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Implementing life-cycle costing

Data integration between design models and cost calculations

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IMPLEMENTING LIFE-CYCLE COSTING: DATA INTEGRATION BETWEEN DESIGN MODELS AND COST CALCULATIONS

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SUMMARY: *The objectives of this study were to develop, test and summarise lessons learned using two different methods for data integration between autonomous software packages for design models, cost calculations and cost databases with regard to generating life-cycle costing analysis. The two developed methods followed the principles of compatibility and interoperability and were tested in three test cases: a simplistic design model, a university building model and a private company's office building model. The compatible method entailed an MS Excel tool while the interoperable method followed a more automated procedure through a visual programming environment. Both methods were, however, facing several obstacles with regard to data integration across autonomous software packages and automated procedures for calculation of life-cycle cost which in turn left plenty of manual work and made the results prone to human errors.*

KEYWORDS: *Life-cycle costing (LCC), Building Information Modelling (BIM), data integration, interoperability, compatibility, data management*

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1. INTRODUCTION

In a long-term perspective, the running costs of buildings equal the initial construction costs (Haugbølle and Raffnsøe, 2019; Goh and Sun, 2016). Hence, life-cycle costing (LCC) is a vital methodology for promoting a life-cycle perspective on buildings ensuring a fair comparison of solutions with different cost profiles over time, informing the decision-making process and improving risk management (Hofer *et al*, 2010). LCC has become a mature concept governed by two international standards (CEN, 2012; ISO, 2008), several industry guidelines (e.g. Caplehorn, 2012; Dhillon, 2010, Farr, 2011) and a multitude of tools (Sørensen *et al*, 2016). Still, the uptake has continued over the years to be rather weak due to significant challenges with regard to constraints in data accuracy and in current design practices (e.g. Bird, 1987; Cole and Sterner, 2000; Fu *et al.*, 2007; Gluch and Baumann, 2004; Marshall, 1987; Ruparathna and Hewage, 2015). In recent years, three new trends have strongly revitalised the focus on LCC in the built environment.

Firstly, the challenge of sustainability has fostered a renewed focus on LCC. Various certification schemes like LEED and DGNB require the use of LCC, while new integrated methodologies of life-cycle costing and life-cycle assessment are being developed (Du, 2015; Hoogmartens *et al.*, 2014). In a European context, the Level(s) framework for sustainability assessment of buildings, introduced in 2017 by the Joint Research Institute, entails LCC as one of its core indicators (European Commission, 2017). Secondly, new procurement policies are pushing for an increased use of LCC through the recent European Procurement Directive from 2014 (Directive 2014/24/EU) (European Commision, 2014) and local regulations, like the recent Danish national regulation on LCC in public construction (Bygningsstyrelsen, 2017). In addition, the new Danish Building Regulations 2020 will introduce a new voluntary sustainable building class addressing resource efficiency, hazardous materials, indoor environment and long-term value stability, including LCC (Mortensen et al., 2018). Thirdly, researchers and practitioners have lately shown increasing interest in LCC in relation to the new technological opportunities offered by building information modelling (BIM) (Liu *et al.*, 2015; Lu *et al.*, 2014; Miettinen and Paavola, 2014; Xu *et al.*, 2014).

BIM offers significant benefits of advanced productivity (Azhar *et al.*, 2008; Love *et al.*, 2011) and collaboration as the information can be stored and accessed any time (Meadati, 2009) and shared within the project team (Miettinen and Paavola, 2014; Eastman *et al.*, 2018). Through BIM, project variables such as cost, time and quality can be controlled from an early stage and contribute to more valuable decision-making (Fischer and Kunz, 2004) and thereby increase the information availability (Ahuja *et al.*, 2009; Dainty *et al.*, 2006).

This promising integration of BIM and LCC is pursued through a number of different approaches such as embedding LCC in existing 5D BIM tools (Kehily and Underwood, 2017), developing plug-ins to support the use of BIM for better maintenance accessibility (Liu and Raja, 2014) and developing a unique collaboration tool for asset and maintenance management (Spagnolo, 2018). Other approaches include applying standards like COBie to bridge the differences between BIM design tools and facility management systems (Tu et al., 2016), adding new techniques on multi-criteria decision-making for BIM use (Jalaei et al., 2015) and using semantic web for integration of IFC objects and information on facility management work (Kim et al., 2018).

Despite this revitalised focus on LCC, data management continues to be a significant obstacle for its application. While the use of BIM design tools promises to automate e.g. quantity take-offs, the real-world problems persist with regard to establishing robust and reliable models without flaws in the quantities (Chiurugwi *et al.*, 2015; Edirisinghe *et al.*, 2017; Owen *et al.*, 2010). More importantly, the absence of interoperability between different independent software solutions is a major hindrance to easing design simulations and exploiting data on geometry, quantities and cost flows across tools (HM Government, 2015; Hooper, 2015; Monteiro and Martins, 2013; Tsai *et al.*, 2014).

The same significant obstacles with regard to data management can be observed in the Danish architecture, engineering and construction (AEC) industry. Currently, the Danish AEC industry typically execute an LCC calculation based on a combination of three tools: (1) Sigma Estimates: a 5D BIM cost estimation tool (Sigma Estimates, 2003), (2) LCCbyg: a Danish application for LCC analysis (LCCbyg, 2018) and (3) internally developed spreadsheets. Although Sigma Estimates provides the possibility of a direct link and connection to cost libraries, the present value of future costs cannot be calculated, and the price development rates cannot be inserted. On the other hand, LCCbyg offers the latter although the link to design models and cost libraries for direct calculations is not established. Hence, the AEC industry needs tools in which specific costs in the future can be imported and a link between cost databases, the design model and the LCC calculations can be made.

Therefore, the objectives of this study are threefold:

- to develop two different methods of data integration between design models and cost databases based on the principles of compatibility versus interoperability of software solutions,
- to test the two different methods on three different test cases, and
- to evaluate the lessons learned and summarise these in five hindrances to the implementation of LCC in the AEC industry.

2. METHODOLOGY

This study is based on the combination of four different methods. An extensive literature review was performed and followed by a small number of interviews. Based on insights from the literature review and interviews, two different methods for data integration were developed and tested in three case studies.

2.1 Literature review

An extensive literature review was conducted with regard to LCC, BIM and different approaches to data integration between different types of autonomous software applications. The literature review draws on other previous literature reviews done by Haugbølle & Raffnsøe (2018)in relation to LCC, Thurairajah & Boyd (2017) in relation to BIM, and Toth et al. (2012) and Negendahl (2015) in relation to data integration. These reviews were supplemented with additional searches using Google Scholar and various literature databases like EBSCOhost.

