions	100	–	–
Lime plaster	100	Under 50	30
Lime-cement plaster	100	Under 50	30
Cement plaster	100	Under 50	30
Gypsum plaster	100	Under 50	30
Clay plaster	100	Under 50	30
Thermal insulation plaster	100	Under 50	30
Barite plaster	100	Under 50	30
Prefabricated partitions	**Lifetime (years)**	**Repairs**	
		Scope in percentage (%)	**Frequency (years)**
Plasterboard partitions	100	Under 50	30
Fibreboard partitions	100	Under 50	30

The case study will present how the model can be used in different stages of preparing project documents:

COS – Neither the type of partition or plaster nor the thickness is relevant.

Tab. 9: Specification of requirements for the partition at various levels of project documentation (own work)

Project documentation level	Partition type	Plaster type	Partition thickness
COS	0	0	0
PPD	0	1	1
CPD	1	1	1

'1' denotes specified, and '0' not specified.
COS, construction study stage; CPD, construction permit documents; PPD, planning permit documents.

PPD – The type of partition is not relevant; only standard plaster will be used and for space-saving reasons, the maximum thickness of the partition is set to 150 mm.

CPD – Masonry partition; only standard plaster will be used and for space-saving reasons, the maximum thickness of the partition is set to 150 mm.

CID – Selection of a specific partition based on the lowest discounted LCC

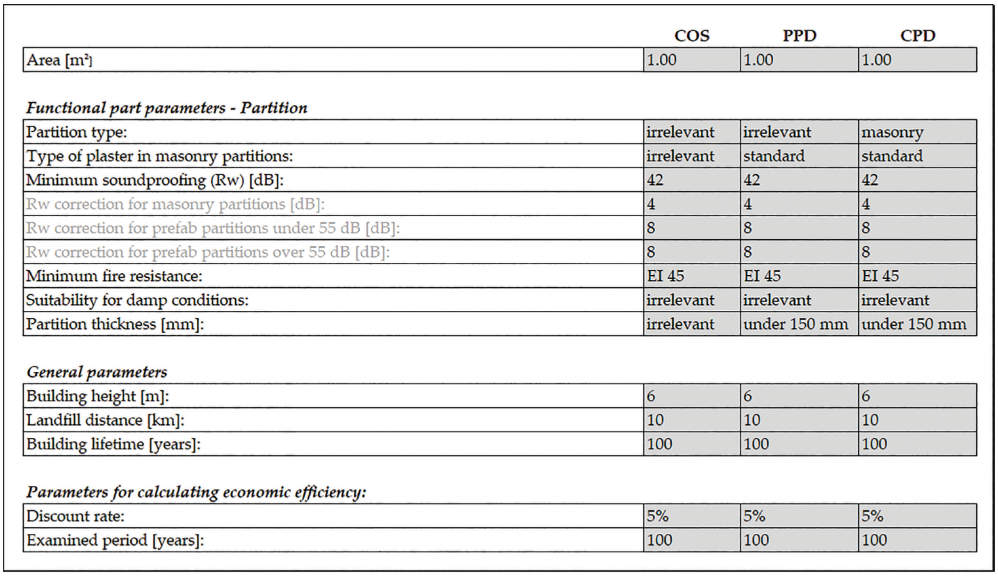
Specification of requirements for the partition at various levels of project documentation is given in Table 9. For the calculation, it is also necessary to enter general parameters of the building, where it is necessary to specify the height of the building (for the calculation concerning the movement of bulk material and debris), the distance of the landfill from the building and the expected service life of the entire building, which in this model case is considered to be 100 years (Kupilík 1999).

According to the LCC calculation, it is also necessary to specify the discount rate and the length of the examined period over which the investor wants to evaluate the LCC. In accordance with the general approach (Lazzarin et al. 2008; Korytárová and Papežíková 2015), the discount rate was set at 5% and the examined period at 100 years. The input of each parameter and property into the computational model is shown in Figure 3.

3 Results

Based on the input information (see Section 2.6), the model considered 373 possible solutions for the COS stage, 155 solution options for the PPD stage and 80 options for the CPD stage. The solution with the lowest discounted LCC is selected for the CID level according to the specifications.

