A BIM-BASED DECISION SUPPORT SYSTEM FOR THE EVALUATION OF HOLISTIC RENOVATION SCENARIOS

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SUMMARY: Future building renovation concerns sustainability within broader perspectives facilitated by holistic renovation scenarios. This paper builds upon previous work related to RE-VALUE research project on the development of "a hybrid Decision Support System (DSS)" for the generation of a countless number of holistic renovation scenarios. The research presented in this paper aims to integrate the outcome of using the DSS including optimal generating renovation scenarios, within the Revit BIM framework. This is performed by the integration, development, and demonstration of a plug-in for Autodesk Revit. Integration of the results of the use of DSS with Revit BIM has a potential to aid architects together with the other stakeholders (specially the non-experts such as owners) to develop holistic renovation scenarios during the early design stages and to make informed decisions in a shorter period with more significant impacts on the engineering aspects of the renovation projects. In addition, the updated result on the BIM model incorporating both the Hard (quantitative) and Soft (qualitative) criteria, can advantageously be used for visualization of renovation scenarios for non-architects, i.e. building occupants, encouraging them to accommodate holistic renovation scenarios. The outcome is verified through visualization and evaluation of optimal renovation scenarios for a dwelling in this paper.

1. INTRODUCTION

Buildings account for 40% of the EU's energy consumption, 36% of its CO2 emissions and 55% of its electricity consumption (EC [European Commission], 2014). This plays a crucial role to meet the EU's climate, energy targets, and sustainable development in a bigger perspective. The existing building stock in the EU is relatively old and about 35% of it is over 50 years old (JRC [Joint Research Centre], 2015). It grows less attractive, if not maintained thoroughly during life time (for the reasons such as insufficient indoor air quality and thermal comfort). These buildings consume more energy than new buildings (BPIE [Buildings Performance Institute Europe], 2011). EU (2016) states that the rate at which new buildings either replace this old stock, or expand the total stock, is low (about 1% a year). This implies that renovation of existing buildings is a key in reducing energy consumption. In addition, SBi [Ministry of Climate, Energy and Building – Danish government] (2014) addresses renovation initiatives can often be more cost-effective than new building projects.

Focusing on the application of early stage decision support systems (DSS) for sustainable building renovation (Nielsen et al., 2016; Ferreira et al., 2013), the improvement of existing buildings can be divided into two major tasks, (1) current condition assessment and (2) formulation of upgrade strategies (Juan et al., 2010). Juan et al. (2010) state that most of the methods focus on the first part of the improvement process, understanding or exploring of a renovation project (i.e. energy usage). Whilst the latter is about proposing of the future upgrade renovation scenarios through generation of holistic renovation scenarios. Focusing on the latter, the renovation scenarios should be generated holistically together with embracing and evaluating more objectives and criteria attached to the sustainability.

1.1 An integrated design methodology for the development of holistic renovation scenarios

The term 'holistic scenario' in this paper is adopted from (Kamari et al., 2018a). It serves to underline a holistic approach where various objectives linking to the sustainability in its full sense are achieved in a balanced way. Identification of sustainable renovation objectives and criteria (Kamari et al., 2017c), an indication of the renovation approaches (Kamari et al., 2018c), and consequently how to deal with the complexity of decision-making, are the key points and essential factors for the development of holistic renovation scenarios. To position them, application of a Holistic Multi-Methodology for Sustainable Renovation - HMSR from (Kamari et al., 2017b) is considered as an integrated design methodology for development of holistic renovation scenarios. HMSR is a multi-methodology, mixed of Soft Systems Methodologies - SSM (Checkland, 2000) and Multiple Criteria Decision Making – MCDM (Climaco, 1997) methods. This two-pronged, mixed-methodology strategy alternates between techno-economic and socio-cultural decision-making to set renovation objectives and criteria as design goals, generate and evaluate a set of renovation alternatives (as renovation scenarios) against these objectives and criteria, and then guides stakeholders in selecting the option that best accommodates their needs. The HMSR includes three decision-making levels within a sequence of 23 activities where a renovation project can primarily be explored ('A' in Figure 1), the problem is structured, the scenarios are generated and improved, and ultimately the decision is made at level 3 about which renovation scenario to pursue.

The HMSR, in the decision-making level 2, distinguishes between the evaluation of Hard (quantitative) and Soft (qualitative) criteria. It therefore proposes application of a DSS (Nielsen et al., 2016; Ferreira et al., 2013; Juan et al., 2010) that can be used for generation and evaluation of the holistic renovation scenarios focusing on the evaluating Hard (quantitative, i.e. cost, energy consumption etc.) criteria ('B' in Figure 1). After this stage, the top ranked generated scenarios are further improved, focusing on the Soft (qualitative, i.e. spatial quality etc.) criteria ('D' in Figure 1).

This paper outlines development of a plug-in[1] tool, so as to integrate the results of using the DSS ('B' in Figure 1) for the evaluation of holistic renovation scenarios within a BIM-based tool, to be used in the main body of the

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[1] Plug-in (or add-in) is a term used for the description of a software utility or other program that can be added to a primary program. Hence, it gives extra features or functions, often in response to certain events, such as commands in menus or as buttons. Therefore, an add-in for Revit is an extension of its current platform possibilities. Add-ins are created pro-grammatically.

HMSR ('C' in Figure 1). This work builds upon previous work related to RE-VALUE[2] (Value Creation by Energy Renovation, Refurbishment and Transformation of the Built Environment, Modelling and Validating of Utility and Architectural Value) research project by the authors on development of "a hybrid Decision Support System for generation of holistic renovation scenarios – concentrating on *Energy Consumption*, *Investment Cost*, and *Thermal Indoor Comfort* (Kamari et al., 2018b).
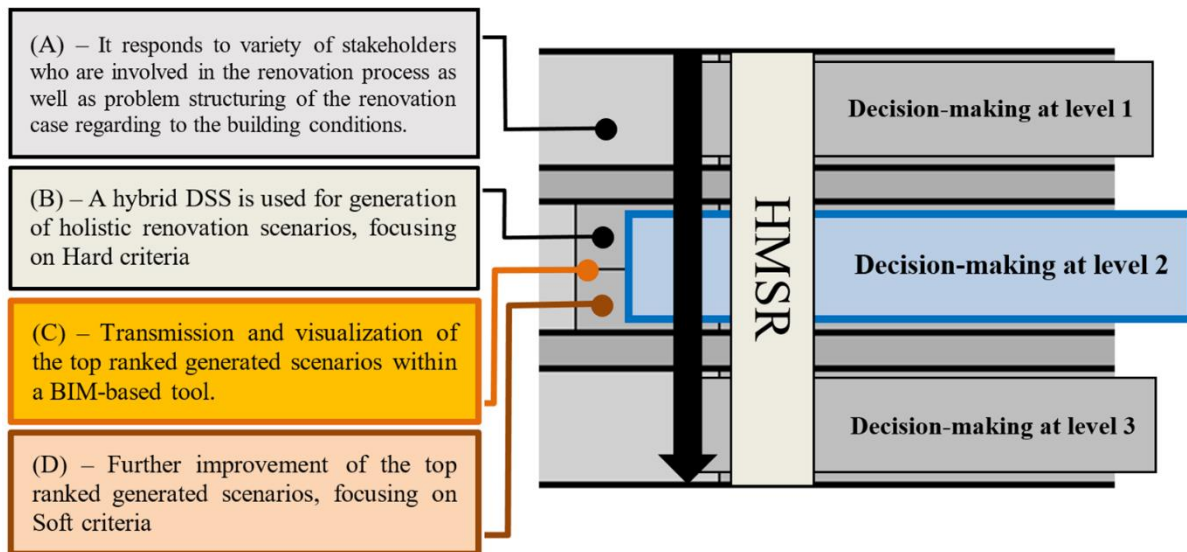
Figure 1. Overview of decision-making level 2 in HMSR (adopted from Kamari et al., 2017b)

In the present paper, a methodology is described that incorporate the outcomes of the application of the hybrid DSS ('B' in Figure 1) including the top ranked generating renovation scenarios into BIM. The goal is to upgrade the existing BIM model by the optimal generating renovation scenarios ('C' in Figure 1), and finally implementation of an evaluation mechanism that leads to improving the scenarios further, concentrating on Soft criteria ('D' in Figure 1), i.e. improvement of the spatial quality. The impact of BIM on the design practice is significant because it raises new ways and processes of delivering design, construction, and facilities management services (Jalaei et al., 2015). Eastman et al. (2011) discuss that developing a parametric model within BIM tool is capable of capturing project information and generating documentation. With special care taken on the software side (Jalaei et al., 2015), an enhanced BIM application could potentially resolve what used to be obstinate problems in delivering sustainable design (i.e. dealing with the complexity of conducting full building energy simulation, acoustical analysis, and day-lighting design). According to Becerik al. (2010), the development of a schematic model earlier to producing a detailed building model aids architects/designers to build a more precise evaluation of the proposed design and to recognize whether the scheme meets the functional and sustainability requirements pronounced by the owner; this manages to improve the project overall performance and quality (Kubba, 2012). The advent of BIM, along with the emergence of more significant global scale issues such as sustainability, requires designers to incorporate primary performance analysis at the early phase of design (e.g. spatial quality or energy performance analysis) by extra developing the virtual space or virtual building concepts (Kam et al., 2004). An integrated BIM system can aid the process of collaboration and communication between the project key players in the early design stage to implement a well-performing building through operations adequately.

1.2 Integrated design through Building Information Modelling (BIM)

In this paper, BIM is considered as a link to the relevant technologies and hence the development of a plug-in tool for a BIM-based software. BIM is an emerging methodology in the AECO[3] industry, since the intelligent digital three-dimensional model-based process of BIM can be used to plan, design, structure, manage, and analysis

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[2] Participated by Brabrand Housing Association – with energy renovation in the Aarhus suburb of Gellerup – as well as DEAS, an administration company on the private rental housing market (for more info: http://www.revalue.dk)

[3] Architecture, Engineering, Construction, Operation

buildings (Krygiel et al., 2008; Autodesk, 2017a). CPIC [Construction Project Information Committee] defines "BIM is a digital representation of physical and functional characteristics of a facility creating a shared knowledge resource for information about it and forming a reliable basis for decisions during its life cycle, from earliest conception to demolition" (RIBA, 2012). Succar (2009) [based on Penttilä, (2006)] echo that BIM is a "set of *technologies*, *processes* and *policies* enabling multiple stakeholders to collaboratively design, construct and operate a facility". This underlines three critical factors to BIM including *people*, *process*, and *technologies*. BIM technology allows integrated design to flourish, encourages - and provides a vessel and conduit for - the sharing of information between the design and construction team (Deursch, 2011). The developing plug-in in this study strives to increase collaboration between engineers and architects in the early design stages that is a requirement to an integrated design process - IDP (Hansen et al., 2005; Kamari et al., 2017a). The IDP is holistic in that it involves all the stakeholders from the earliest stages, each having input into what goes into making the decisions that will lead to the completed project. It is holistic in that it takes every team member's point of view into consideration (Deursch, 2011). Moreover, it is holistic in that these decisions are made with all the information shared at one time, up front – and not in the more traditional linear fashion, each entity maintaining and controlling the distribution of its own focus of information. In this framework, BIM enables integrated design and therefore it makes it possible (Eastman et al., 2011). The IDP through BIM simplifies and streamlines working relations and decision-making by removing the traditional obstacles to a successful outcome for all. In order to create a more coordinated and complete project in less time and for less cost, IDP through BIM becomes the shortest distance between the two points of conception and completion (Deursch, 2011).