2.2 Interviews

Three interviews were conducted to identify current LCC practices in the Danish AEC industry. Collaboration was established with a leading engineering consultancy company for gathering information on current LCC practices and for testing the developed data integration methods. Two interviews were conducted with employees of the company. The first interviewee was a consultant/client advisor of the company who is responsible for the project and financial management of sustainable building projects. The second interviewee was a DGNB Practitioner from the Energy and Sustainability Group of the company. The aim of the two interviews was to clarify:

- The current work process of the company when performing LCC analysis.
- The different tools and software used for cost or LCC calculation.
- The data gathering procedure for LCC calculation.
- The challenges that the company faces when performing an LCC analysis.
- The room for improvements regarding the LCC analysis.

A third interview was conducted with a senior researcher of the Danish Building Research Institute (SBi). SBi has developed the application LCCbyg (LCCbyg, 2018), which is the main tool used for LCC calculations in the Danish construction industry, as it also supports the required calculations for DGNB certification. The aim of the interview was to clarify:

- The benefits and limitations of the LCCbyg application.
- The need for improvement of the LCCbyg application.

2.3 Development of two different methods

Two methods based on the compatible and the interoperable approaches were developed. The aim was to develop tools that can directly link design models and cost databases and accurately calculate the life-cycle costs of an entire building or individual building components. In both methods, the main results are generated through Sigma Estimates (Sigma Estimates, 2003) – a 5D BIM cost software that is commonly used in the Danish AEC industry. Sigma Estimates was chosen as it provides an established connection with Revit Autodesk software (design tool) (Autodesk Revit, 2018) and with Molio Price Database (a database on Danish construction prices) (Molio Prisdata, 2018). Through the connection with Revit Autodesk, data from a Revit Model can be extracted to Sigma Estimates through the plug-in function. The extraction creates a 'Sigma Project' in the Sigma Estimates software in which all the elements and their quantities from the Revit model are automatically imported. The Sigma project can then be connected with a 'Sigma Library', which includes all unit costs of the elements' activities and calculates the costs of the project. However, Sigma Estimates cannot be used for LCC calculations as it does not consider the effect of time on cost values (inflation and discount rates). Hence, in both approaches a tool is needed for transforming the cost values into life-cycle cost values.

In the compatible approach, the transformation of cost values is facilitated through an MS Excel-based tool. MS Excel is selected in this approach, as it is a standard tool that offers a graphical user interface and can be used by a wide target audience. Moreover, data from Sigma Estimates can be easily exported into and imported from an MS Excel file. In the interoperable approach, the transformation is performed through Visual Programming Language (VPL) which offers a more advanced and automated way of generating results. Dynamo, a VPL tool, is used in this case as it collaborates efficiently with Revit through its plug-in function.

2.4 Test cases

In order to identify the challenges of integration between different tools, an LCC analysis was performed of three different case studies: a simplified building model, a university building model and an office-building model by the engineering consultant company.

The initial intention was to calculate the life-cycle costs of the company's office building model and compare it with the analysis that is currently being carried out by the company. However, as significant challenges occurred early in the procedure, it was decided to design a simple building model in Revit and use it as 'test model' for the tools' development.

This simplified model consists of five basic types of components (four walls, six windows, one door, one roof, one floor and one floor covering). This simple building model could not only be easily handled, but also enabled the validation of the results by manual calculation due to the limited number of elements it contained.

Afterwards, a university building model was used for testing the functionality on a large scale and validating the methods. This large-scale model was also used for optimising the procedure of LCC calculations.

Finally, after the development, validation and optimisation of the methods, the company's office building model was examined. The model is an office building consisting of eight floors and with a gross floor area of 13,223 m^2, located in the metropolitan area. Due to the high level of complexity of the model, the research focused on the window elements only as these are the main elements of the building's façade and have a considerable impact on the total LCC of the project.

3. STATE-OF-THE-ART: LCC, BIM AND DATA INTEGRATION

3.1 Life-cycle costing and data requirements

While the term of a total cost of ownership (TCO) is applied in the recent European directive on public procurement (Directive 2014/24/EU) and more widely in other business sectors (Ellram, 1993), the term of life-cycle costing (LCC) or whole life costing (WLC) is more commonly used in building and construction industries. LCC/WLC belongs to the broader field of strategic investment and financing (Hedegaard and Hedegaard, 2008). The terminology is defined by the ISO 15686 series on service life planning (ISO, 2008) followed by the EN 15643 series on sustainability of construction works (CEN, 2012). Different approaches and guidelines of LCC have been described within various business areas of application (Dhillon, 2010), product development of complex systems (Farr, 2011), choice of materials (Caplehorn, 2012) and national guidelines e.g. in Norway (Bjørberg et al., 1993). The greatest advantage of LCC analysis is that it can be used to compare different alternatives (Dell'Isola and Kirk, 2003; Norman, 1990) based on several key factors such as costs, quality and comfort over the entire life cycle of the product (Haugbølle and Raffnsøe, 2019; Collier, 2009; Flanagan, 1989).

An LCC analysis requires data from different sources (Lansink, 2013) (FIG. 1):

- Data on actual costs in each of the five distinct life-cycle stages of the construction project. These costs include construction costs as well as costs for energy and water demand, drainage etc.
- Data regarding specific quantities of elements (e.g. areas, pieces etc.).
- Data for conversion of costs occurring in different time periods (discount rate, price development of different cost groups etc.).
- Data regarding the quality and purpose of the construction, its technical parameters and its expected lifespan as well as the life cycle of the materials used. Additionally, the frequency of maintenance and other work should be defined.

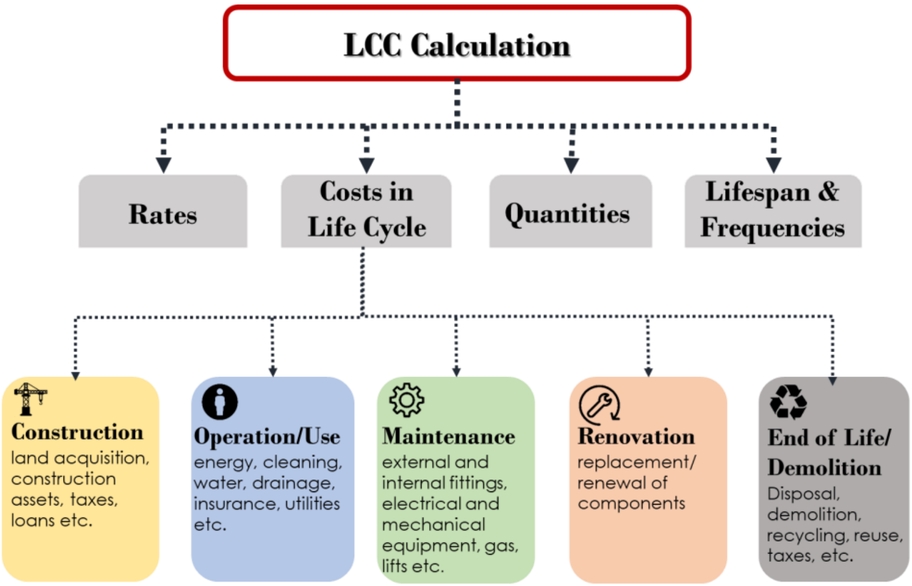

FIG. 1: Data requirements for LCC.