Table 10 shows the specific LCC modelling results, with both discounted and undiscounted values. The data illustrate the different values of the results obtained depending on the details of the information input at different stages of the project documentation. The data marked as 'Maximum' represent the most expensive possible



	COS	PPD	CPD
Area [m²]	1.00	1.00	1.00
Functional part parameters - Partition			
Partition type:	irrelevant	irrelevant	masonry
Type of plaster in masonry partitions:	irrelevant	standard	standard
Minimum soundproofing (Rw) [dB]:	42	42	42
Rw correction for masonry partitions [dB]:	4	4	4
Rw correction for prefab partitions under 55 dB [dB]:	8	8	8
Rw correction for prefab partitions over 55 dB [dB]:	8	8	8
Minimum fire resistance:	EI 45	EI 45	EI 45
Suitability for damp conditions:	irrelevant	irrelevant	irrelevant
Partition thickness [mm]:	irrelevant	under 150 mm	under 150 mm
General parameters			
Building height [m]:	6	6	6
Landfill distance [km]:	10	10	10
Building lifetime [years]:	100	100	100
Parameters for calculating economic efficiency:			
Discount rate:	5%	5%	5%
Examined period [years]:	100	100	100

Fig. 3: Input of individual parameters into the computational model for all stages of project documentation (own work). COS, construction study stage; CPD, construction permit documents; PPD, planning permit documents.

Tab. 10: LCC results for the individual stages of documentation – COS, PPD, CPD (own work)

Descriptive statistics measure	**LCC discounted (EUR/m²)**			**LCC undiscounted (EUR/m²)**		
	COS	**PPD**	**CPD**	**COS**	**PPD**	**CPD**
Average	74.5	62.3	56.0	155.2	128.6	121.1
Maximum	172.6	111.8	67.3	402.3	178.0	144.7
Minimum	42.5	42.5	43.7	97.8	97.8	97.8
Standard deviation	24.3	13.3	5.5	57.1	16.8	11.1
Coefficient of variation	33	21	10	37	13	9

COS, construction study stage; CPD, construction permit documents, LCC, life-cycle costs; PPD, planning permit documents.

option for the partition from the LLC perspective, while ‘Minimum’ represents the cheapest option. The data are further supplemented with the average, standard deviation and coefficient of variation.

At the CID stage, the task was to select the most suitable solution with the lowest discounted LCC, and the result is presented in Table 11.

4 Discussion and Conclusion

The case study of non-load-bearing partition structures shows the possibilities of using the model for LCC calculation. The designer enters individual requirements into the model based on known information about the partition at different stages of preparing the design documents. The more accurate the information entered, the narrower the number of structures selected that meet the requirements and, therefore, the more accurate the LCC value with a narrower cost range. Conversely, the lesser the quantum of information available (i.e. earlier in the initial stages of the project life cycle), the wider the range of options selected will be, and the model will offer a wider price range.

An example of the options for a non-load-bearing partition between living space and a corridor (designated as a PER) was addressed in this case study. This specification, as per the standard, defines minimum requirements for laboratory soundproofing (42 dB) and minimum fire resistance (EI 45). The model simulated the different stages of documentation from the initial study to construction implementation documents. As the documentation became more detailed, the requirements were refined, from general to specific partition solutions.

At the study stage, when the specification corresponded to the requirements according to the standards, the average discounted LCC were 74.5 EUR/m² (coefficient of variation 33%); for the PPD stage, when specifying the requirement for partition thickness and plaster

Tab. 11: Partition selected for CID (own work)

Description	Partitions or simple partitions of concrete slip bricks on cement mortar, 120 mm thick + 20 mm plaster thickness
Partition type	Masonry
Material type	Brick partition
Type of plaster	Lime-cement plaster
Base layer type	Acrylic-silicone primer
UoM	m^2
LCC	104.3 EUR/m^2 undiscounted; 43.7 EUR/m^2 discounted
Acquisition costs	39.1 EUR/m^2
Costs per one repair (according to Tab. 8)	45.4 EUR/m^2 undiscounted; 4.51 EUR/m^2 discounted
Demolition costs	19.9 EUR/m^2 undiscounted; 0.2 EUR/m^2 discounted
Total weight	0.147 tonne
MH total	1.7 MH/m^2
Laboratory weighted soundproofing (Rw)	44 dB
Fire resistance	EI 90
Suitability for damp conditions	Yes
Partition thickness	140 mm

CID, construction implementation stage; LCC, life-cycle costs; MH, man-hours.