Use of BIM in this project is expected to enhance the renovation design *process* and influence to make informed decisions while the renovation scenarios are being developed. Autodesk Revit dominates the Danish market based upon a survey made by BIPS (2015), and therefore is selected and Revit Application Programming Interface (API) is used to integrate the outcome of the application of the hybrid DSS with Revit, to the aforementioned information. The developing plug-in integrates and visualizes the renovation scenarios (see 'A' Figure 1) in Revit, three-dimensionally. It also demonstrates an evaluation of selected Hard (quantitative) and Soft (qualitative) criteria. While, shifting into the BIM framework could encompass various advantages of using a BIM model (Volk et al., 2014) upon all the stages of the building renovation process (from design to construction and operation phases), the developing plug-in can specifically be exploited during the early design stages of renovation projects where a decision has a strong influence throughout the rest of the process and thus the final decision-making. It therefore (a) increases the likelihood that the owners' project goals will be met; (b) optimizes the schedule and project time frame, eliminating schedule waste and time overruns; (c) streamlines share of information between design and construction; (d) increases team communication, collaboration, and cohesion; (e) enhances productivity of the design and construction team, providing the right and best information; (f) mitigates conflicts and eliminates adversarial relations between architect, contractor, and owner; (g) and ultimately integrates building components into a synthetic whole. For further clarification related to the IDP through BIM, the paper also investigates the outcome of the use of the plug-in for a case study, giving details about a discussion over the application of the tool with an experienced architect. This paper is structured in six sections. Section 2 outlines some background to the hybrid DSS developed in (Kamari et al., 2018b), whilst Section 3 provides information about the integration of the outcome of the hybrid DSS within Revit 2017. The result informs Section 4 where the developing plug-in is implemented for the Autodesk Revit. Finally, section 5 applies the tool to a case study dwelling and Section 6 discusses the implications and future direction of this work.

2. THE HYBRID DECISION SUPPORT SYSTEM (DSS) FOR GENERATION OF HOLISTIC RENOVATION SCENARIOS

2.1 Systems architecture

Figure 2 demonstrates the flow diagram of the hybrid DSS in three steps from the study by Kamari et al. (2018b). It is an approach to generate holistic renovation scenarios using a combination of two Multiple Criteria Decision Making - MCDM methods (Triantaphyllou et al., 1998; Parnell, 2013; Climaco, 1997) including Multiple Objective Decision Making - MODM and Multiple Attribute Decision Making - MADM (Climaco, 1997). Each step is briefly described below.
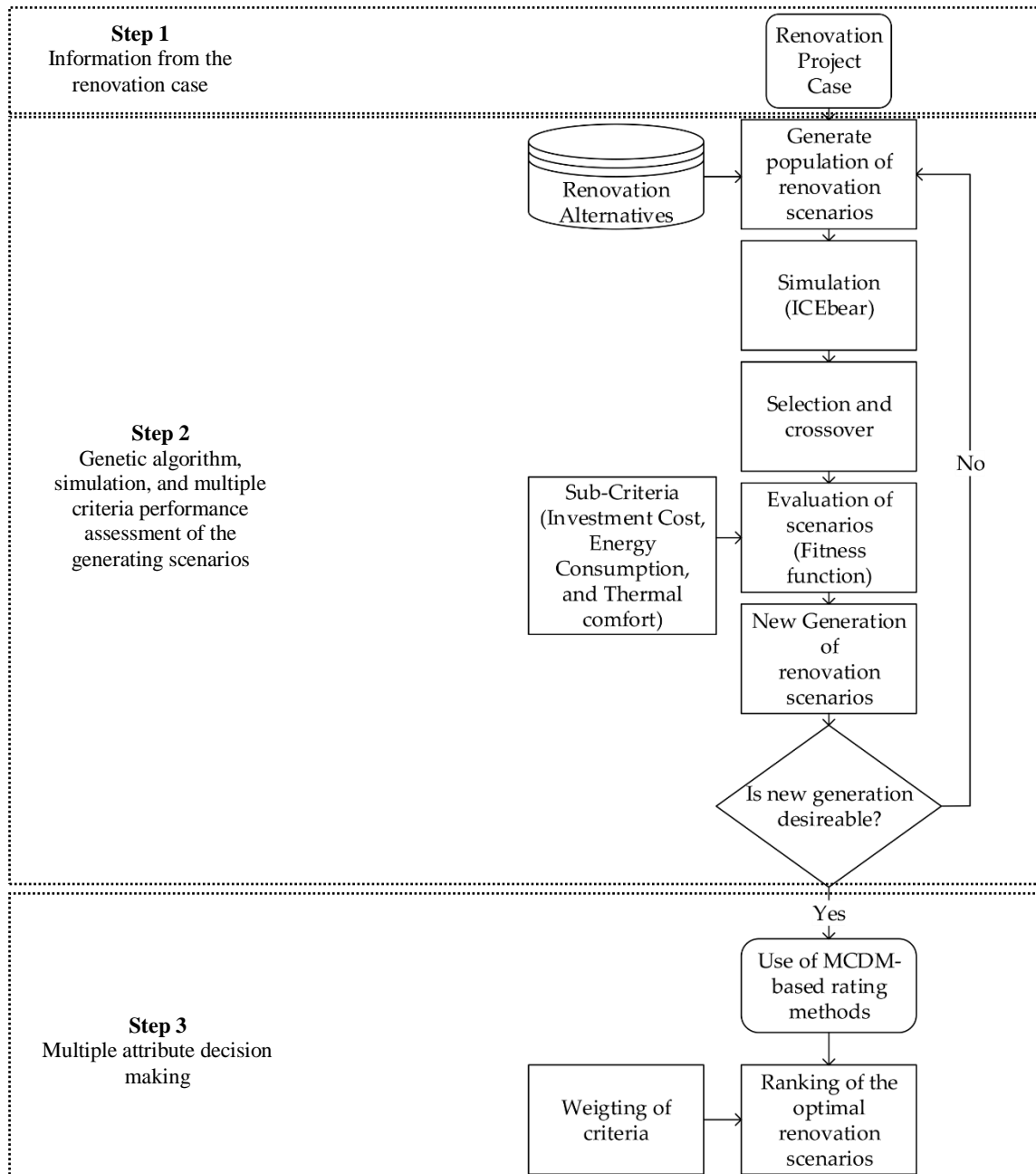
***Figure 2.** Flow diagram of the hybrid DSS for generation of holistic renovation scenarios (Kamari et al., 2018b)*

Step 1: The DSS is related to the principles of the use of a proposed DSS in the decision-making level 2 at the HMSR (see 'B' in Figure 1). It hence is used into the main body of HMSR. Following the activities that has been designed for decision-making level 1 at the HMSR (see 'A' in Figure 1), the renovation project is explored, relevant stakeholders are identified and their demands or their relevant concerns are investigated; then the design objectives are set up. Thereafter and by moving into decision-making level 2, the hybrid DSS is used for generation of holistic renovation scenarios, focusing on Hard (quantitative) criteria. This means step 1 in Figure 2 is parallel to the performing activities in decision-making level 1 in the HMSR and is instinctively carried out if the DSS is used within HMSR methodology. Consequently, the outcome of this step influences selection of the criteria as well as development of a hierarchical list referred as the database (see section 2.3) including detailed properties of the different renovation alternatives.

Step 2: A genetic algorithm - GA (Engelbrecht, 2007; Leu et al., 1999) is initially used to combine renovation alternatives so as to develop renovation solutions/scenarios. While the list can be extended, here the scenarios are generated and evaluated in terms criteria for *Energy Consumption*, *Investment Cost*, and *Thermal Indoor Comfort*. The applied GA in this study from (Bader et al., 2011; Grosan et al., 2007), searches for new scenarios based on the knowledge of the previous generation. With an iterative process, the GA approaches the scenarios with the lowest price. The hourly dynamic simulation tool ICEbear (Purup et al., 2017) is used to simulate the energy consumption and evaluate the thermal indoor comfort (for further information about the evaluating criteria see section 2.2). The trade-off between the criteria is addressed using Pareto-front approach (Pareto, 1896); also known as multi-objective programming, or Pareto optimization.

Step 3: It is difficult to judge which of the many available rating methods that would be 'the best' method (Wang et al., 2009; Mardani et al., 2015). To this end, one can use different MADM methods and compare their outcome. In this paper, the optimal generated scenarios are determined using AHP (Saaty, 1980; Wang et al., 2009), TOPSIS (Hwang et al., 1981; Wang et al., 2009), WSM (Wang et al., 2009) and ELECTRE (Roy, 1968; Wang et al., 2009). The MADM methods include a weighting of the criteria, reflecting the priorities of the involved stakeholders. The influence of the weighting on the developed ranking is ultimately examined by a sensitivity analysis using a Monte Carlo simulation (Jiménez, 2011).

2.2 The simulation criteria

The focus in the developed hybrid DSS has been on dealing with the three criteria *Energy Consumption*, *Investment Cost*, and *Thermal Indoor Comfort*. Reduction of energy consumption is a highly motivating criteria for renovation purpose. In this study, *energy consumption* is evaluated as reduction of energy consumption for heating measured in kWh/m2/year. Similarly, the *investment cost* is often prioritized as one of the most essential criteria particularly from customers or clients views. In this study, the cost is calculated as the cost of procurement in DKK[4]/Unit of the material to be in alignment with the cost data provided in (Molio, 2016), which is used for calculation of the construction cost in Denmark. *Thermal comfort* is evaluated according to class I of the adaptive method in DS15251 (EN, 2007) as it is assumed that people in their home adapt their amount of clothing and vent when necessary. Overstepping of class I is calculated as degree hours. As mentioned in the previous section, the simulation tool ICEbear (Purup et al., 2017) is used to evaluate the mentioned criteria. ICEbear is a tool that strives to facilitate design buildings for architects and engineers, evaluating the impact of the geometry on the indoor climate and energy demand at the same time. Hereby, the aim of ICEbear is to generate more sustainable building designs by consistency conscious design decisions. The tool is based upon algorithms for auto-generating hourly building performance data at a room level basis. It was originally developed to be operationalized in the programming environment of the Grasshopper, which is integrated in the three-dimensional drawing program Rhinoceros, so that parametric modelling can be utilized (Purup et al., 2017). However, presently an upgrade and expansion of ICEbear is in development at Aarhus University, including an owned Microsoft Windows based platform.