An LCC tool should be able to exchange data between various sources for example (FIG. 2):

- Design models in order to extract quantities (e.g. Revit, SketchUp).
- Data sheets containing product information in order to extract the information regarding the life cycle, maintenance, operation activities of the elements.
- Cost databases in order to extract the costs of different elements and activities.
- Financing data like inflation and discount rate.
- Facility management software in order to be used for e.g. maintenance planning.

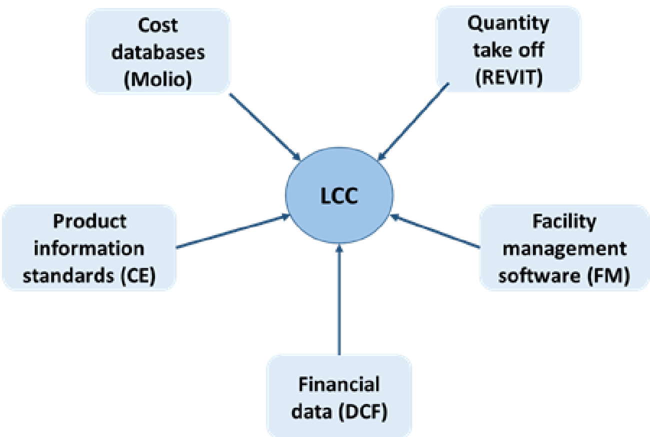

FIG. 2: Data requirements of an LCC tool.

3.2 Building Information Modelling

The concept of BIM is increasingly adopted by the AEC industry especially when performing sustainable building design as it offers significant advantages of increased productivity and collaboration (Bryde *et al.*, 2013; Doumbouya *et al.*, 2016; Liu *et al.*, 2015). In recent years, several definitions have been applied to describe the concept of BIM (Abbasnejad and Moud, 2013; Holzer, 2007; Latiffi *et al.*, 2014). The US BIM standard defines BIM as "a digital representation of physical characteristic of a facility, a shared knowledge source of information about a facility forming a reliable basis for decisions during its lifecycle, defined as existing from earliest conception to demolition" (NBIMS, 2010).

Although the concept has existed since the 1970s (Eastman *et al.*, 2018) the term of BIM as an innovative approach to building design and construction management was introduced by Autodesk in 2002 (Autodesk, 2008). In order to support the purpose of BIM, Autodesk acquired the software Revit, which is based on object-based parametric building modelling technology that represents the building as "an integrated database for coordinated information" and delivers all the BIM benefits (Autodesk, 2008; Demchak *et al.*, 2009). Other CAD software has been developed, adopting the object-based parametric modelling concept, like Graphisoft – ArchiCAD (1984); Bentley Building Information Modelling (2002); and Nemetscheck – AllPlan (2003) (Eastman et al., 2018). Currently, a variety of software and tools are used to support BIM in terms of designing, simulating, visualising, collaborating as well as gaining the advantages of data interconnection within a BIM model (Pluralsight, 2013). Nevertheless, the BIM concept does not rely on unique applications, but represents a process of gathering, holding, updating and exchanging information on a building through the project life cycle (Azhar et al., 2012; Tse et al., 2005).

BIM fosters an environment where the model information is contained (Aouad et al., 2006). Therefore, BIM models are files consisting of objects that hold, update and document all information related to the building, including its physical and functional characteristics and project life-cycle information. Those BIM objects consist of a unique set of information, which forms its identity. Thereby, it is crucial to enhance the information of a BIM object by calculating and adding additional information. Subsequently, information should be openly accessible by different software and be able to be extracted and used by other software in order to enrich the model by continuously adding new information (Hallberg and Tarandi, 2011).

The implementation of BIM can make the industry more flexible, effective and innovative (Patil and Khandare, 2017). As pointed out by Thurairajah and Boyd (2017), harvesting the digital dividends of BIM is not simply about efficient processes but also easy accessibility to information and more importantly the transformative power towards smart construction, new business and financing models, and the emerging digital economy based on e.g. Internet of Things. Even though the use of BIM has increased in the AEC industry, there are still limitations for its full adoption. There are several formats for data exchange such as IFC, BSDD etc., however one of the main challenges is the lack of harmonisation among BIM standards for model integration and management by different stakeholders. The standardisation activities in CEN TC 442 (DIN, 2018) and ISO TC59/SC 13 (ISO, 2018) are working towards the direction to unify those methods and increase the interoperability among different tools. .. Hence, a harmonised approach towards data integration still remains a crucial factor for the further development and enrichment of BIM models.

3.3 Approaches to data integration

Several approaches of BIM implementation have been described in the AIA diagram for digital technology in architectural practices (Singh et al., 2009) and BIM levels UK diagram (NBS, 2018). Both diagrams refer to various approaches that were used in the past, are currently being used and expected to be used in the future. However, in this study, the authors focus on the currently used approaches of data integration between different kinds of autonomous software that can be achieved by following two basic conceptual approaches: compatibility and interoperability (Zhang et al., 2006).

Compatibility is a controlled and restricted approach of data integration where one or more tools are 'built' on one main tool in order to address a specific issue or opportunity (FIG. 3). An example of compatible software is plug-in solutions and application-programming interfaces.

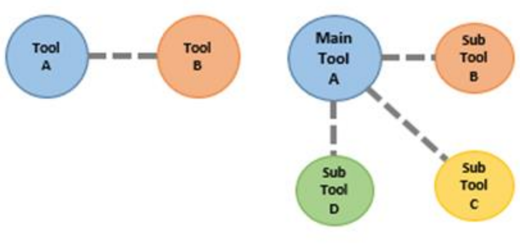

FIG. 3: Compatible approaches to data integration: 3a. Two main tools; 3b. One main tool and several sub-tools. Source: Adapted after (Zhang et al., 2006)

In both cases, the main tool (Tool A) is able to control the design and accuracy of the model, while the calculation functionalities are essentially integrated and thus enable domain integration of data between the tools (Davis and Brady, 2013). The main limitation of compatible approaches is that the user is restricted to the options that are offered by a specific software environment. Hence, this approach does not comply with the concept of BIM as the information that is generated is limited to the use of specific tools (Davis and Brady, 2013; Areo, 2016).

