Towards a BIM-based Decision Support System for rapid generation and evaluation of holistic renovation scenarios

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Abstract

Recent research in building renovation seeks methods for the development of more holistic renovation scenarios that live up to a broader set of sustainability objectives and criteria, and that are involved in the earlier stages of the design process. One decision to be made by stakeholders is what and how a renovation scenario can be developed that fulfills various types of competing criteria and sub-criteria attached to the sustainability in its whole sense such as investment cost, energy consumption, indoor thermal comfort etc. Building Information Modeling (BIM) has the potential to aid designers in providing the required geometrical and analytical data of an existing building 3D model to select and evaluate the proper type of renovation actions during the early design stage and to make decisions that have a significant impact on the life cycle of the renovated buildings.

This paper presents a methodology for the development of a BIM-based decision support system, named PARDIS (Process integrAting Renovation DecIsion Support), which generates and evaluates optimal and holistic renovation scenarios tailored towards dwellings. PARDIS supports the renovation sector with the following features: (a) optimizing the selection process of renovation alternatives, and the generation of renovation scenarios, through specific renovation typologies and constraints, (b) evaluating standard sustainability Key Performance Indicators - KPIs (e.g. energy consumption, investment cost, indoor thermal comfort, indoor air-quality etc.) over the generated renovation scenarios, as well as (c) visualizing the generated renovation scenarios for ease of comprehension by the designers, and for enabling discussion between expert stakeholders (i.e. architects, engineers, contractors etc.) and non-expert stakeholders (i.e. building occupants, owners etc.). As such, PARDIS supports informed decision making in early design for the development of optimal renovation scenarios. The first prototype of the PARDIS Revit plug-in is demonstrated in this paper and empirically evaluated on a large apartment block in Denmark). Likewise, the tool's outcome is explored through a focus group workshop with practitioners in Aarhus, Denmark. For further clarification of the potential use of PARDIS related to the studied case, the tool's application is discussed with three BIM specialist-architect engineers (from different consultancy corporations).

Keywords: Sustainable Building Renovation, Holistic Renovation Scenarios, Decision Support Systems (DSS), Integrated Design (ID), Building Information Modeling (BIM).

1. Introduction

Research on the barriers for building renovation in Denmark has revealed that an important obstacle is a lack of simple and holistic tools that can assist stakeholders in prioritization and decision-making during the early stages of building renovation projects (Jensen et al., 2015). In developing renovation scenarios through an integrated schema in early design stages (Kamari et al., 2017a), designers and especially architects tend to look for different design solutions before going in depth into one fixed theme of solutions However, engineers are much more likely to be content with finding one possible solution and sticking to it without investigating other possible solutions that might be valuable (Akin 2001). According to Rice (1996), once a solution appears to solve the problem for an engineer, she/he is not willing to change it. Rice (1996) adds that it is characteristic for engineers to come to only one conclusion in design since they are working with objective parameters. On the other hand, contractors and owner preferences embraces a rapid exploration of various concepts and solutions in terms of budget and period, primarily focusing on the construction cost and construction period.

This paper presents a methodology for the development of a BIM-based decision support system (BIM-based DSS), named PARDIS (Process integrAting Renovation DecIsion Support), which can be used in an integrated renovation design schema (2019a) to generate and evaluate optimal and holistic renovation scenarios for the renovation of dwellings. PARDIS is structured to support the renovation sector with the following features:

a) optimizing the selection process of renovation alternatives, and the generation of the renovation scenarios, through the use of specific renovation typologies and constraints,
b) evaluating standard sustainability Key Performance Indicators - KPIs (e.g. energy consumption, investment cost, indoor thermal comfort, air-quality etc.) over the generated renovation scenarios,
c) visualizing the generated renovation scenarios for ease of comprehension by the designers, and for enabling discussion between expert stakeholders (i.e. architects, engineers, contractors etc.) and non-expert stakeholders (i.e. building occupants, owners etc.) towards making an informed decision about the most appropriate and optimal renovation scenario in a short time frame.