2.3 Renovation approaches and alternatives

There is a broad range of renovation approaches that need to be considered for the renovation of existing buildings. Kamari et al. (2018c) based on analysis of a real case study and available literature (Baker, 2009; Boeri et al., 2014; Burton, 2012; Molio, 2016) identified a total of 139 renovation alternatives and grouped them into 26 approaches. The following list displays some of the commonly applied renovation approaches that mainly were used for generation of renovation scenarios in the current study including: approaches. The

- External wall insulation,   A.a
- External wall finish,   A.b
- Internal wall insulation,   B.a
- Internal wall finish,   B.b
- New wall construction,   C.a

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[4] Danish Krone (currency)

- Internal roof insulation,   D.a
- Internal roof finish,   D.b
- Roof outside,   E.a
- New floor construction,   F.a
- New windows,   I.a

There is a list of renovation alternatives (e.g. A.a.1 : Insulation [Class 37] – 30 mm) within the above-listed renovation approaches that is used for generation of the renovation scenarios. The data includes detailed properties of the different alternatives such as cost, thickness, thermal conductivity, heat transfer coefficients, and thermal resistance. The database is enclosed in appendix A.

2.4 Constraints and rating rules

When searching among countless possibilities to combine renovation alternatives in order to generate holistic renovation scenarios, constraints can help to limit the solution space. Various recommendations and regulations exist on building renovation for evaluation of the *energy consumption* and *thermal indoor comfort*, some of which can be included in the GA. In Denmark, the Danish Building Regulation (DBR, 2015) issues out the building rules for both commercial and private buildings. For instance, the DBR demands certain U-values for reconstructed or refurbished construction parts, i.e. exterior walls must obtain a U-value of maximum 0.2 W/m^{2}K after a renovation. The regulations for the building elements of interest for this project are presented in Table 1.

Table 1. *Minimum requirements of U-value cf. DBR for Renovation*

| Building elements	W/m^{2}K
Exterior walls	0.20
Ground slab	0.12
Roof	0.15
Doors and windows	1.65

DBR also recommends the 95% of time that the building is in use, should be within thermal category III cf. EN 15251, allowing 5% of the time outside this category, which may correspond to the recommended maximum of 100 hours above 27°C and 25 hours above 28°C. Furthermore, a renovation project may have a budget perhaps depending on the intended energy savings, which will limit the possibilities on the price. Similarly, unrealistic renovation alternatives may be discarded, i.e. replacement of a bearing wall with a new wall, or combination of existing walls and additional layers of insulation causing unrealistic thick constructions.

2.5 Outcome of the application of the hybrid DSS

The application outcome of the hybrid DSS is a ranking of optimal scenarios/solutions. As an example, Figure 3 demonstrates a ranking of optimal generated solutions that include all renovation alternatives.

These scenarios are generally preferable according to the MADM methods. In Figure 3, two scenarios marked with a blue dot have a particular low rank by all methods. In the following, Table 2 represents the relevant renovation alternatives for those two scenarios. The notation "Ref" before a building component means that, this component was not included for renovation in the generated scenario by the algorithm.

Extending the outcomes of application of the hybrid DSS including the top-ranked generated renovation scenarios (i.e. the two scenarios represented in Table 2), transmitting and visualizing them within a BIM-based tool (Revit), and subsequently to improve them further concentrating on Soft criteria (i.e. spatial quality), is described and implemented in the following sections.
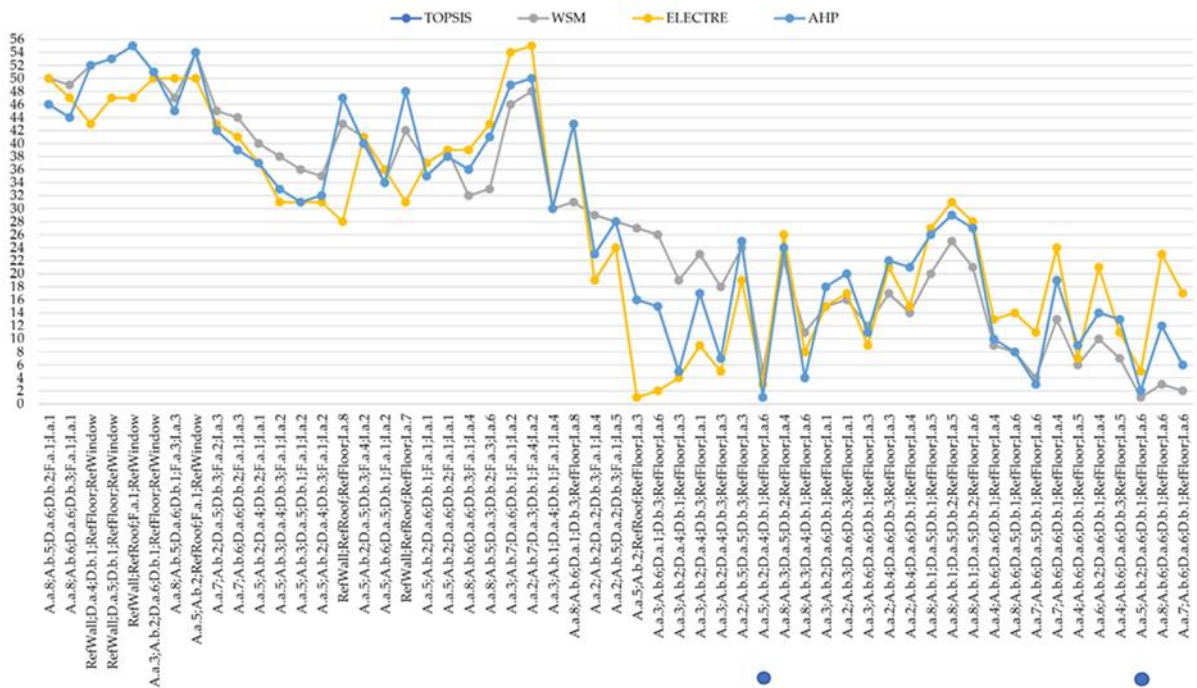
Figure 3. Ranking of the results using four different MADM methods: AHP, ELECTRE, WSM, and TOPSIS from Kamari et al. (2018b)

Table 2. *Typical optimal generated scenarios by use of the hybrid DSS*

A.a.5;A.b.2;D.a.4;D.b.1;RefFloor;I.a.6		A.a.5;A.b.2;D.a.6;D.b.1;RefFloor;I.a.6	
A.a.5 :	"Insulation (Class 37) - 150 mm",	A.a.5 :	"Insulation (Class 37) - 150 mm",
A.b.2 :	"Plaster",	A.b.2 :	"Plaster",
D.a.4 :	"Insulation (Class 37) - 125 mm",	D.a.6 :	"Insulation (Class 37) - 200 mm",
D.b.1 :	"Plasterboard",	D.b.1 :	"Plasterboard",
------	"RefFloor",	------	"RefFloor",
I.a.6 :	"New windows - Hvidbjerg Everluxx Classic"	I.a.6 :	"New windows - Hvidbjerg Everluxx Classic"

3. INTEGRATION OF THE HYBRID DSS WITH BIM FOR THE BUILDING RENOVATION

The object-based digital model by Revit contains information about the entire project which is stored in an integrated database (Krygiel et al., 2008), including geometric and semantic information (Schlueter et al., 2009), and able to articulate itself three-dimensionally. Kim et al. (2015) discuss that addressing the three-dimensionally geometrics and the semantics of a Revit model by the Revit API allows stakeholders to assess design scenarios more quickly than before. This includes the possibility of visualizing design scenarios through the conventional Revit platform which helps to review spatiality and other similar qualitative architectural values (Jalaei et al., 2015). In addition, the integrated data enables a quick and accurate collection and extraction of the required information from the model components, which in the next step can be exploited in the simulation and evaluation tools as part of the design process (Kim et al., 2015). The Revit API allows access to some of the transactions and commands that are possible during conventional usages of Revit (Autodesk, 2017b). Thus, not all transactions and commands are included, which set limitations towards the possibilities. Nevertheless, the Revit API allows automation of the possible transactions and commands which traditionally is done manually.

3.1 Methodology of integration

The development of the plug-in for Revit that integrates the generated scenarios in the previous section, as represented in Figure 4, will be carried out through five stages, and subsequently in the next stages (stages 6 and 7) the tool will be implemented and the outcome will be verified by use of a case study.
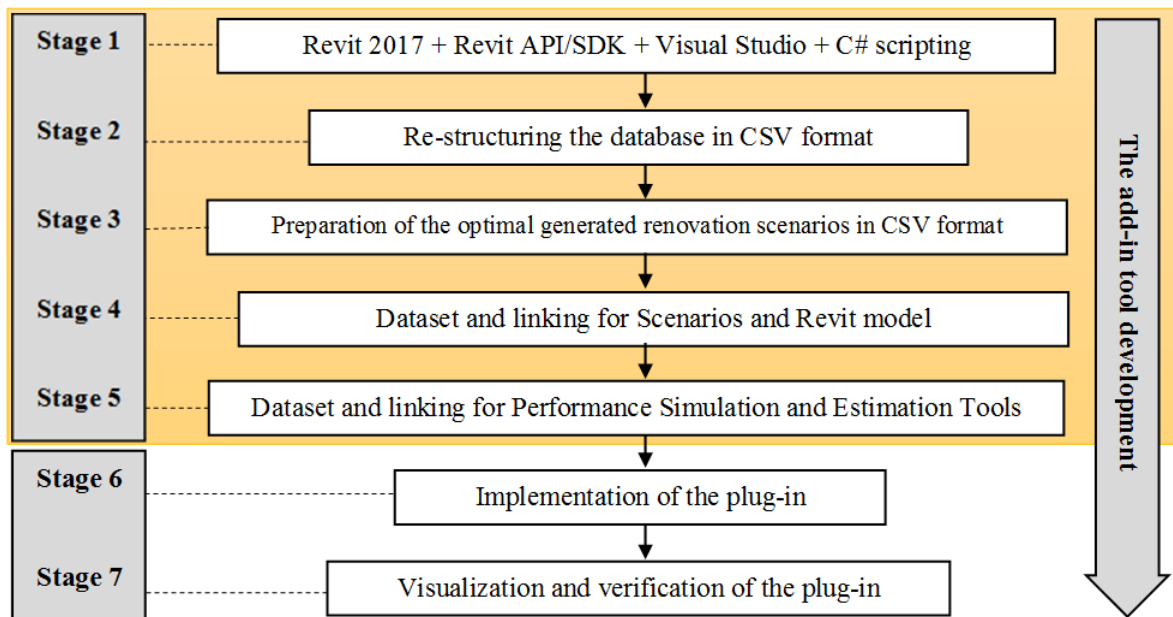

Figure 4. The methodology of integration the hybrid DSS with BIM for building renovation

3.1.1 Re-structuring the database in CSV format

Following the information provided in section 2.3 about the renovation approaches and alternatives, for the development of the plug-in in this paper, the following list of renovation approaches is used:

- External wall insulation,   A.a
- External wall finish,   A.b
- Internal wall insulation,   B.a
- Internal wall finish,   B.b
- New wall construction,   C.a
- Internal roof insulation,   D.a
- Internal roof finish,   D.b
- Roof outside,   E.a
- New floor construction,   F.a
- New windows,   I.a
- Interior door replacement   J.a
- Painting of interior walls   K.a

Even though Ms. Excel provides a good overview, it is not a perfect platform for integration of the database (see appendix A for the database). An Excel document contains more data than needed by default, which increases the processing time and the Excel database does not make it easy to retrieve data to Visual Studio. Therefore, the database has been converted to a comma-separated-value (CSV) document.