In contrast, interoperability refers to the ability of software to communicate, exchange data and use the information that has been exchanged (IEEE, 1990; Wegner, 1996). In interoperable approaches, the different kinds of software share the same work place to enhance the collaborative process and to achieve significant improvements in the life-cycle management of projects (Plume and Mitchell, 2007). At the highest level of interoperability, automation and avoidance of data re-entry can be accomplished.

More specifically, the main concept of interoperability refers to the ability of various tools to share the same data schema, and thereby, can read and write in the same data model (FIG.a). The introduction of shared data schemas such as IFC, COBie and XML has significantly contributed to solving interoperability issues (Pazlar and Turk, 2008; Smith and Tardif, 2009; Berlo *et al.*, 2012). However, the effectiveness of such a collaboration relies on the design and the quality of the model. Thereby, it imposes restrictions on how designs can be described and thus explored and shared (Plume and Mitchell, 2007; Patacas *et al.*, 2014).

FIG. 4: Different concepts of interoperability: 4a. Shared data schema; 4b. Shared mapping process; 4c. Linking individual tools via file transformation. Source: Adapted after (Toth et al., 2012; Negendahl, 2015)

Toth et al. (2012) suggest another method of achieving interoperable data integration by linking tools through a shared mapping process (FIG.b). In this approach, tools do not share the same schema, however, data of one tool are automatically transformed to the target data set of another tool through a custom data-mapping interface that includes visual definitions of transformation rules. An advanced algorithm will offer guidance to the users in matching data across schemas, so that mapping can be created in less time, with less errors and fewer mistakes (Fagin et al., 2009). Although this approach provides a framework to embed current tools in a more cohesive, shareable and customisable digital workflow, it requires great effort to script data-maps and transformation rules for the various tools (Toth et al., 2012).

Finally, another more decentralised approach of interoperability is achieved by linking individual tools through file transformation (FIG.c). In this case, VPL can be used not only as a simple converter between formats but also for adjusting, conforming, enhancing or eliminating data between the tools (Negendahl, 2015). The maximum number of converters that are required in this approach is n(n-1), where n is the number of tools. However, in theory but rarely in practice, a converter enables bi-directional link between the tools. In those cases, the maximum number of converters required is n(n-1)/2. Although this is a flexible approach, it relies on human interpretation of semantic meaning (Toth et al., 2012).

4. FINDINGS: TWO DIFFERENT APPROACHES

Before developing the two methods, the different activities of the elements during their life cycle and their current cost should be identified. For this reason, a new Sigma library of all the elements' activities during the life cycle was created in Sigma Estimates. The Sigma library was structured in three levels. At the first level, the examined elements are categorised based on their types in the Revit model (wall, window, etc.). At the second level, subcategories for the different life-cycle stages for each element are created (construction, maintenance, etc.). The life-cycle stages selected for this analysis are the construction stage, the maintenance stage, the operation stage and the renovation stage. At the third level, the different activities of each element for each stage are selected from the Molio Price Database. By creation of the library, all the costs of all the activities through the life cycle of the examined elements were set (FIG. 4).

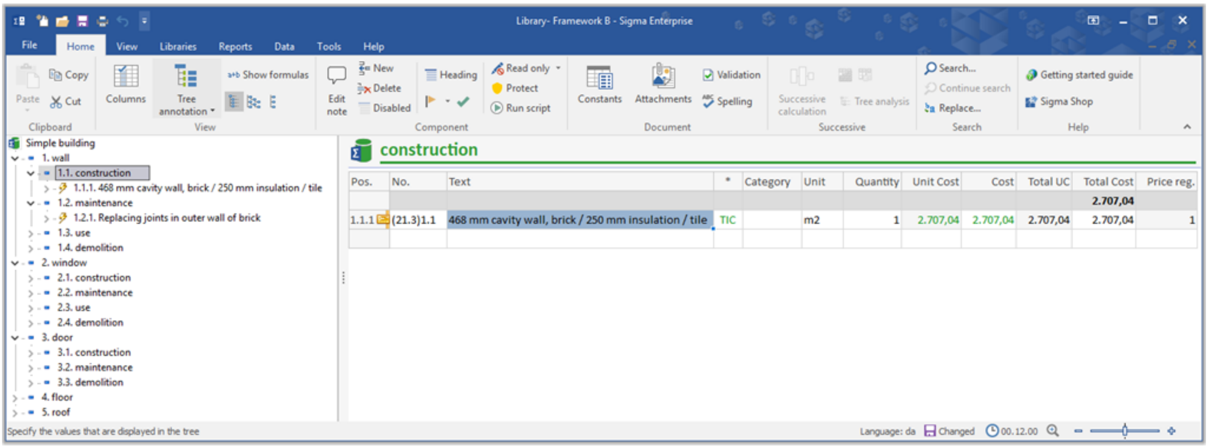

FIG. 4: Structure of Sigma Library (print screen from Sigma Estimates tool).

The following sections present the framework of each method along with the definition of the coding system used and the structure of the developed tool.

4.1 Method A – a spreadsheet-based tool

The first method is based on the principles of compatibility. The compatible solution includes the development of an MS Excel tool, which is used for transforming the costs of the activities that are included in the Sigma library into life-cycle costs. The method is based on the capability of Sigma Estimates to export and import files in excel format. In the MS Excel-based tool, the LCC equation is scripted and optimised by Visual Basic for Applications. FIG. 5 provides an overview of this method in six steps.