Building Information Modeling – BIM (Eastman et al., 2011) aids designers by providing salient 3D geometric and analytic data about the building, thus enabling designers to select and evaluate renovation actions during earlier stages of design, and to make decisions that have a significant impact on the life cycle of buildings under renovation. While shifting into the BIM framework encompasses various advantages of using a BIM-model (Becerik et al., 2010) upon all the stages of the building renovation process (from design to construction and operation phases), development and application of a BIM-based DSS (Nielsen et al., 2016; Volk et al., 2014; Schlueter et al., 2009; Jalaei et al., 2015; Kim et al., 2015; Kamari et al., 2018a,b) can specifically be exploited during the early design stages of renovation projects where a decision has a strong impact throughout the rest of the process and thus final decision-making. As such, it increases the likelihood that the owners' project goals will be met and streamlines the stakeholders' communication, collaboration, and cohesion, towards facilitation and development of holistic, optimal, and sustainable renovation solutions in a significantly reduced period.

The key contribution in this paper is the development of a plug-in for Autodesk Revit that architects or engineers can use on an existing BIM-model to invent, animate, and assess the enormous number of potential renovation scenarios, through an integrated design schema. After selecting a renovation scenario, the PARDIS Revit plug-in is intended to demonstrate the scenario by proposing the renovation changes in preparation to support the decision process. This paper builds upon our previous work related to the ReVALUE[1] research project concerning the development of a rapid constraint-based renovation design support framework through the application of a formal (logic-based) domain specific renovation modeling language (see Phase 2 in Figure 1), that enables architects and engineers to readily express their project-specific renovation design space at a range of abstraction levels. In this paper, the first prototype of the PARDIS Revit plug-in system is demonstrated and empirically evaluated on an apartment block that is renovated as phase one in an extensive transformation of a larger residential area in Aarhus, Denmark.

[1] http://revalue.dk./?page_id=196

2. Methodology

Revit dominates the Danish market based upon a survey made by BIPS (2015), and therefore is selected as the platform for development of the PARDIS. The developing plug-in is intended to rapidly generate and evaluate optimal and holistic renovation scenarios for the renovation of dwellings. In addition, the most suitable user or pilot for the tool is considered to be an Architect or Architect Engineer who is a Revit-user. Figure 1 presents the development process of PARDIS through an implementation of six specific activities or tasks as well as the tool executing process phases. The map is drawn based on a set of core elements according to the Business Process Modelling Notation – BPMN[2]. It therefore includes the tool application and executing process. The information about the implementing activities or tasks have briefly been presented in Figure 1, and the activities' focus is implementation of the tool's main programing or code blocks using the Revit Application Programming Interface (API) and Software Development Kit (SDK), besides Visual studio and C# programing. The tool executing process encompasses one plus seven (1 + 7) phases. Each phase is briefly described below.

Phase 0 requires the development of as-built 3D BIM-model of the existing building in Revit. The 3D model includes the basic elements of buildings (such as walls, windows, floors etc.), where the quantity, size, shape, location, and orientation of the element as designed can be measured directly from the model without referring to non-modeled information such as notes or dimension call-outs. According to the "2019 Level of Development - LOD Specification" released by BIMForum (2019), the requirements for development of the as-built 3D BIM-model for the application of the developing tool in this paper in Revit needs to be aligned with a BIM LOD 300 (for further info. see BIMForum, 2019).

Phase 1 comprises the extraction of the required data from the developing 3D BIM-model in Phase 0. The data consists of essential geometry information that later are exploited to calculating, i.e. the investment cost or energy consumption when running simulation on the generating renovation scenarios. The data such as the heated floor area, the exterior wall area, the windows area, the roof area, the height of the building, the orientation etc. This is done by firing-up the tool within the Revit, and picking-up a room or apartment. The extracted data are displayed in the tool, which enables the user to control them constantly. Figure 2 demonstrates the tool's user interface developed as a plug-in to Revit.

Phase 2 embraces the system for the generation of holistic renovation scenarios. The term 'holistic renovation scenario' in this paper is adopted from (Kamari et al., 2018c). It serves to underline a holistic approach where various renovation objectives (i.e. energy consumption, indoor thermal comfort etc.) linking to the sustainability in its full sense (Kamari et al., 2017b) are achieved in a balanced way, through the development of a renovation scenario. A 'renovation scenario' refers to a set of particular design changes that will be made to a building, e.g. replacing all north-facing windows with triple glazing, adding a new cladding system (i.e. composite panels), and HVAC equipment.