Tab. 12: Distribution of undiscounted LCC components according to the individual stages of preparation of design documents (own work)

Descriptive statistics measure	Acquisition price (EUR/m^2)			IRL (EUR/m^2)			Demolition costs (EUR/m^2)		
	COS	PPD	CPD	COS	PPD	CPD	COS	PPD	CPD
Average	67.1	56.3	50.5	73.2	59.6	53.8	15.1	12.9	16.9
Maximum	149.7	105.3	60.8	225.6	81.5	63.5	27.1	20.8	20.8
Minimum	36.6	36.6	39.1	42.8	42.8	42.8	5.5	5.5	11.4
Standard deviation	21.2	12.9	5.1	36.6	8.7	5.3	5.7	4.8	3.0
Coefficient of variation	32	23	10	50%	14	10	38	37	17

COS, construction study stage; CPD, construction permit documents; IRL, information concerning repairs and service life; LCC, life-cycle costs; PPD, planning permit documents.

type for masonry partitions, the LCC equalled 62.4 EUR/m^2 (coefficient of variation 21%); for the CPD stage, the requirement for a brick partition was added, where the discounted LCC equalled 56.0 EUR/m^2 (coefficient of variation 10%); and for the CID stage, a specific solution was selected, resulting in discounted LCC of 43.7 EUR/m^2.

Table 12 shows the different components of the LCC, namely acquisition cost, IRL cost and demolition cost, in undiscounted form. These sub-values may be another possible decision criterion for the selection of the final option for the CID, due to the emphasis on, for example, the lowest acquisition price or low costs in the operational stage of the building.

Figure 4 illustrates the range of discounted LCC values at different documentation stages according to input information. In this case study, the investor's requirements were undemanding throughout the project preparation (standard plaster was sufficient instead of special plaster, smaller thickness, etc.) and, therefore, the price range in terms of LCC was narrowed by the gradual elimination of more economically demanding solutions (i.e. the maximum possible values decreased). If the situation arose that the investor was forced to increase the requirements for the partition, the price range would be adjusted also in terms of eliminating the cheapest potentially available solutions.

Figure 5 presents the distribution of the different components of LCC, namely acquisition price, IRL cost and demolition costs at different stages of documentation, in undiscounted form. The figure shows a gradual decrease in the share of the acquisition price, which for the selected variant makes up about 38% of the total LCC. The costs of the operational stage make up 44% of the total LCC, while 19% are demolition costs. It is the demolition costs that increased their share of the LCC in the COS by about 10%, which was caused by the selection of the masonry option,

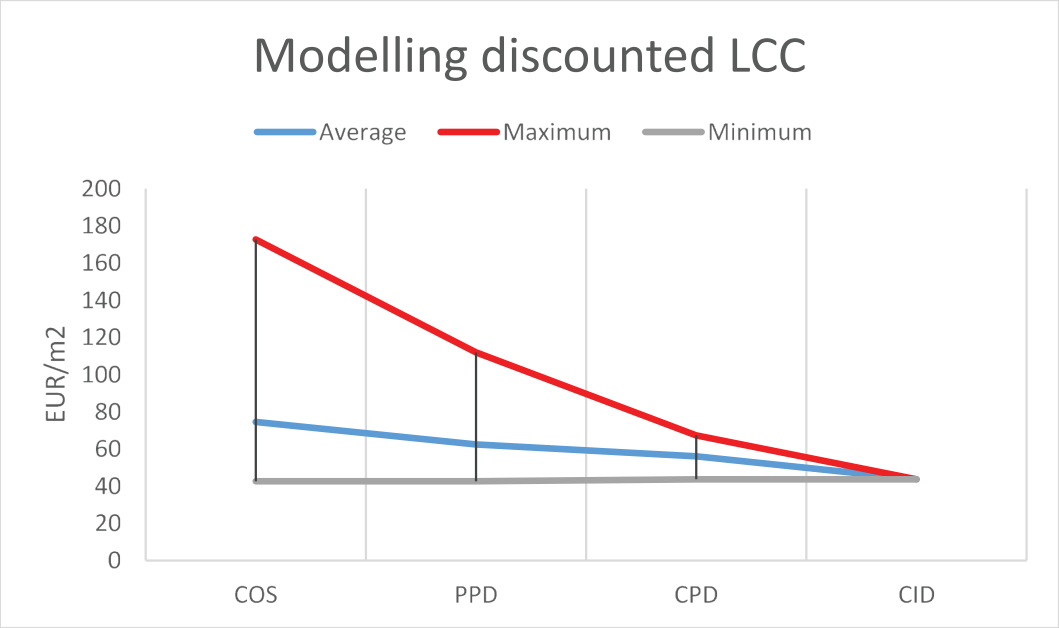


Fig. 4: LCC ranges for the individual stages of documentation (own work). CID, construction implementation stage; COS, construction study stage; CPD, construction permit documents; LCC, life-cycle costs; PPD, planning permit documents.