3.1.2 Preparation of the optimal generated renovation scenarios in CSV format

In order to integrate the generated renovation scenarios within the BIM environment of Revit, a scenario file is developed. The scenario file is a CSV text document that includes a matrix of data regarding the combined renovation alternatives for generating the scenario. The structure of the CSV text document and the data matrix is demonstrated in Figure 5.
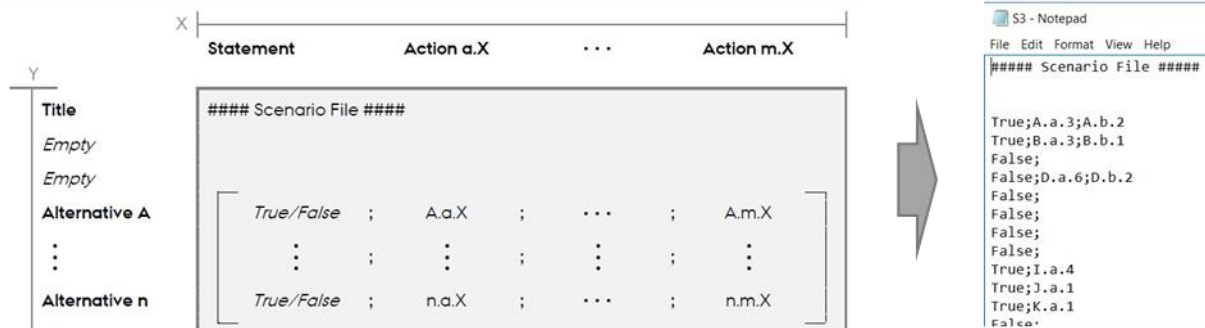

Figure 5. Demonstration of the data matrix in a scenario file

As it is illustrated in the Figure 6, the provided information regarding the included alternative in the scenario file is initially examined based upon the terms used in the database for each alternative. In the next step, the developing script code makes a lookup in the CSV database to get the right data information for their integration. The true or false statement indicates if either the alternative is included in the specific scenario, whereas the title statement is an error handler, making sure that the considered CSV text document is consistent with the developed script code.
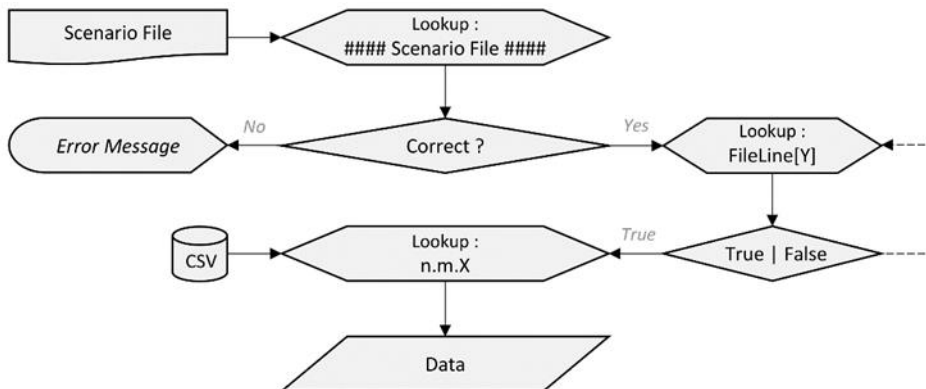

Figure 6. Flow diagram of data processing principle for a scenario file

Then, the scenario data is processed for the next step through linking in the Revit.

3.2 Datasets - Integrating (or linking) renovation alternatives to Revit
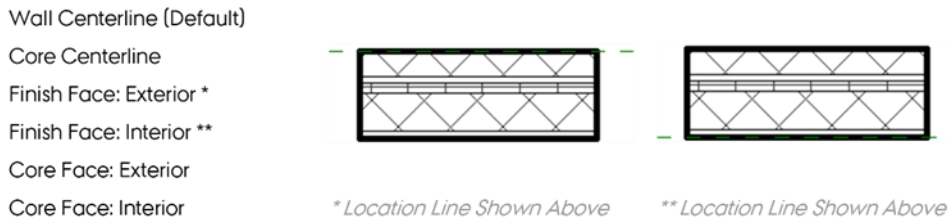
Even though the Revit API can make transactions and commands automatically and in sequences within Revit, it is not a simple task to integrate the alternatives from the database and thus a scenario file. The reason is how Revit operates regarding its data structure. In the following, we will elaborate on transaction and linking of the data for three different renovation approaches, including Façade, Roof, and Windows.

3.2.1 Renovation approaches A and B (Insulation of Exterior Walls)

For the renovation approach A and renovation approach B, the purpose of the integration is to add the additional layers in the Revit model and visualize the changes. This relates alternatives A.a and A.b as well as B.a and B.b within the database.

Revit uses compound structures, to show mass of the walls and similar elements as well as provides the textures for the visualization. However, Revit likewise uses the properties of the compound structures for the location line of the walls. The location line of a wall within Revit specifies which of a wall's vertical planes is used to position

the wall in relation to the path sketched or otherwise specified in the drawing area. Figure 7 illustrates the planes that can be selected regardless of the compound structure and hence wall type, as it is the precise term for compound structures of walls. It should be mentioned that in Revit terminology the core of a wall refers to its main structural layer or layers. This transaction is done manually in Revit by using the options bar before placing the wall in the drawing area or on the properties palette after placement.
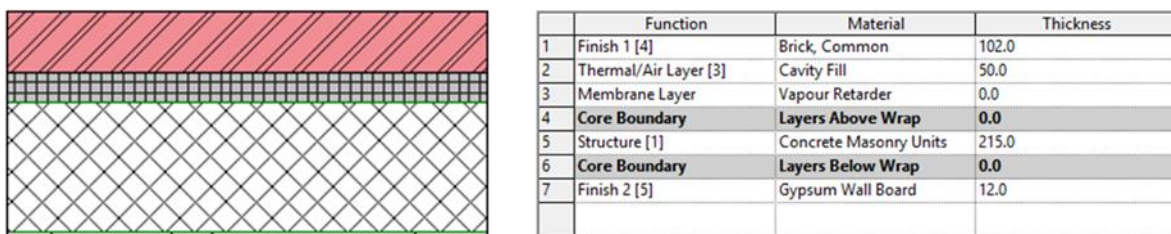
Wall Centerline (Default)

Core Centerline

Finish Face: Exterior *

Finish Face: Interior **

Core Face: Exterior

Core Face: Interior

*Location Line Shown Above   **Location Line Shown Above

Figure 7. Possibilities for the location line property of wall elements

The significance of the wall location line is that when a new segment of layers is integrated, it dictates how the given wall is expanded. For renovation approach A, this logically must be done in an external direction. Thus, before adding layers to a wall type for alternative A the location line of a wall must be set to; Finish Face: Interior, as the new segment is placed above the reference line, see the green dotted line in Figure 7. That means the wall placement is locked to the location of the inner wall. For renovation approach B, the location line most be set to: Finish Face: Exterior.

To make the new segment of layers the properties of each of these layers must be specified. The corresponding script function in the Revit API requires data information for the material, thickness and function of each layer. The material dictates in terms of visualization the applied texture. However, the current possibilities of the Revit API as of Revit 2017, as well as Revit 2018, it is not possible to create materials from scratch. To this end, the materials must be created manually, or loaded from a material library. This is also the reason why a Revit material is included for each renovation alternative in the database. In the present study, to deal with this issue, a corresponding material library is developed by default of Revit textures.

The thickness of a layer is due to the length measurement and in this study needs no further explanation. However, the Revit operation system uses the imperial unit system for length units as default, even if the project units is set to metric (Autodesk, 2017c). Hence, the standard operation system converts automatically from imperial to metric. Nevertheless, for any other base unit, for example mass, Revit uses the metrical unit system (Autodesk, 2017c). Thus, the developing code include unit conversion from metric to imperial where needed for the integration.

When the additional layers of either renovation approach A or B is created by the Revit API, then they should be added to the current compound structure of the wall type that is applied for the exterior walls. In this regard, it is necessary to distinguish between exterior and interior walls. This is accomplished by sorting the walls of a Revit project by a wall type function property, which dictates if the wall type is either exterior or interior. However, wall elements can have the same wall type ascribed, that the developed script code sorts out in the used wall types. Hence, that an alternative is not applied to the same exterior wall type more than once. Furthermore, the sequence of the layers which constitute a compound structure is based on a numerical order from external to internal. This means the first layer is the external finish and the last layer is internal finish. Consequently, the developed script code should make sure that the layers are consistent with this numerical order, see Figure 8 as an example.

	Function	Material	Thickness
1	Finish 1 [4]	Brick, Common	102.0
2	Thermal/Air Layer [3]	Cavity Fill	50.0
3	Membrane Layer	Vapour Retarder	0.0
4	**Core Boundary**	**Layers Above Wrap**	**0.0**
5	Structure [1]	Concrete Masonry Units	215.0
6	**Core Boundary**	**Layers Below Wrap**	**0.0**
7	Finish 2 [5]	Gypsum Wall Board	12.0

Figure 8. Example of the numerical order for layers in Revit

In the following, Figure 9 summarizes the integration process for renovation approach A and renovation approach B.
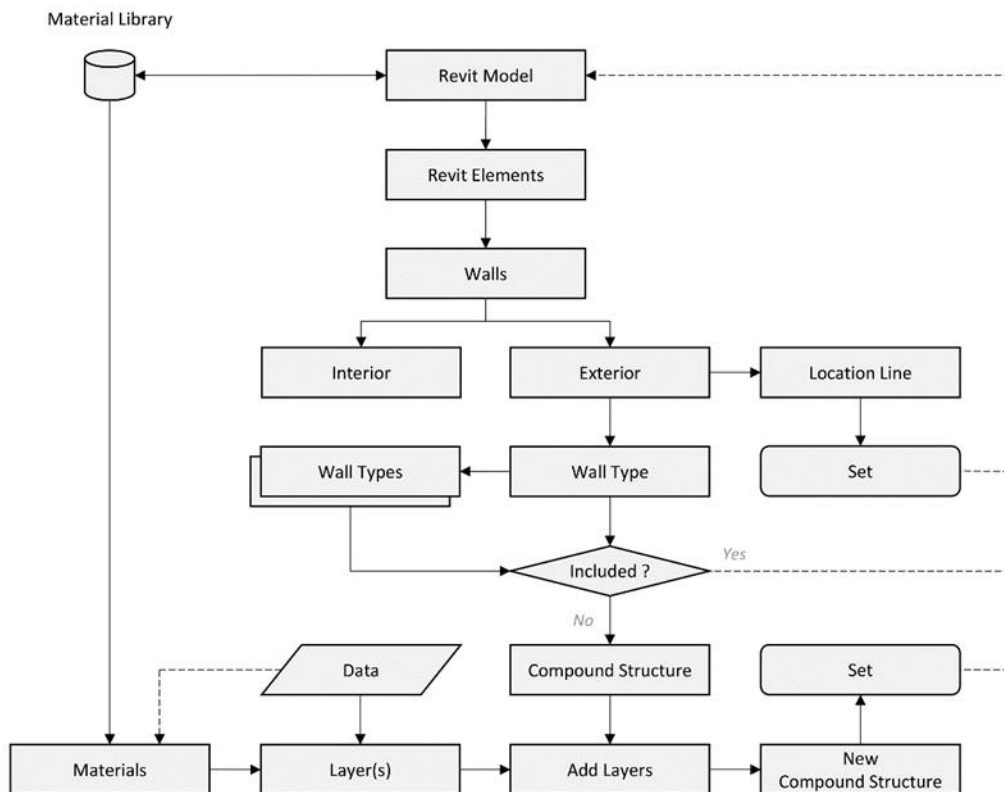
Figure 9. *Flow diagram of data processing principle for renovation approach A and B (Insulation of Exterior Walls)*