Figure 3 illustrates the workflow of the scenario generation system that has been discussed and presented by the authors in (Kamari et al., 2019b,c), on the development of a rapid constraint-based renovation design support framework through the application of a formal (logic-based) domain specific renovation modeling language, named NovaDM (Kamari et al., 2018d). First the design team specify the (a) project-specific renovation alternatives in the form of a NovaDM action tree, (b) renovation scenario constraints, and (c) the BIM-model of the design to be renovated. The scenario generator parses the action tree into Answer Set Programming (ASP) facts and generates (optimal) scenarios that are consistent with the given constraints using the ASP reasoning engine Clingo (Gebser et al., 2016).

In addition, the scenarios are built on the basis of different constraints, primarily related to the renovation depths and level of interventions that illustrate the impact of different ambition levels concerning the European environment and economy (TECNALIA, 2015; EU, 2016). The depth of renovation refers to the extent and size of measures applied, as well as to the level of resulting energy and emissions reduction. It is used to generate scenarios with various depths of renovation including *Minor*, *Moderate*, *Deep*, and *Nearly Zero Energy Building – NZEB.*

[2] https://cloud.trisotech.com/bpmnquickguide/

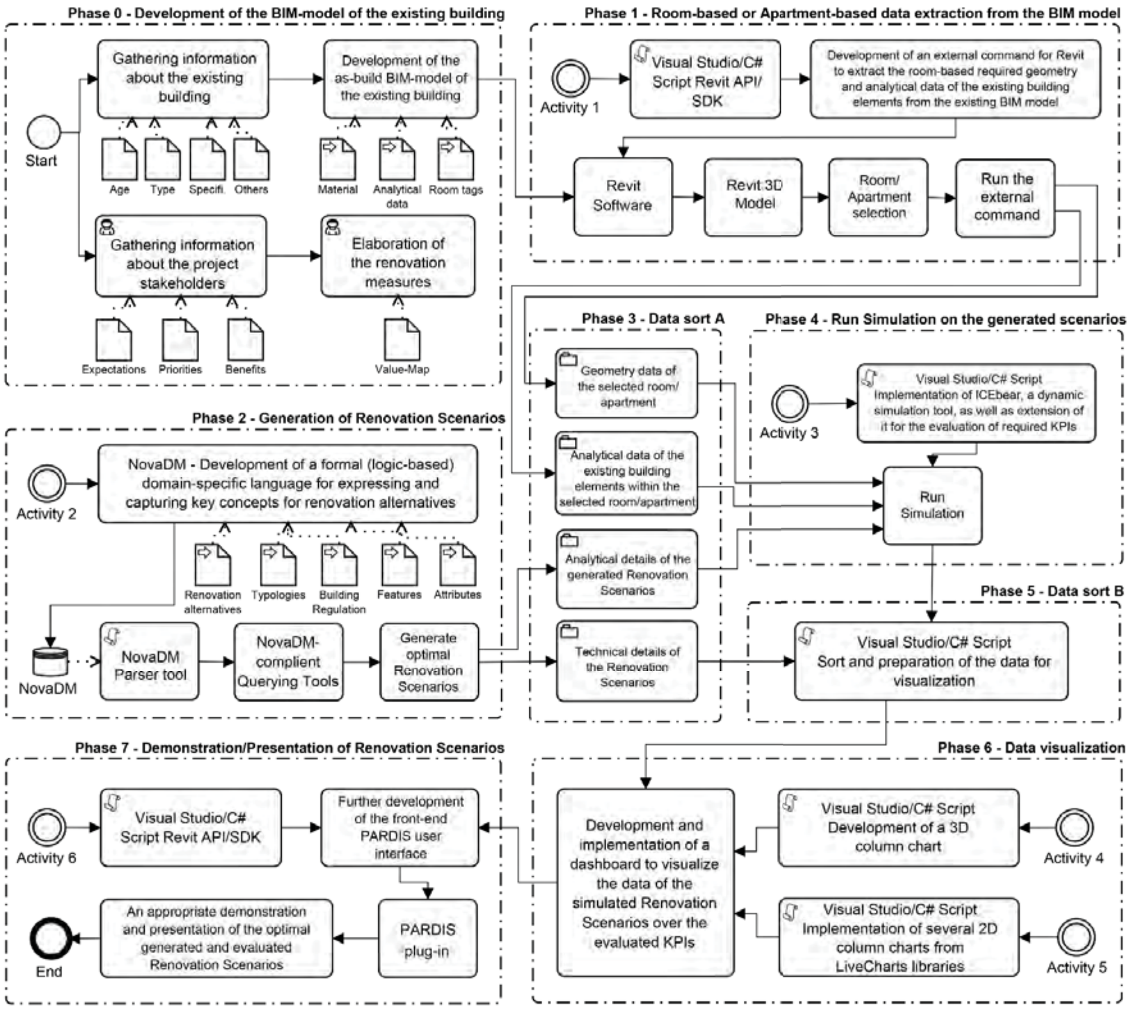

Figure 1. The development process of PARDIS as a plug-in to Revit

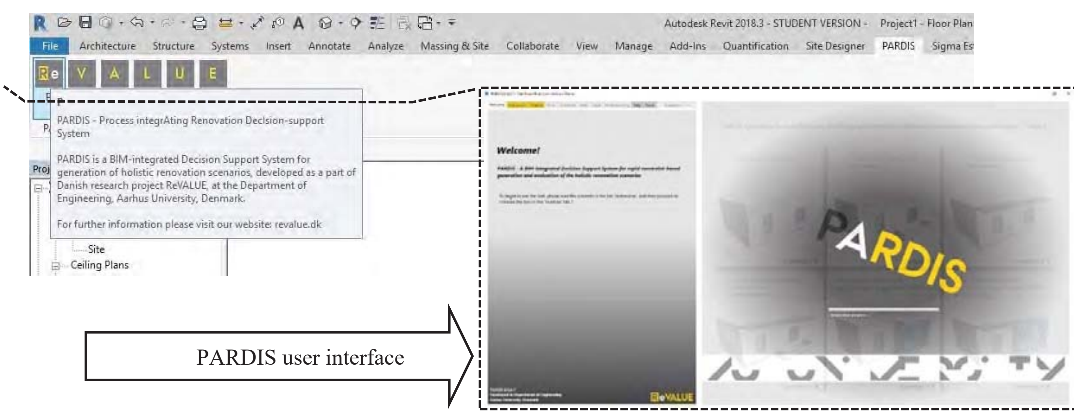

Figure 2. The PARDIS front-end user interface developed as a plug-in to the Autodesk Revit[3]

The second level of constraints link to the typologies of the existing building according to TABULA (2015). Likewise, the third level of constraints target the architectural aspects and the

[3] A video of the PARDIS first prototype can be watched in the following link: https://www.youtube.com/watch?v=u7ITPqlAiVE&feature=youtu.be

appearance of the renovation scenario (Boeri et al., 2014), especially related to the buildings' facades.