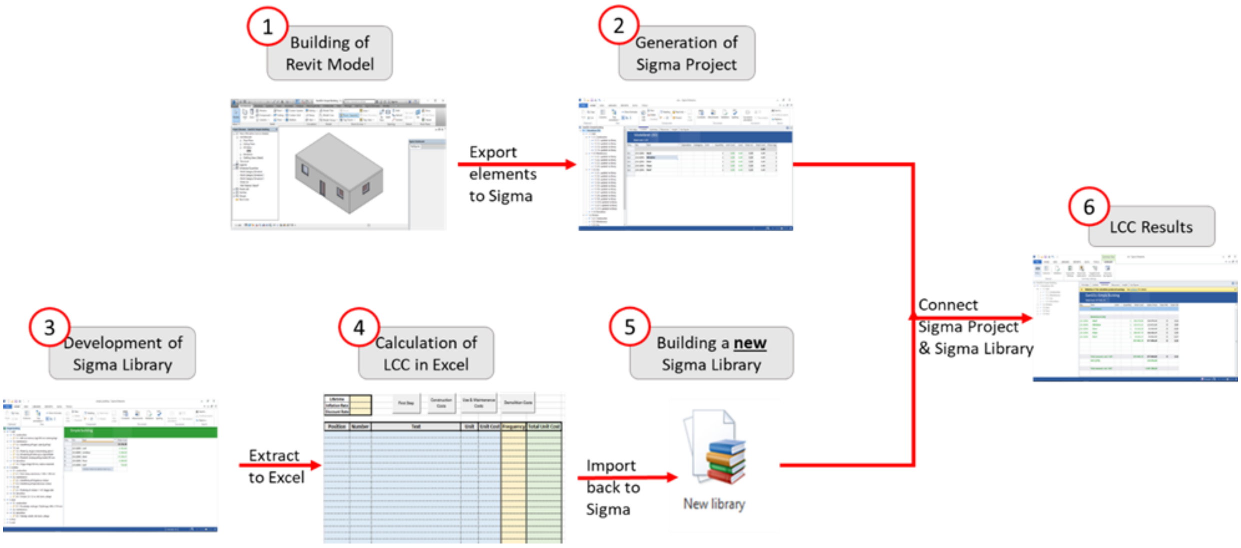

FIG. 5: Overview of method A: a spreadsheet based tool.

After building the Revit Model (Step 1), information from Revit (elements and quantities) is exported through the plug-in function in Sigma Estimates and a Sigma Project is generated (Step 2). Then a Sigma Library is developed in Sigma (Step 3). The library is extracted to the MS Excel-based tool where the elements' unit cost values are transformed into LCC unit values (Step 4). The next step is to import the new values back to Sigma Estimates by building a new Sigma Library (Step 5). Finally, the Sigma Project and the new Sigma Library are connected and the final LCC results are calculated (Step 6).

The connection of Sigma Project and Sigma Library is facilitated through a coding system. In this case, a coding system is proposed based on the BIM7AA encoding system (BIM7AA, 2017), which is based on the international classification system SfB. According to the proposed coding structure, each code consists of two parts: the first part is represented by the BIM7AA classification code of the element and the second part by a serial number of the elements of the same category (FIG. 6). The codes of all elements are first assigned in the Sigma Library in the field 'No.' and then set in the Revit Model as project parameter for each element type, which will later be exported in the Sigma Project along with the quantities.

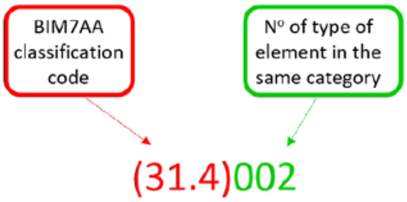

FIG. 6: Proposed coding system for method A – case related.

Finally, the structure of the MS Excel tool developed for the first method is presented in FIG. 7. As described above, the user exports the Sigma Library, where all the activities of the elements during their life cycle are included along with their units and costs, in the developed MS Excel tool. In the tool, first the user sets basic information regarding the project such as its lifetime, the inflation and discount rates as well as the frequency and the renovation year for each activity. Next, the unit costs are converted to unit life-cycle costs by simply clicking the appropriate buttons. The user can then import the life-cycle cost values back to Sigma Estimates by generating a new Sigma Library.

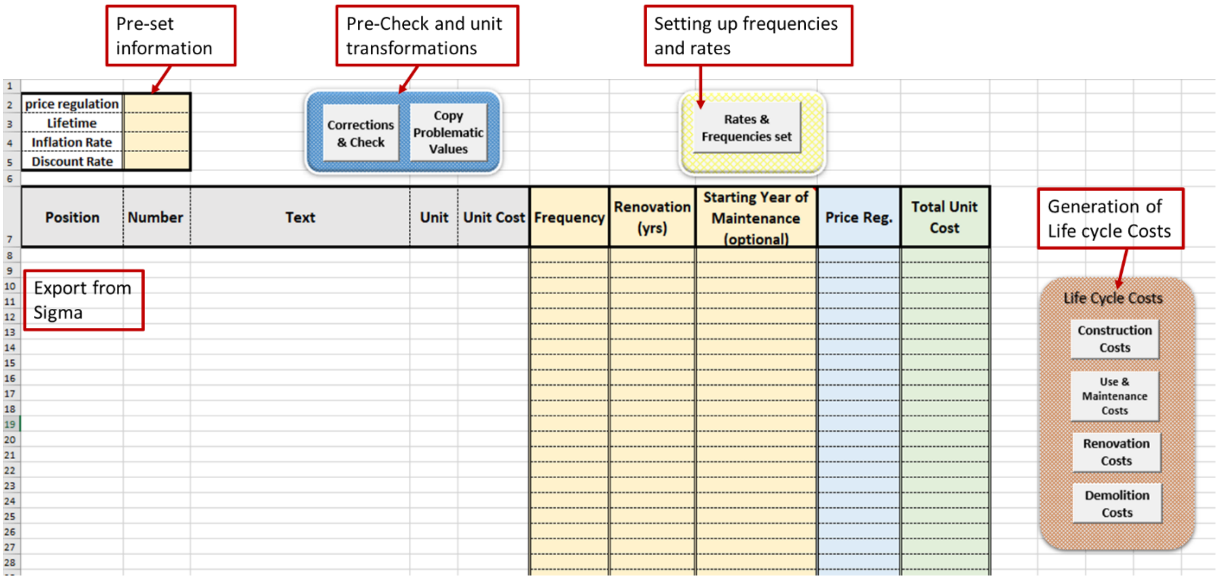

FIG. 7: Structure of the MS Excel- based tool.

4.2 Method B – a dynamic model based on VPL

The second method is based on the principles of interoperability. In particular, the approach of linking tool via file transformation (Section 3.3, Fig. 4c) is followed. In this case, Dynamo (DynamoBIM, 2017), a VPL tool, is used for performing the LCC analysis. FIG. 8 provides an overview of this method in five steps.