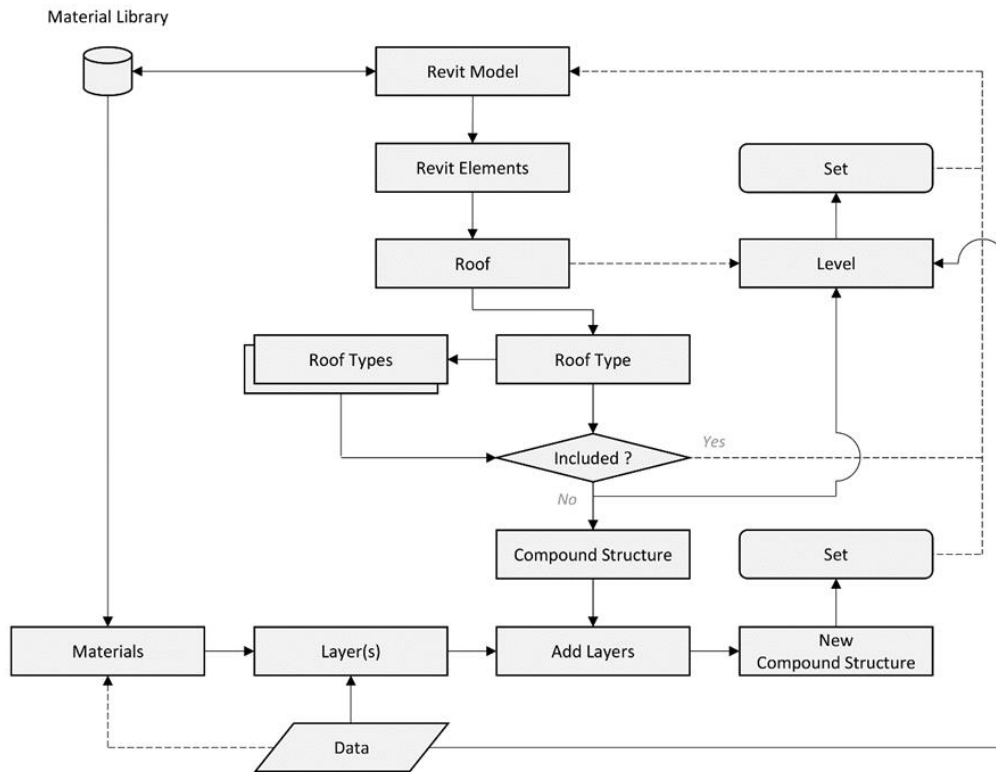### 3.2.2 Renovation approach D (Roof Insulation (Internal))

For renovation approach D, the implementation of the layers is similar with the renovation approaches A and B. However, the location line is not a necessity for this integration. In Revit, roof as a compound structure is bound to a level (vertical height or story within a building). Thus, by integrating additional interior insulation, the bounded level should be lowered in order to visualize the adding layers. If not, the roof for the Revit model would simply expanded outward from the bound level. Thus, as it was necessary to distinguish between internal and external wall types for approaches A and B, similarly for approach D it is necessary to distinguish between the bound level and all others. In the following, Figure 10 summarizes the integration process for renovation approach D.

3.2.3 Renovation approach I (Window Replacement)

For renovation approach I, the purpose of the integration is to replace the windows in the Revit model, hence alternative I.a within the database.

Windows in Revit are an element same as walls. However, instead of assigning a predefined type to its composition, such as wall types, a family instance is assigned to it. Family instances in terms of the Revit terminology are types for elements such as beams, columns, furniture etc. and of course windows, which provides more detailed properties and appearance possibilities to the considering elements in the Revit model.

In order to avoid any misfit, a default Revit family is loaded into the Revit project for alternative I. It should be underlined that a Revit family is a group of family instances with the same properties, but not necessarily with the same setting. For example, for windows, the family instance can have different height and width size values. Using a default Revit family make sure that the correlated Revit transactions can be consistent. Hereby, a family instance for the default Revit family is assigned to all the Revit model window elements.

Figure 10. Flow diagram of data processing principle for renovation approach D (Roof insulation)

For implementing a window replacement, the default geometrical properties should be equal to the typology of previous instance as a requirement. Thus, these properties must be collected and used to create a corresponding family instance for the default Revit family along with the data from database.

Like wall elements, the same family instance can be assigned to different window elements. Thus, when the properties are collected for the old windows, the same data information can be obtained. For the exterior walls, the developed script code sorts out in the used wall types. Nevertheless, because a window replacement not necessarily mean the same window size, the used family instance for the window elements are not sorted, in order to integrate some design freedom to the considering renovation scenario. In the following, Figure 11 summarizes the integration process for renovation approach I.
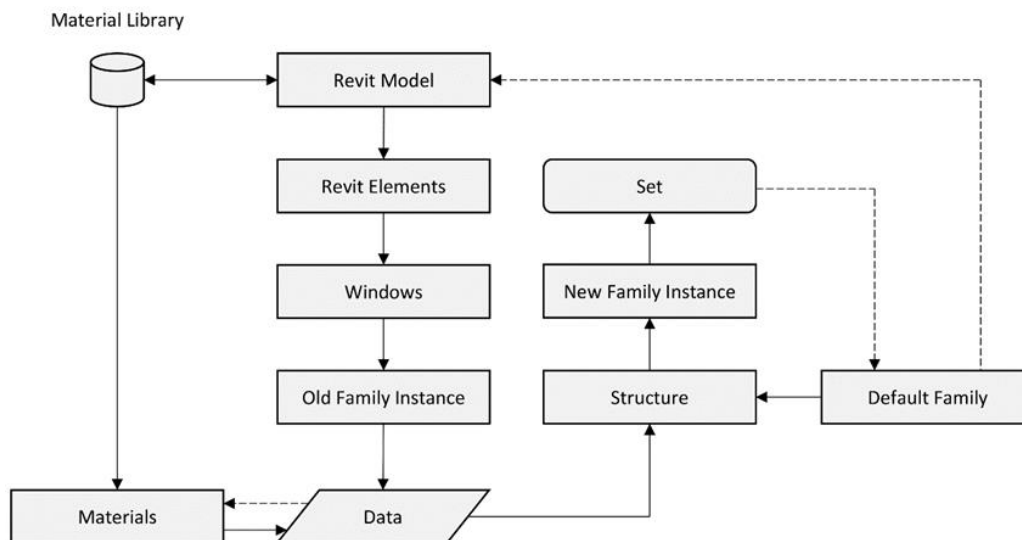
Figure 11. Flow diagram of data processing principle for renovation approach I (window Replacement)

4. IMPLEMENTATION OF THE PLUG-IN FOR AUTODESK REVIT

4.1 Criteria for evaluation

As discussed in section 2, the generating scenarios are simulated and their performance are evaluated in terms criteria for *Energy Consumption*, *Investment Cost*, and *Thermal Indoor Comfort*. Therefore, these criteria will be included in the developing plug-in. In addition, the criteria for *Aesthetic* and *Spatial quality* are also added in the present study. Table 3 summarizes the selected sub-criteria for the developing plug-in, regarding to the study by Kamari et al. (2017c). These are used for the evaluation and comparison of the scenarios.

***Table 3.** Outline for the selecting criteria for evaluation of holistic renovation scenarios for the developing plug-in*

	Criteria	Sub-criteria	Parameter	Measurement	Significance
Functionality	Energy efficiency	Reduction of energy consumption	Energy demand	kWh/m2/yr	1.00
	Indoor climate	Thermal comfort	Summer comfort	°C	*
			Adaptive comfort	Comfort categories	0.5
		Daylight comfort	DF (daylight factor)	%DF	*
			UDI (useful daylight illuminance)	%	0.5
Accountability	Spatial quality	The articulation between space…	Visualization	Perception	0.33
		Color	Visualization	Perception	0.33
		Lighting	UDI (useful daylight illuminance)	%	0.33
	Aesthetic quality	Temperature	Visualization	Perception	0.50
		Harmony	Visualization	Perception	0.50
Feasibility	Investment cost	Procurement	Cost	DKK	1.00
	-	-	-	-	-

* In terms of the guidance of the Danish Building Regulations 2015

In the Table 3, the column "Significance" refers to the importance factor of a sub-criteria, and later it is applied to a five-score ranking system to provide a comparison between the top optimal renovation scenarios that is made based upon the concept of the Likert method (1932) and the ranking system in Kamari et al. (2017c). Table 4 represents the applied score ranking system for the parameters linking to the sub-criteria in Table 3. The result is used for performance evaluation and illustration of each scenario within a Radar chart (see for instance Figure 19 and 20 in section 5). This is demonstrated in section 4.3.

***Table 4.** Applied Score Ranking System for the evaluating parameters*

Specification		Ranking Score (rs)				
Parameter	Measurement	1	2	3	4	5
Energy	kWh/m²/yr.	G F E	D	C	B	A 2010, A 2015, A 2020
Adaptive comfort	%	$\|rs\| = \sum \dfrac{(\text{Cat. 1, [\%]}) \cdot 5 + (\text{Cat. 2, [\%]}) \cdot 3 +}{(\text{Ca. t 3, [\%]}) \cdot 2 + (\text{Cat. 4, [\%]}) \cdot 1}$				
UDI	%	50 >%	70 ≥ % > 50	80 ≥ % > 70	90 ≥ % > 80	% ≥ 90
Cost	DKK	100% of budget DKK>	100% of budget ≥ DKK > 80 % of Budget	80% of budget ≥ DKK > 65 % of Budget	65% of budget ≥ DKK > 50 % of Budget	DKK≤ 50% of budget
Visualization	Perception	Based on perceived				

In terms of calculation of the total energy demand of a building in this paper, an energy labelling system based on the development of the Danish Building Regulations is developed, that is explicit for Danish application (Danish Energy Agency, 2017). The labelling system for dwellings is shown in Table 5 where the stated constant of A is the heated floor area in square meters. Renovation classification 1 requires a labelling of A2010 and for classification 2 a labelling of C is required (Videncenter for Energibesparelser I Bygninger, 2017).