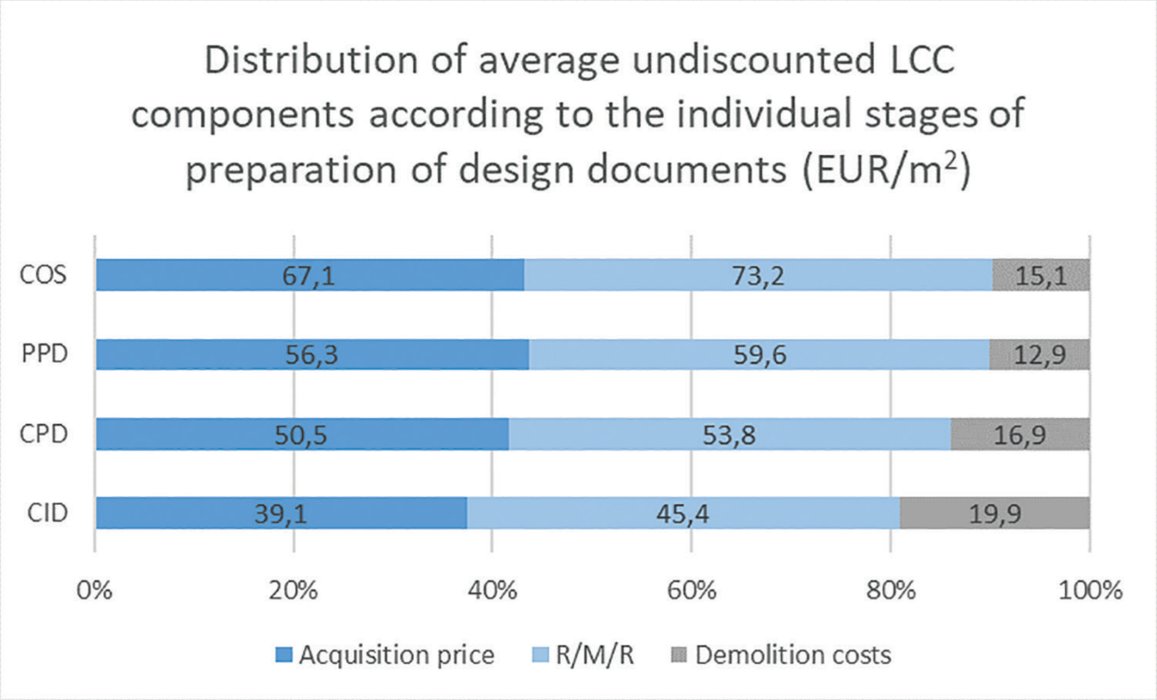


Fig. 5: Distribution of average undiscounted LCC components according to the individual stages of preparation of design documents (own work). LCC, life-cycle costs.

which is heavier in weight than the prefabricated partition and hence the demolition costs are higher.

Costs at the operational stage of the building (IRL) enter the LCC calculation. For the case study of non-load-bearing partitions, the IRL database was taken from the literature (Marková 2011), and the same service life and repair scope were considered for both masonry and prefabricated partitions. Indeed, the investor or the facility manager may have a different experience with specific types of partitions, and thus may adjust the IRL database