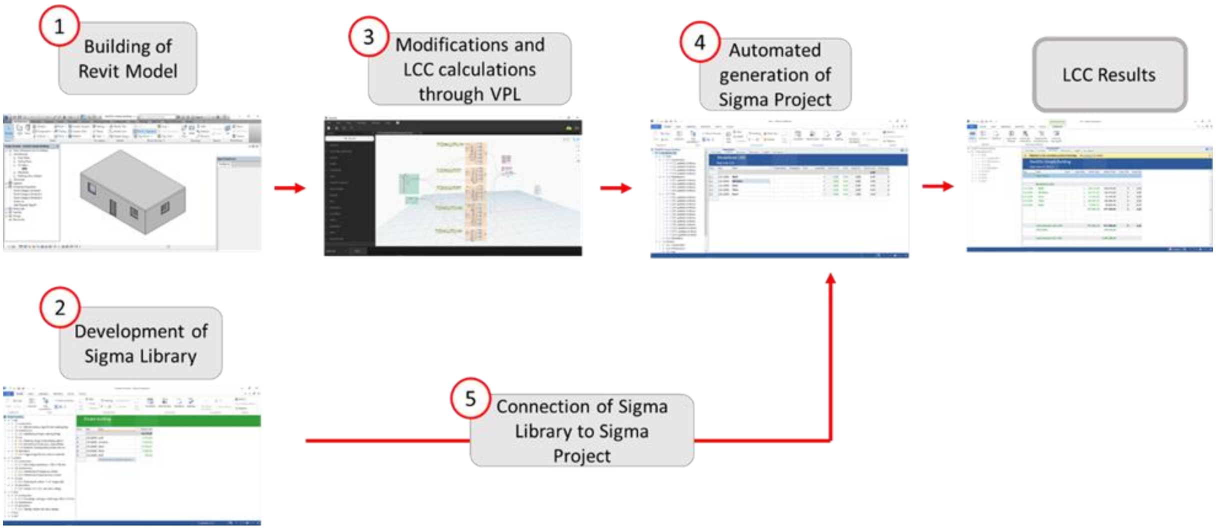

FIG. 8: Overview of Approach B: An integrated Dynamic Model.

In this method, the Revit model and Sigma Library are developed in parallel (Step 1 & Step 2). Then, the quantities of the examined elements are extracted from the Revit design model to the Dynamo model where the LCC calculation is performed (Step 3). The Dynamo model not only operates the LCC calculations but simultaneously controls, filters and enhances the integration of information between Revit and Sigma Estimates. According to Negendahl (2015), the model can be characterised as an integrated dynamic model as it is a middleware between two tools (Revit and Sigma Estimates) based on VPL. When running the Dynamo tool, a Sigma Project is automatically generated (Step 4). The Sigma Project is connected with the Sigma Library and the LCC results are calculated (Step 5).

A coding system is required to facilitate the connection between the Sigma Project and the Sigma Library. However, the coding system in this method differs from the one used in the first method as the code should refer not to each element but to each activity as each activity carries its own unique information. Subsequently, the coding system now consists of three parts (FIG. 9). The first part, which refers to the element, is based on the classification suggested by BIM7AA. The second part is a number that refers to the life-cycle stage based on its time sequence in the life cycle of the project. Finally, the last number is a serial number for the activities of an element of a specific life-cycle stage. The numbering in this part depends on the number of different works in the life-cycle stage of the unique element.

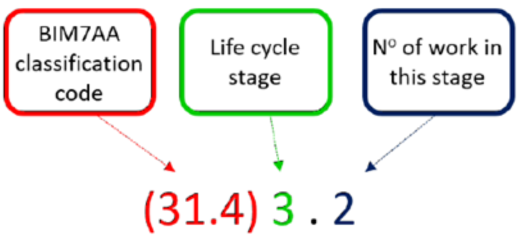

FIG. 9: Proposed coding system for method B – case related.

The codes are inserted in the field 'No.' in Sigma Library. Additionally, the same codes are set in Revit Model, by creating new project parameters for each element. The amount of project parameters for each element is equal to the amount of activities that are assigned to it (FIG. 10).

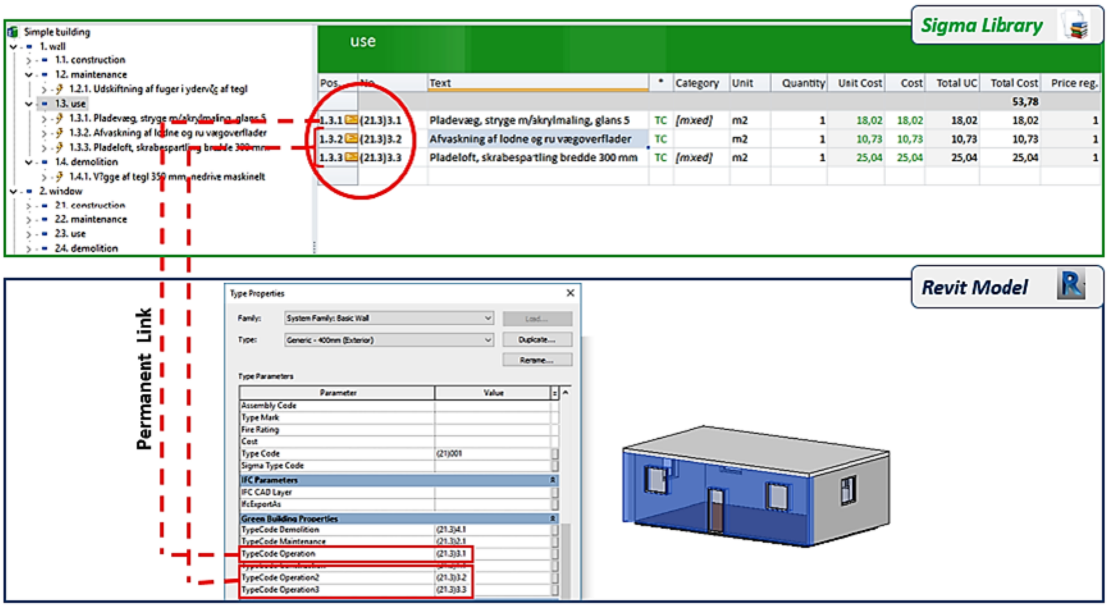

FIG. 10: Coding setting in Sigma Library and Revit Model.

Finally, the structure of the Dynamo model is illustrated in FIG. 11. In the figure, the different coloured areas represent a specific function of the model. In the light pink area on the right, all the pre-sets are defined. In the grey area on the left, the LCC calculations of an LCC parameter are processed as the LCC equation of the LCC parameter is scripted in Python (Python, 2018). The user can modify the default inputs of the LCC equation (the service life, inflation and discount rates as well as the price development). In the green area, the elements of the Revit Model are selected and grouped. In the orange area, the structure of the exported project is developed and in the blue area, the exportation is facilitated.