Table 5. Energy labelling system for dwellings

| A 2020	A 2015	A 2010	B	C	D	E	F	G
≤ 20	< 30.0 + 1000/A	< 52.5 + 1650/A	< 70.0 + 2200/A	< 110 + 3200/A	< 150 + 4200/A	< 190 + 5200/A	< 240 + 6500/A	> 240 + 6500/A

4.2 Performance Simulation and Estimation Tools

The main agenda for development of the plug-in in this study is integration of the outcome of application of the hybrid DSS, and upgrading the BIM model of the existing building on the transmitting generated scenarios. However, to improve the capability of the developing plug-in, application of external tools is established. As they are external BPS (Building Performance Simulation) tools, they will only be scrutinized overall in regard to their influence upon the developed script code for the tool and how they can be integrated.

Since the BIM environment of Revit is the core for the potential demonstration by a Revit model, it is considered to be a condition for the tools that they to some extent have a connection to Revit. Hereby, utilization of the data. The application process of applying Revit for performance analysis is in general terms highlighted by Figure 12.
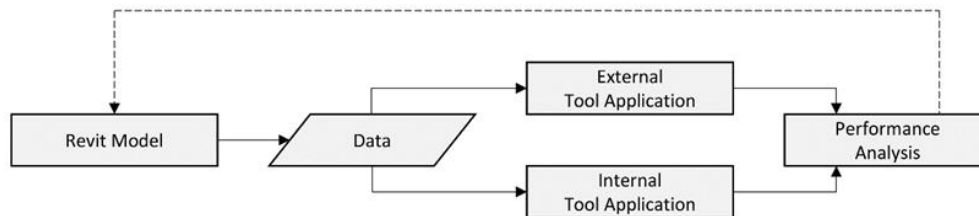
Figure 12. The BIM flow diagram for performance analysis of the renovation scenarios

CADVES (Bøving et al., 2018) is used for the data transferring. It provides the possibility of automatically providing the types and family instance within a Revit model with the required Revit parameters (i.e. U-value [heat transfer coefficient], Psi [line of loss] etc.) for them. This naturally requires the CADVES plug-in to be installed and when completed it is accessible by the Revit ribbon. The principle is highlighted in Figure 13 for a window. The developed script code for the plug-in in this paper, updates these value sizes in in accordance with the datasets and linking in section 3.2.
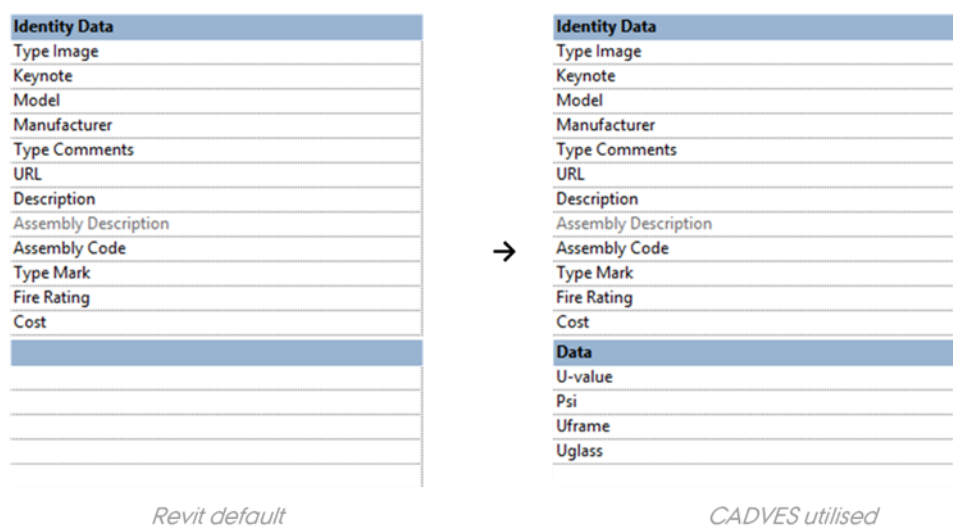
Figure 13. CADVES parameters, e.g. windows

The data is extracted solely one-way to ICEbear by CADVES. Therefore, it is essential to return and input the performance data to the developing plug-in manually, in order to provide evaluation scores. The principle of proving the required data information to the plug-in is consistent with the illustrated in Figure 14. In terms of the data extraction towards ICEbear, CADVES uses a similar data procession as highlighted by Figure 6, just reversed.

Figure 14. Data transfer principle between Revit, ICEbear and the plug-in

4.3 User Interface

To provide the implementation for the proclaimed in previous section, an interface for the plug-in is developed. It is developed by Windows Presentation Foundation (WPF) within Visual Studio. The reason is that WPF combined with XML is a rich presentation system, which provides the possibility of creating visually user experiences for applications, such as a plug-in for Revit.

The plug-in is entitled VCBR DSS Tool, where VCBR is an acronym for Value Creation by Building Renovation. The interface of plug-in is made by two main grids. The first is a main menu (in green color) which emphasize the various steps and capabilities of the plug-in. This is showcased in Figure 15. It should be noted that some of the buttons are not initially enabled due to it secures the use and the correlated progression. The buttons are only enabled when the previous step is completed.
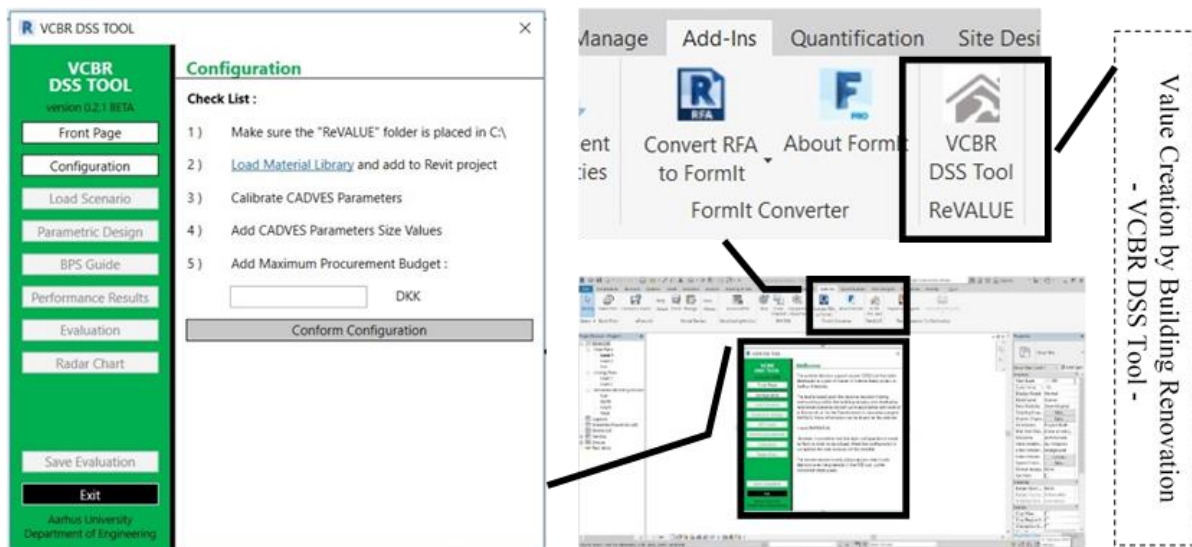

*Figure 15. The plug-in for Revit user interface in Revit*

The second grid enables linking to the buttons of the main menu including a set of various sub-grids. The first sub-grid occurs when launching the plug-in in Revit. This states some basic information about the DSS etc. The next sub-grid (button labelled: Configuration – see Figure 15) is intended to make sure the correct configuration is set to secure the usage of the plug-in. The third sub-grid ('A' in Figure 16) handles the integration part as discussed in 3ection 3. In doing so, when a scenario file is loaded, the buttons labelled; Parametric Design ('B' in Figure 16), BPS Guide ('C' in Figure 16) and Performance Results ('D' in Figure 16) are enabled in the main menu.
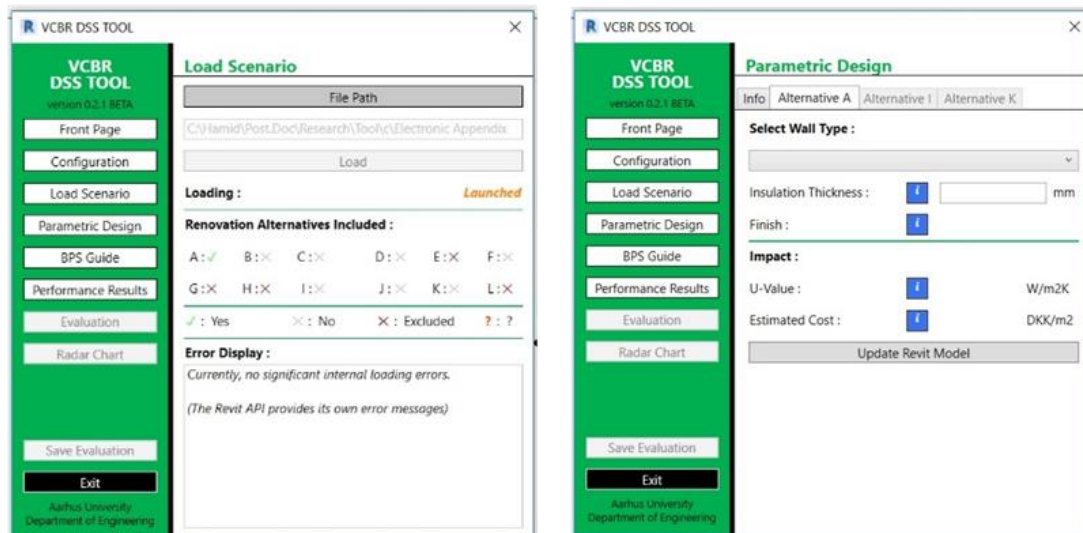
(A) Load Scenario   (B) Parametric Design
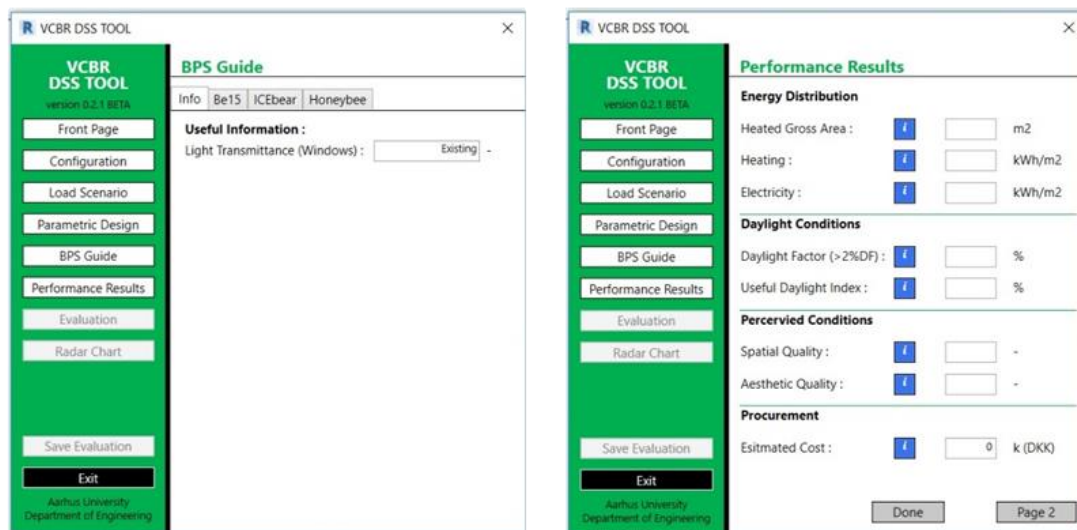
(C) BPS Guide   (D) Performance Results
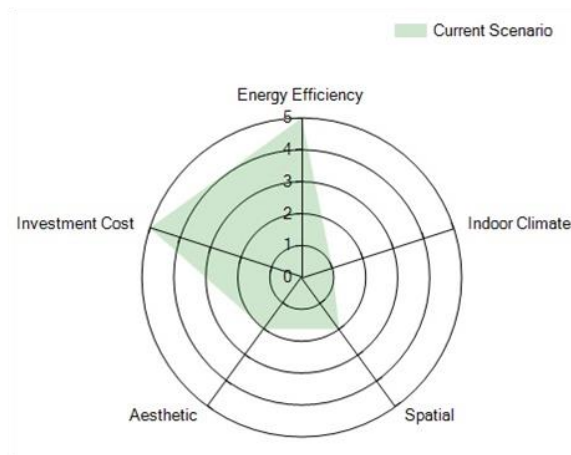
Figure 16. The plug-in's sub-grids