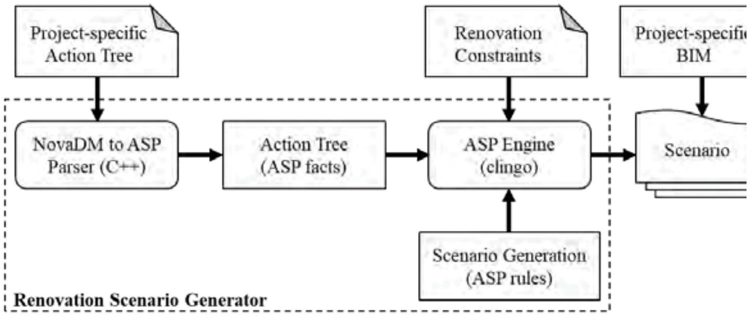

Figure 3. Workflow of the renovation generation system

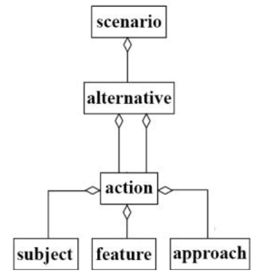

Figure 4. The relationships between concepts in NovaDM

As demonstrated in Figure 4, the scenarios are structured through the use of various layers and concepts including: *Renovation Approach*: the way that the subject will be renovated, e.g. repair, replace, remove, refurbish, or modify; *Renovation Feature*: the aspect of the subject being renovated, e.g. window frame material. Features have types (e.g. material) and values (e.g. fiberglass, uPVC, etc.); *Renovation Action*: an instance of a subject, an approach, and a set of feature types and values, e.g. "window frames will be replaced with fiberglass material"; *Renovation Alternative*: the set of (mutually exclusive) actions for a given subject, e.g. all the ways that windows can be renovated according to the specified approaches and features; *Renovation Scenario*: a set of actions such that each action belongs to a different alternative, e.g. one action for windows and one action for floors.

For each renovation project, the design team needs a way of specifying the particular subjects, features and approaches that are available. For this, a formal action tree language for compactly specifying sets of actions is developed (adopted from Kamari et al., 2019c). Each action tree (see Fig. 5) corresponds to a renovation alternative. Traversing an action tree corresponds to generating an action in a scenario, starting from the root node. Each node assigns zero or more aspects (subject, feature or approach) to the action. Tree nodes can be either xor-nodes "-" (meaning that the current action must be built by traversing exactly one child), or and-nodes "+" (meaning that the current action must be built by traversing all children).

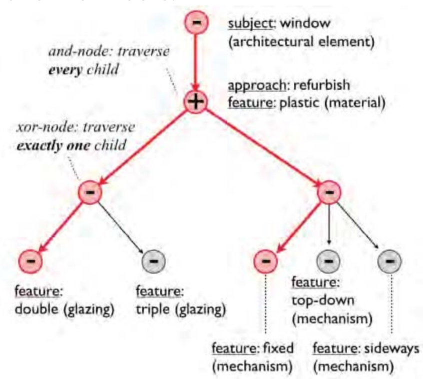

Figure 5. A NovaDM action tree

Phase 3 focuses on customizing and sorting the data outcomes from the Phases 1 and 2. Hereafter, the geometry information and the generating scenarios' data are customized and prepared to pipe into the simulation tool in the next phase.

Phase 4 includes the use of an extended version of the hourly dynamic simulation tool ICEbear. Each generated scenario in Phase 2 is then evaluated according to user-specified sustainability Key Performance Indicators - KPIs such as energy consumption, indoor thermal comfort, daylight comfort etc. 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. It is based upon algorithms for auto-generating hourly building performance data at a room level basis. Table 1 summarizes the evaluating KPIs for generated renovation scenarios in this study.

Phase 5 focuses on customizing and sorting the data outcomes from the Phases 3 and 4. Hereafter, the technical details of the generated scenarios besides the outcome of the running simulation on the generated scenarios pipe into the visualization dashboard in the next phase.

Phase 6 consists of the data visualization dashboard for the mentioned evaluating KPIs. It includes one Interactive 3D bar chart custom control in WPF, besides several basic row, dynamic column charts.

Table 1. Outline for the selecting KPIs for evaluation of the generating renovation scenarios

KPIs	***Evaluation [value measurement]***
Energy consumption (Danish Energy Agency, 2017)	Reduction of energy consumption for heating measured in kWh/m2/year [less better]
Energy frames defined in BR18 (Danish Building Research Institute,2017)	Renovation energy classes (I and II) in kWh/m2/year [less better]
Indoor Thermal Comfort (Dansk Standards, 2007)	% in Class I, II, III according to EN 15251 [bigger better]
Discomfort hours above 27 and 28 (°C) (Dansk Standards, 2006)	Number of hours [less better]
Indoor Air Quality – IAQ (Dansk Standards, 2013)	% out of Class III according to EN 15251 [less better]
Investment Cost, (Molio, 2016)	Price of the procurement in DKK (Danish Krone) [less better]
DF (daylight factor), (VELUX, 2016)	$0<DF<5$ [bigger better]
Daylight according to BR18 (Danish Building Research Institute, 2017)	$\% \geq 10$ [bigger better]
View-out quality and Degree of privacy	% of openings area on façade regarding adjacent buildings [client dependent]
Degree of Satisfaction, (Xu et al., 2018)	% regarding effects of building space and thermal and luminous environments on satisfaction with Indoor Environment Quality – IEQ. [bigger better]
Health & Well-being, (Norback et al., 2014)	% regarding Energy improvement, indoor thermal comfort, air quality and their effects on Asthma, Allergy, and Eczema diseases [bigger better]

Phase 7 focuses on a suitable demonstration and presentation of the generated and evaluated scenarios ensuring that the outcomes are easy to be read, understood, and exploited in an actual renovation context by the involved stakeholders.