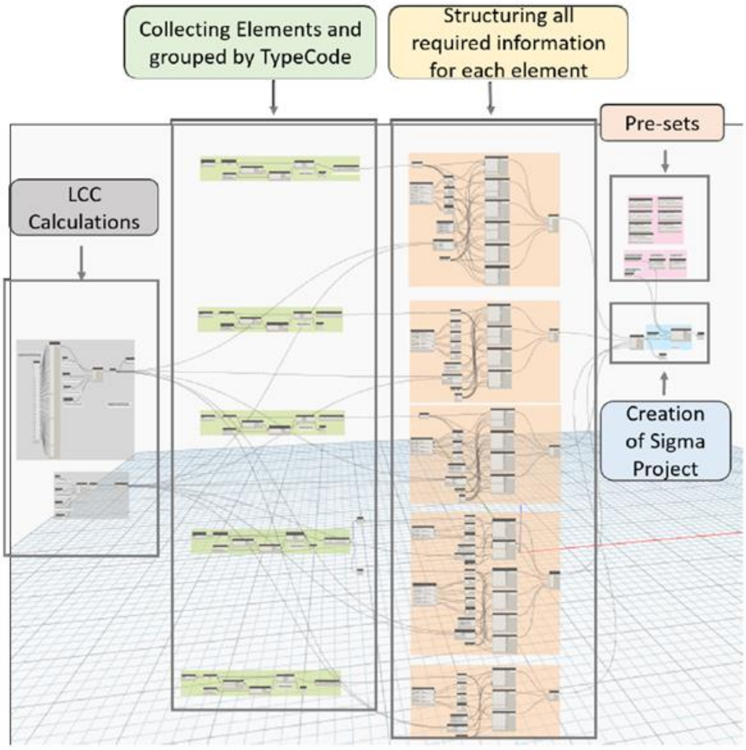

FIG. 11: Structure of Dynamo Model.

5. DISCUSSION: FIVE LESSONS LEARNED

Although both methods succeed on generating LCC results, during the development and the testing, five issues became apparent with regard to data integration between different approaches in order to support LCC calculations. These five issues, however, are not tied to the specific methods that are developed in this study, as similar methods can be developed by using different BIM tools (like ArchiCAD and Grasshopper, instead of Revit and Dynamo, respectively). Hence, they are in general relevant to data integration approaches and the existing limitations of BIM models. These issues include: non-conformity of unit values, lack of classifications and coding systems, extensive manual work requirements, poor design of models and insufficient methodology for and exchange of life-cycle data.

5.1 Non-conformity of unit values

Early during the development of the tools, it was observed that there is a significant issue of non-conformity between the unit quantities that are extracted from Revit to Sigma Estimates and the unit that costs are given in Molio Price Database. For instance, the number of window elements is exported automatically from Revit to Sigma Estimates as 'pieces' through the plug-in function. However, even if cost is given per piece for most of the activities that correspond to window elements, there are others where cost is given per square meter, for example in activities that are related to cleaning of window elements. Due to this misalignment of the unit value, the connection between the Sigma Project and Sigma Library cannot be performed correctly automatically. Therefore, the unit transformation should be executed before the connection either on the extracted quantities in Sigma Project or on the costs in Sigma Library, otherwise connection problems can occur. This challenge is not related to the developed tools nor to the LCC calculations, but to the restricted extraction of quantities from Revit to Sigma Estimates.

The integrated dynamic model, based on the principles of interoperability, is capable of extracting the requested unit quantity without any restrictions. However, in the first method the MS Excel-based tool is not interceded on the extraction of the elements as it is a simple transformer of costs into life-cycle costs based on the values offered by the Sigma Estimates (as the tool is compatible with Sigma Estimates). To handle this limitation, a VPL-Dynamo model is developed to correct the quantities and introduces a generic solution to this issue requiring minimum user interference, which will be applied subsequently to every project. The non-conforming values are identified in the MS Excel sheet (which had different unit measurement than the one extracted from Revit) and then, the VPL Dynamo model performs the unit transformation and imports them back into the spreadsheet tool.

The issue of mismatch between the units of building materials between the different tools is very common. Therefore, in order to cope with this issue unit convertors are required in order to enable the correct transfer of quantities between the tools.

5.2 Lack of commonly used coding system

In order to facilitate the connection between the tools in both methods, the establishment of a coding system is crucial. However, there is an urgent need to establish or rather implement common standards for the digital transfer of information. There is a lack of a generic coding system that is commonly adopted and integrated in the AEC industry. More precisely, there are several classification systems available to the Danish AEC industry, but there is a lack of industry consensus on which classification system to use and a lacking willingness and ability to pursue the implementation of one such system.

This study proposed using a coding system for each method based on the BIM7AA encoding system (BIM7AA, 2017). In both methods, effort and time are required to apply the codes for every element especially in case of large-scale projects. Although different Dynamo models are developed to facilitate the creation of the parameters and setting their values in Revit, it is still a challenging, mainly manual, procedure which is both time consuming and prone to human error. Additionally, the existing classification system does not cover facility management needs (Howard and Björk, 2008).

Since the establishment of a common classification system worldwide has proven unsuccessful so far, an achievable solution could be a shared mapping process, similar to the method 4b, introduced in section 3.3. In that respect, a translator would be required between different coding systems, in order to enable integration of information between models with different classification systems.

5.3 Extensive manual work required

The full integration of LCC and automation of calculation is crucial in order to speed up the procedures and make calculations less exposed to errors by minimising the human error and producing more reliable results. However, the automation of cost calculation is one of the main barriers of the current work processes. Due to the large amount of data required, LCC becomes an incredible time-consuming process when performed manually (Fu et al., 2007).

The two methods of this study proposed to integrate the calculations to avoid the manual insertion of values in an LCC application. However, both methods require human intervention to a varying degree. Especially the first method requires manual work at different steps (from Step 3 to Step 4, and from Step 4 to Step 5 as it is illustrated in FIG. 5) in order to produce LCC results. For instance, due to the performance of the specific tool to extract data only by creating a new spreadsheet, the user needs to transfer the extracted data from Sigma Project to the MS Excel tool manually (Step 3 to Step 4). Moreover, when a change is implemented in either the design model or the Sigma Library, the entire procedure has to be repeated from the beginning, and thus it takes time to generate LCC results. The second method follows a more automated procedure and provides a permanent link between the design program, Sigma Estimates and LCC calculations, offering the user the possibility to directly view the effect of any change to the costs by simply pressing a button. Even though implementation of changes is easier in this method, much effort and time are still required since the model must be correctly configured at the first time when it is used in a project.