The sub-grid for Parametric Design is attached to renovation approach I (window replacement). It makes it possible for windows to change the window height, width, insert, and sill height, while getting information towards the parameters of the window such as U-value, cost per window etc. When clicking the update button, the new geometric and schematic data is transferred to the Revit model, and is thus instantly performed. This is done in accordance with Figure 11. In addition, for renovation approach A, the insulation thickness can be changed. This results in changing the U-value of the wall type etc.

The information labels (blue info icons) in 'B' and 'D' in Figure 16 are created to support decision-making. For example, for windows is stated that the sill height should be a maximum of 1.00 meter.

Following the guidelines that are provided in sub-grid for BPS Guide, the uploaded scenarios can be evaluated further for the criteria discussed in section 4.1. The sub-grid for Performance Results is where the performance analysis results by BPS tools are stated, as discussed in section 4.2. Furthermore, it is in this sub-grid where the total investment cost is estimated and demonstrated. When all the data is stated within the DSS, the Evaluation and Radar chart buttons are enabled.
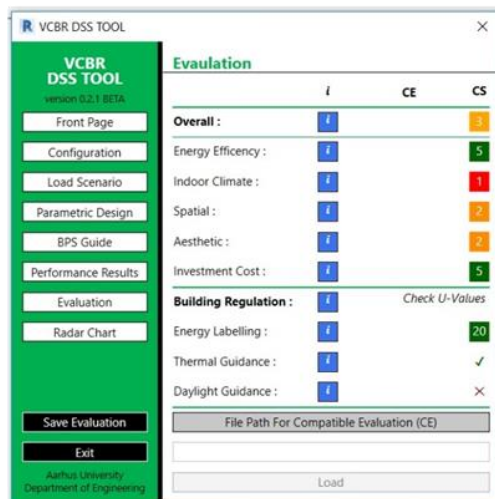
(A) Evaluation   (B) Radar chart

Figure 17. *The plug-in's Evaluation and Radar chart sub-grids*

The sub-grid of the *evaluation* is showcased by an example in Figure 17. From the figure, it is clear to see the integration highlighted in subsection 4.1. The corresponding Radar chart is showcased for the evaluation values. The data highlighted under current scenario (CS) is the data saved by Save Evaluation button. As the evaluation require no interaction with the Revit model or the BPS tools, the aggregated scores and the Radar chart is performed instantly.

The Radar chart is integrated by System Forms within Visual Studio, utilizing the scores from the ranking module. However, to take advantage of the benefits of Radar chart, the developed script code makes it possible to save the evaluation, and as such to include an additional evaluation in the Radar chart. This is integrated by the same data processing principle in Figure 6. Furthermore, as the developing plug-in is intended for application for dwellings in Danish context, the evaluation not only includes the ranking score system, but also an estimate for the requirements of the renovation classification (as discussed in section 4.1). Therefore, the evaluation and the developed script code include a displaying for the building energy labelling, and a control of the thermal and the minimum daylight requirements, as demonstrated in section 4.1.

5. CASE STUDY

To verify the application of the developed plug-in, it is examined through visualization and evaluation of optimal renovation scenarios for a single-family dwelling that is located in a coastal context in the suburb of Hjerting near the city of Esbjerg, Denmark. The dwelling is a typical dwelling in terms of its building typology; yellow brick finish on the exterior walls, colorful building elements and dark color selections on the interior finishes. It has a heating floor area of approximately 92 m^2, basement excluded, and use district heating as its heat supply. Furthermore, from the existing drawings, it is seen that despite the regular and periodical appearance it has strong architectural features. The family residents have decided to renovate the building, and their budget is about 200,000.00 DKK.

The applied value size (i.e. U-values) for the existing building, as input to the CADVES (Bøving et al., 2018) parameters is presumed based on the building typology and the construction period as well as value guidelines stated in SBi 213 (Aggerholm et al., 2014) and within the platform of Be15 (Danish Building Research Institute, 2017). The applied value sizes resulted in an energy labelling of D by the calculation of Be15, which is consistent for the period and the building topology. Nevertheless, as the BPS tools and their results is not in focus in present paper, but as an advantageous of using the plug-in, these will only be used towards the evaluation and does not necessarily reflect the actual results.

Figure 18 demonstrates the Revit model of the dwelling, that was developed overall based upon the obtained drawing material and pictures.
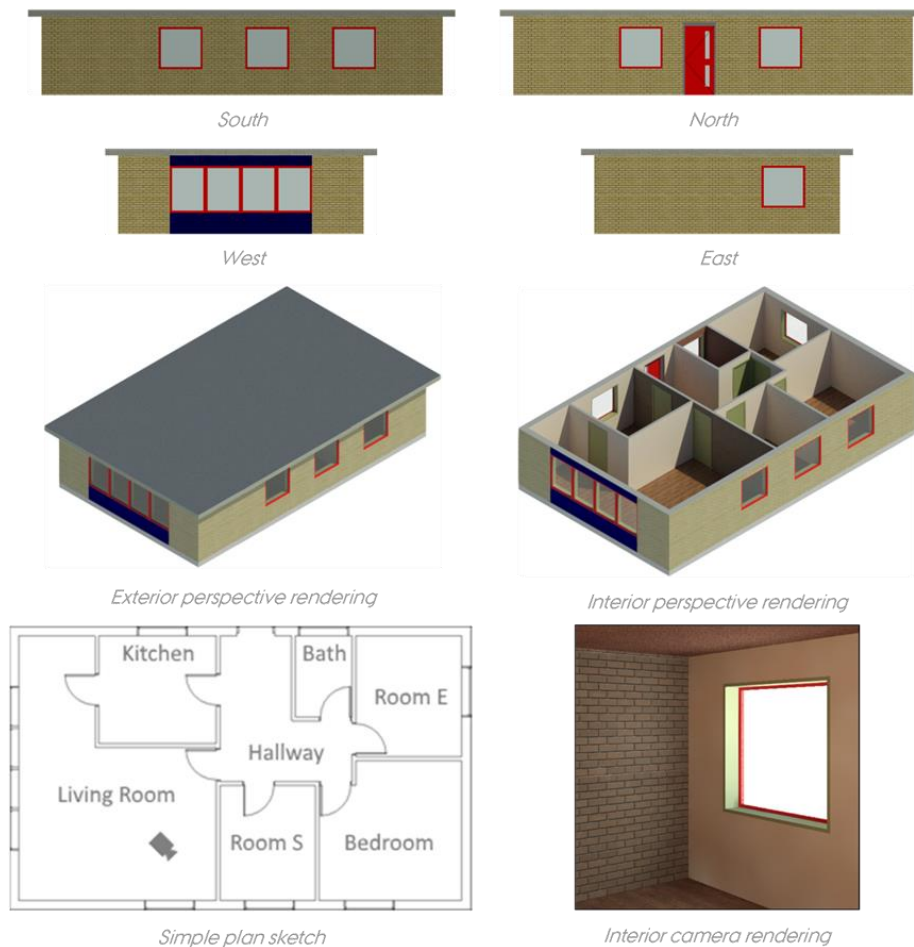
Figure 18. The developed Revit model for the dwelling

For renovation purpose, after conducting some meetings with the family residents and finding out about their priorities besides following the regulations from the municipality of the region, the hybrid DSS has been used to generate optimal renovation scenarios for the case. Table 6 summarizes the top two ranked scenarios that have been selected for the renovation of dwelling. The scenarios have been influenced via the chosen criteria, the user input, as well as the tendency in dwelling terminology towards a modern functionalism style; minimalistic, affordable for the common client as well as black-and-white architecture.

Table 6. The proposed renovation scenarios for the dwelling

Scenario	Renovation approach	Renovation alternative
Scenario 1	External wall insulation,	A.a.6
	External wall finish,	A.b.2
	Internal roof insulation,	D.a.7
	Internal roof finish,	D.b.1
	New windows,	I.a.5
	Painting of interior walls,	K.a.1
Scenario 2	External wall insulation,	A.a.3
	External wall finish,	A.b.2
	Internal wall insulation,	B.a.3
	Internal wall finish,	B.b.1
	New windows,	I.a.4
	Interior door replacement,	J.a.1
	Painting of interior walls,	K.a.1

In the following, the outcome of application of the tool to visualize and evaluate the above generated renovation scenarios, is represented in Figure 19 (scenario 1), and Figure 20 (scenario 2).

Figure 19. Evaluation of the scenario 1

Figure 20. Evaluation of the scenario 2

Following the evaluation demonstrated in Figures 19 and 20, the plug-in is able to plot the evaluation for both scenarios 1 and 2, which enables comparison between them. As it is seen in Figure 21, scenario 2 entails higher investment cost, but it improves the perceived spatial quality due to that a more contemporary harmony is achieved. The renovation alternative I (window replacement) however provides a great design initiative, yet requires further deliberation and discussion. Thus, in terms of a preferable scenario, it would depend on the opinion of the family residents. It was therefore concluded that both scenarios should be illustrated to them, to make the final decision.
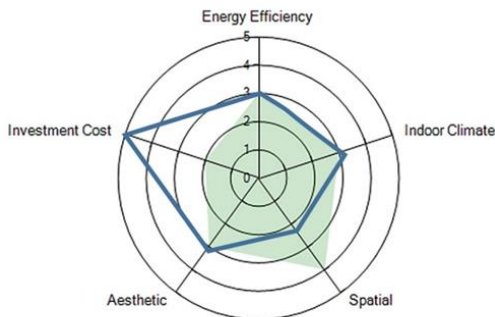
Figure 21. Radar chart with plot for both scenarios 1 and 2

5.1 Deliberation exposition

For further clarification of the potential use of the plug-in and visualized scenarios regarding to the studied case, in this sub-section a summary of a dynamic dialogue-based commentary deliberation collected from an architect by an engineer is represented.