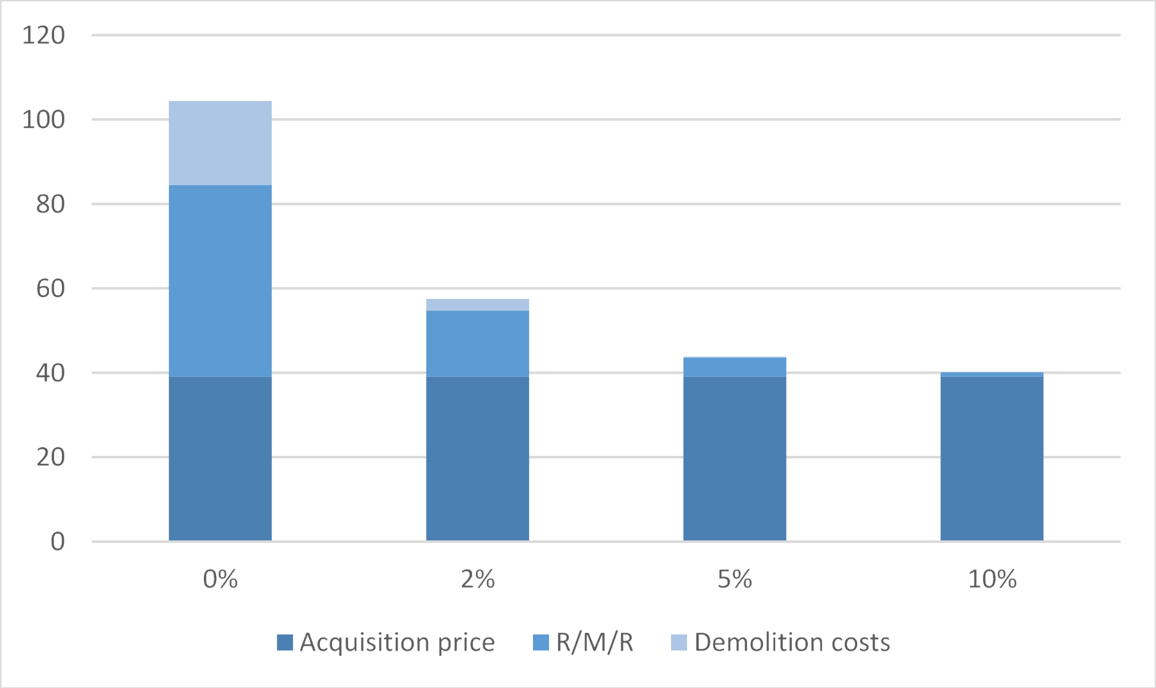


Fig. 6: Distribution of LCC (on the CID level) for various discount rates (own work). CID, construction implementation stage; LCC, life-cycle costs.

according to their knowledge or actual numbers. Therefore, the individual parameters of the proposed model can be adjusted so that the outputs correspond as closely as possible to the circumstances and conditions of the examined building.

Sensitivity analysis has also been performed in order to reveal how the discount rate affects the resulting LCC value. The analysis is performed for the following discount rates: 0%, 2%, 5% and 10% (see Figure 6). The analysis is performed on the final partition wall option for the CID. It can be seen from the graph that the higher the discount rate, the lower the influence it has on the LCC costs within the operational and demolition phases, which confirms the theory presented in Section 2.4. More specifically, the share of operational and demolition costs in total LCC with discount rates of 0%, 2%, 5% and 10% amounts to, respectively, 63%, 32%, 11% and 2%.

It is clear from the data presented that the use of the methodology brings a number of benefits for various actors in the construction project process, starting with the investor, through the designer to the facility manager. In addition to the LCC calculator itself, the methodology allows for an appropriate assessment of different material alternatives and, last but not least, to monitor costs not only during design and construction but also during the actual operation of the building.

On the other hand, the methodology is dependent on good quality input data. It is essential that comprehensive building-economy systems and databases containing all possible variations of individual functional components be available. This requirement can be problematic, especially in the case of unavailability of a sufficiently robust and up-to-date source of information, which can lead to a lack of accuracy in calculations and analyses.

The above-proposed system shows the diversity in building design at the level of individual structures, specifically partitions. From the theoretical perspective, the presented model has contributed to the current body of knowledge by addressing the importance of the early informed decision-making of investors regarding the selection of the most suitable solution variant in terms of the LCC.

In parallel, the proposed model has several managerial implications. Practitioners can use the model as a tool that, based on the input requirements, provides outputs in the form of LCC values, while allowing the selection of the most suitable solution taking into account the detail of the available design documents. Each solution or set of solutions carries cost information broken down into investment, operating and demolition costs, but as an added value the model also provides a measure of labour intensity (expressed in terms of the time required to construct one unit of a given partition), which could serve as a useful input for construction scheduling. The cost of repairs and their distribution over time serve as an input for the operational stage of the building's life cycle in terms of investment planning. An important piece of information that the system can evaluate is the known variance of possible solution options, which is important for monitoring compliance with the projected costs from the investor's perspective. In this light, the presented model contributes to the higher performance of construction projects in the planning phase from the cost and scheduling perspectives.

This research is limited in two ways. Firstly, the study has been conducted in the context of the Czech construction industry. Therefore, the input data used in the model reflect the corresponding cost levels. If the model was applied in a different country, it might provide somewhat different results due to different prices of building materials and works or due to different technical requirements applied for a given structure. Nevertheless, the presented concept is generally applicable when making the necessary modifications to a model that is flexible in this regard. Secondly, the model has been created just for partitions; therefore, applying the model to other types of building structures would necessitate the determination of their essential technical properties.

Future research directions should enable the extension of the model's use cases to other types of structures so that in the future it would be possible to model the LCC for an entire building. Furthermore, the principles of model operation can also be taken into account when designing BIM models aiming to estimate the LCC (i.e., BIM models on the 6D level).

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