Furthermore, in both methods manual effort and manual checks are required for setting the codes in both design model (Revit) and the cost library (Sigma Library) and for ensuring that all codes have been placed correctly. For this reason, both tools were optimised, and several checker models were additionally developed using Dynamo software. Nonetheless, the testing of the methods in the three test cases indicated that the main factor affecting the validity of the LCC results is often a human error.

Another time-consuming task proved to be the comparison between alternative solutions for the windows' material in the third case study, the company's office building model. As Revit is able to present only one design alternative at a time, the model has to be changed several times. Likewise, a new Sigma Library was required for each case of comparison and the whole procedure for producing results had repeatedly to be carried out from the beginning.

5.4 Poor design of models

As underlined by Plume et al. (2007) more than 10 years ago, one of the main challenges of data integration is that the engineers do not design with collaboration interchange in mind. Unfortunately, this still seems to be a main issue. During the testing of both methods, the inappropriate design of both the university and company's office design models turned out to be counterproductive for facilitating a proper BIM connection. The lack of distinctive types of elements in both models led to significant difficulties of extracting the required quantities and thus implementing an LCC analysis.

More specifically, window and door elements were designed as curtain walls in the design model of the university building, resulting in the existence of elements with different dimensions under the same type. The lack of distinctive types was a challenge when the first method was followed as in this method the functionality of the Sigma Library as well as the assignment of the codes is structured based on the assumption that all the elements of the same type have the same properties. However, this was not an issue when the second model applied.

Additionally, in the company's design model of the office building there are significant issues related to the design of the model. Specifically, the window elements are designed as part of 'sandwich panels' which belong to the 'Generic Model' category. The building contains 35 'sandwich panels' and each panel consists of a wall with one or two windows or none. Therefore, since the windows are not designed as window elements, they cannot be selected, and their quantities cannot be easily retrieved. Consequently, the methods could not be applied appropriately due to the design of the model, and manual modifications were required in order to implement the developed methods.

In order to overcome this challenge, the different sandwich panels were grouped according to the type of window they contained. Each group contained panels with windows of the same material and the same dimensions. Based on that description, ten different groups were created. A unique code was afterwards assigned to each group in order to facilitate the connection between Revit and Sigma Estimates. It is assumed that each extracted sandwich panel, depending on the number of windows in the specific sandwich panel, represents one or two pieces of windows.

To facilitate the process of LCC calculations, the integrated dynamic model of method B and the Dynamo model that was used for unit transformation in method A were modified, in order to group the sandwich panels based on their type code. After the categorisation, 10 different groups of sandwich panels were identified.

However, in Sigma Library there are activities the costs of which are given in square meters (m^2) or running meters (lbm). As the area and the length of the sandwich panels are not equal to the area and length of the windows, the Dynamo model should be modified in order to extract and use the correct area and length quantities of the windows. For this reason, a new group of nodes is created in the Dynamo model where the area of an element's material is retrieved from the sandwich panel.

Based on the case studies, it was concluded that the output of design models is usually still geometry-oriented and not actual BIM models. Hence, in order to enable data integration, the general common BIM requirements (COBIM) should be followed by the designers. COBIM series 3 (Oy and Henttinen, 2012) includes modelling principles in architectural design underlining the importance of proper design of the elements in distinctive types, as well as the content requirements for architectural BIM in different project phases.

5.5 Insufficient methodology for and exchange of life cycle data

When performing the LCC analysis, one of the main difficulties is the lack of global standards or standardised methodology to guide the exchange of life-cycle information (Monteiro and Martins, 2013). Specifically, there is seldom much available information regarding the future activities required for the operation and maintenance of a building component. Usually the manufacturers specify the service life of an element, but they rarely provide guidance regarding the maintenance and operation activities in a quantifiable manner. Moreover, there is no standardised way of exchanging information between the engineers, the manufacturers and the facility managers (Chiurugwi et al., 2015). This situation makes the analysis complicated, especially for an inexperienced user.

The lack of life-cycle data affected the analysis of the company's case study especially during the creation of the work library as there were neither standardised activities for the elements' life cycle nor available standardised cost data. Especially for inexperienced users, this lack of guidelines and standardised methods made the creation of a library a difficult and time-consuming procedure.

Additionally, as the manufacturers' environmental performance declarations (EPDs) showed significant discrepancies regarding the recommended works throughout the life cycle, meetings and interviews with windows manufacturing companies were conducted in order to identify the different activities through the life cycle. Moreover, assumptions regarding the different works were made based not only on the interviews but also on recommendations from the DGNB practitioner.

In order to enhance the availability of information, the manufacturers could include in EPD a list of maintenance and operational activities of materials, which can be used by engineers and facility managers. Moreover, the use of Construction Operations Building Information Exchange (COBie) standards that include information like equipment lists, product data sheets, warranties, preventive maintenance lists, etc. will enable communication of information among stakeholders involved in the project.

6. CONCLUSION

LCC is not yet fully adopted by the Danish AEC industry as it requires a high level of data management and data exchange between different types of software. This study developed and tested two methods for automated LCC calculations based on the principles of compatibility and interoperability in order to integrate data across different types of autonomous software packages.

In both approaches, the developed LCC tools were integrated with a cost calculation software (Sigma Estimates) which links with a cost database (Molio Price Database) and has an established connection with a design tool (Revit). Method A followed the principles of compatibility and was based on MS Excel that can be easily applied through a familiar graphical user interface. Method B followed the principle of interoperability and was based on VPL for filtering and controlling the information integration and simultaneously calculating LCC. This interoperable approach had the advantage of offering a permanent link with the design model which enabled the practitioner to see directly the effect of changes in the model to the total LCC by simply running it. Both methods were applied and validated in three different test cases: a simplistic building model, a large-scale university building and a private company's new office building.

Even the successful generation of LCC results, both methods faced a number of obstacles with regard to data integration across autonomous software packages and automated calculation of LCC. The first obstacle was the non-conformity of unit values between the design model and the cost calculation software. The second obstacle was the lack of a commonly used coding system for facilitating data integration. The third obstacle was the lack of fully integrated and automated procedures of LCC calculations. The fourth obstacle was the poor design of models, which often comprise non-geometric or non-distinctive types of elements. The fifth and final obstacle was the lack of a standardised methodology for exchanging life-cycle information.

In conclusion, this study indicates that there are still various hindrances related to data management that need to be overcome in order to integrate LCC and BIM. Even if the development of the two methods enable the integration of LCC into design practices, it still falls short of fully automated procedures which in turn leaves plenty of manual work and exposes the results to human errors.

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