In the daily work of an architect, the perception of space is often processed in a meta-physical sense rather than space and materials on a direct visual plane. Hence, it is imagined how it would look and then it is visualized in a three-dimensional model. With use of the plug-in, the architect is faced with some predetermined scenarios, which considers some necessary requirements (as demonstrated in Figure 18). The intuitive user-interface and the real-time representative visualizations, set a framework for a qualified and well considered decision-making process, which links the transaction from the early design to the completed building. This includes the Radar chart and the score ranking system, which signifies the benefits and disadvantages of architectural possibilities in relation to the UDI (Unified Display Interface), *indoor climate* and *energy consumption* (as demonstrated in Figures 19 and 20). Nonetheless, the concept currently ties the hands of the architect when it comes to design freedom. While the architect's expectation over the use of the tool was in overall satisfactory, the following contents were stated:

- The representative visualization is overall satisfactory, but as an architect, it is easy to imagine space and materials based solely on a rough sketch and references.

- The potential of the real-time visualized representation seems most relevant when it comes to repetitive architecture in large scale renovation projects, where the immediate impact of a small transformation is showcased in a large scale context.

- The plug-in can advantageously be used for visualization of renovation scenarios for non-architects such as building occupants or clients (as demonstrated in Figure 21). Nonetheless, a larger amount of materials and Revit families need to be included.

- The plug-in successfully negotiates the present unresolved potential of integrated design and collaboration between engineers and architects in the early stages of a renovation project.

- The plug-in indeed highlighted the great potential and fitted well within the present digitalization of the building industry and the necessity for interdisciplinary considerations.

- With further development and streamlining regarding its limitations, it can obviously be helpful for a variety of stakeholders.

6. CONCLUSION AND FURTHER STUDIES

6.1 Conclusion

Application of methodologies and methods in the early design stages for interdisciplinary collaborations in renovation projects has a significant role to cope with the multiple criteria, i.e. energy efficiency and indoor comfort together with the existing interactions and trade-offs between them. This paper described the development of a plug-in for Revit that integrates the optimal generated renovation scenarios, within BIM framework and upgrading the BIM model of the exiting building. The aim was to integrate, implement and demonstrate the potential of the plug-in. The tool enables the user (architects expected) to visualize, evaluate, compare, and enhance the optimal generated renovation scenarios further, especially to include, deal, and address the Soft (qualitative) criteria (i.e. spatial quality) beside the Hard and quantitative. However, the risk of neglecting the crucial role of the involved vital stakeholders and their relevant literacies as well as contributions in dealing with the actual conditions and details of the renovation projects that are different for every project. Development and application of such a tool promotes the iterative decision-making methodology within an integrated design – IDP schema in terms of overcoming the issues related to the barriers in renovation projects. Likewise, it serves at addressing the complexity within the modern society and is hereby a help towards time saving, improvement of the accuracy and quality of the final decision, as well as encouraging stakeholders to accommodate holistic renovation scenarios in the early design stages of the renovation projects.

Although, shifting into the BIM framework includes various advantages of using a BIM model upon all the stages of building renovation process (from design to construction and operation phases), the developed tool has its

function limited in terms of providing the required and accurate data for variety of the existing renovation approaches to be used for generation of the realistic and holistic renovation scenarios, in the early design stages. This also entails developing a structured constraint-based mechanism to explore and pick the most appropriate renovation approach to be in alignment with the exact actual condition of the existing buildings. Further, much attention is yet required to support the decision-making process for encouraging useful renovation upgrades, addressing, embracing, and evaluating further sustainability objectives such as minimization of the environmental impacts.

6.2 Further studies

Making the BIM-based DSS more streamlined regarding integration and implementation with the collaboration of a BIM expert would be advantageous. Furthermore, using and testing the tool for a larger target group of relevant stakeholders within the building industry, would provide valid input towards user acceptance and user application. This future work could likewise include upgrades in terms of automatic generation of the comma-separated-value (CSV) database by Visual Basic Application (VBA) from Excel, since Excel is esteemed by many regarding data management. It thus makes it easier to include additional renovation approaches and thus alternatives. An automatic generation of a correlated report with predefined layout and appendixes with more detailed data information would provide valid documentation within the decision-making process.

The research in future concerns implementation and automatization of the developed hybrid DSS in previous research work, into the plug-in, since the plug-in in its current version, was just developed to use the outcome of the use of the hybrid DSS including the generating scenarios. In other words, the efforts are put in place towards merging the DSS and the generating scenarios into the plug-in. In addition, it includes the evaluation of further Soft criteria and sub-criteria (i.e. human health), for the tool to become more holistic. Another interesting topic for further research is the selection and weighting of the evaluation criteria, which can also be decisive about the decision-making. There are a significant potential for application of other BPS tools as well as the use of virtual reality (VR) for further exploration of the Soft criteria, which entails further research in this field.

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APPENDIX A

Figures A1 and A2 represent the database of alternative renovation approaches, which have been used for generation of holistic renovation scenarios.

			Cost	Thickness	Lambda	U-Value	Resistance
			Kr./m2	mm	W/mK	W/m2K	m2K/W
1	A	Facade (External)					
2	A.a	Re-Insulation					
3	A.a.1	Insulation (Class 37) - 30 mm	556	30	0.037	1.233	0.811
4	A.a.2	Insulation (Class 37) - 80 mm	716	80	0.037	0.463	2.162
5	A.a.3	Insulation (Class 37) - 100 mm	780	100	0.037	0.370	2.703
6	A.a.4	Insulation (Class 37) - 125 mm	860	125	0.037	0.296	3.378
7	A.a.5	Insulation (Class 37) - 150 mm	940	150	0.037	0.247	4.054
8	A.a.6	Insulation (Class 37) - 200 mm	1100	200	0.037	0.185	5.405
9	A.a.7	Insulation (Class 37) - 220 mm	1164	220	0.037	0.168	5.946
10	A.a.8	Insulation (Class 37) - 250 mm	1260	250	0.037	0.148	6.757
11	A.b	Finish					
12	A.b.1	Brick	358	108	0.600	5.556	0.180
13	A.b.2	Plaster	90	15	0.800	53.333	0.019
14	A.b.3	Plasterboard	85	25	0.250	10.000	0.100
15	A.b.4	Wood	261	22	0.150	6.818	0.147
16	A.b.5	Cement Fibre Plates	335	13	2.000	153.846	0.007
17	A.b.6	Stainless Steel Trapez Plates	130	1	17.000	17.000.000	0.000
18	A.b.7	Copper Plates	5000	4	380.000	95.000.000	0.000
19	B	Facade (Internal)					
20	B.a	Re-Insulation					
21	B.a.1	Insulation (Class 37) - 30 mm	556	30	0.037	1.233	0.811
22	B.a.2	Insulation (Class 37) - 80 mm	716	80	0.037	0.463	2.162
23	B.a.3	Insulation (Class 37) - 100 mm	780	100	0.037	0.370	2.703
24	B.a.4	Insulation (Class 37) - 125 mm	860	125	0.037	0.296	3.378
25	B.b	Finish					
26	B.b.2	Plaster	90	15	0.800	53.333	0.019
27	B.b.3	Plasterboard	85	25	0.250	10.000	0.100
28	C	New Wall Construction					
29	C.a	Complete Walls					
30	C.a.1	Light concrete wall, 450mm, (LEC	1160	450	0.06	0.140	7.143
31	C.a.2	Light concrete wall, 350mm, (LEC	915	350	0.11	0.310	3.226
32	C.a.3	Steel wall, steelfacade(80)/plaste	2851	482	0.07	0.140	7.143
33	C.a.4	Concrete facade element, prefab	2080	455	0.06	0.140	7.143
34	C.a.5	Concrete facade element, concre	2200	370	0.04	0.120	8.333
35	C.a.6	Brick wall, Brick(108)/insulation(1	2319	416	0.07	0.160	6.250
36	C.a.7	Brick wall, Brick(108)/insulation(2	2278	478	0.06	0.130	7.692
37	C.a.8	Wood wall, plasterboard(13)/wo	1780	295	0.06	0.200	5.000
38	C.a.9	Wood wall, plasterboard(13)/wo	1813	320	0.06	0.180	5.556
39	D	Roof (Inside)					
40	D.a	Re-Insulation					
41	D.a.1	Insulation (Class 37) - 30 mm	556	30	0.037	1.233	0.811
42	D.a.2	Insulation (Class 37) - 80 mm	716	80	0.037	0.463	2.162
43	D.a.3	Insulation (Class 37) - 100 mm	780	100	0.037	0.370	2.703
44	D.a.4	Insulation (Class 37) - 125 mm	860	125	0.037	0.296	3.378
45	D.a.5	Insulation (Class 37) - 150 mm	940	150	0.037	0.247	4.054
46	D.a.6	Insulation (Class 37) - 200 mm	1100	200	0.037	0.185	5.405
47	D.b	Finish					
48	D.b.1	Plasterboard	85	25	0.250	10.000	0.100
49	D.b.2	Wood	261	22	0.150	6.818	0.147
50	D.b.3	Cement-Bond Wood Wool Plates	150	26	0.076	2.923	0.342
51	E	Roof (Outside)					
52	E.a	Finish					
53	E.a.1	Concrete tile	493	50	1.5	30.000	0.033
54	E.a.2	Red tile	608	50	1	20.000	0.050
55	E.a.3	Steel	473	15	17	1.133.333	0.001
56	E.a.4	Plywood	196	20	0.15	7.500	0.133
57	F	Floor (Inside)					
58	F.a	Finish					
59	F.a.1	Laminate	525	11	0.11	10.000	0.100
60	F.a.2	Beech planks on joits, joits(47x50	862	69	1.53	22.174	0.045
61	F.a.3	Untreated slats	883	70	1.56	22.286	0.045
62	F.a.4	Treated slats	943	70	1.56	22.286	0.045

Figure A1. *The database used for generation of renovation scenarios*

	Windows	Cost	Type	d	Ug	gg	LTg	?	Uf
	Glazing Type	Kr./m2		m	m2K/W				
1	I.a.1	1500	VELFAC Classic Træ A	0.093	0.53	0.53	0.74	0.02	1.300.198
2	I.a.2	1412	VELFAC Energy 200	0.054	0.53	0.53	0.74	0.033	1.822.852
3	I.a.3	1324	VELFAC Energy 200 Opt.	0.054	0.55	0.61	0.75	0.033	1.842.852
4	I.a.4	1236	Rolfsted Glas 3 Lags Træ/Alu	0.093	0.61	0.54	0.63	0.037	1.249.649
5	I.a.5	1148	Schüco	0.093	0.63	0.61	0.73	0.01	1.616.129
6	I.a.6	1060	Hvidbjerg Everluxx Classic	0.093	0.64	0.53	0.74	0.01	131.592
7	I.a.7	972	VELFAC Classic Træ B	0.093	1.21	0.73	0.82	0.02	1.359.779
8	I.a.8	884	Futura + I 28	0.054	1.21	0.73	0.82	0.01	2.133.748

Figure A2. *The windows database used for renovation scenarios*