At the time of writing the present paper, the first six phases of the tool have been developed and implemented, and we are currently developing Phase 7 by interviewing and collecting data from the active practitioners within three leading architecture and engineering consultant corporations in Aarhus, Denmark.

3. Case Study – Residential Danish Buildings

In this section we present a case study where we empirically evaluate the PARDIS tool by applying it to real renovation tasks. The selected case study is a competition entry for renovation of an apartment block located in Aarhus, Denmark (see Figure 6). The apartment block is one of three so-called pilot projects, which are renovated as phase one in the extensive transformation of a larger residential area.

Figure 6. The apartment's section plan, east and west elevations located in Aarhus, Denmark

The competition call included renovation of the building envelope, bathrooms and staircases, transformation of the ground and first floors into new two-storey dwellings as well as the addition of new dwellings above a road "cutting through" the building. For the explanatory purpose of this paper, we focus on the renovation of one representative dwelling. The target budget for the renovation of the building block was 92 million Danish kroner.

For renovation purposes in this case study, after conducting some meetings with a team of architects, engineers, and clients finding out about their priorities besides following the regulations from the municipality of the region, the tool was firstly used for preliminary evaluation of what possible renovation approaches can be included in the developing renovation scenario that meet the initial budget. That especially encompassed the renovation of roof, balcony, stairs, and new HVAC equipment, beside renovation of the façade. Next, the tool was used to generate four renovations scenarios, each relevant to different level of intervention (or so called *minor, moderate, deep,* and *NZEB* – see TECNALIA, 2015), investigating their cost, which we refer to *investment cost*.

In order to evaluate PARDIS and the data visualization approaches, we conducted a workshop with a focus group of eight practitioners from three large scale architecture consultancy companies, AART architects, Friis & Moltke, and Cebra, in Denmark. As such, the tool's outcome was presented through three visualization prototypes, a *Bullet graph*, a *Radial Chart*, and a *Heatmap.* Figure 7 demonstrates the visualization prototypes.

Participants reported that PARDIS was helpful so as to increase the awareness of the involved parties via demonstration of the *energy efficiency* (or *reduction of energy consumption), indoor thermal comfort,* and *indoor air quality* evaluation of the renovation scenarios. After the architects developed entirely new interior designs, after exploring the previous architects' proposals and adding the required changes to the existing 3D model, PARDIS was particularly used and was considered very helpful for providing a comparison addressing the *degree of privacy, degree of satisfaction, daylight condition*, and the scenarios' contribution towards creating a more *healthy* environment. The strong point about the tool application in this experience was speed towards generating and evaluating the various renovation scenarios. While the BIM specialists' experience with the tool into the current design process was overall satisfactory, the following points were stated:

- Due to the fact that the application of PARDIS and similar conceptual tools is not very commonly experienced in the current practice of renovation, it is difficult to evaluate how best it can improve the context
- The outcome as the demonstration of evaluating KPIs needs further development to support the decision into the process
- The tool is yet unable to respond to the architectural needs and alterations regarding the need for form and geometrical changes
- The fact that the tool is capable of conceptualizing and generating renovation scenarios in a very short time (max five minutes per generation and evaluation of 50 renovation scenarios per each case) is very strong and desirable aspect
- The tool successfully negotiates the present unresolved potential of integrated design and collaboration between architects, engineers, contractors, and owners in the early stages of a renovation project
- The tool should provide a comparison result for the generating and evaluating scenarios between two or more different apartments
- With further development and streamlining regarding its limitations, the tool can significantly support the involved stakeholders in the renovation process

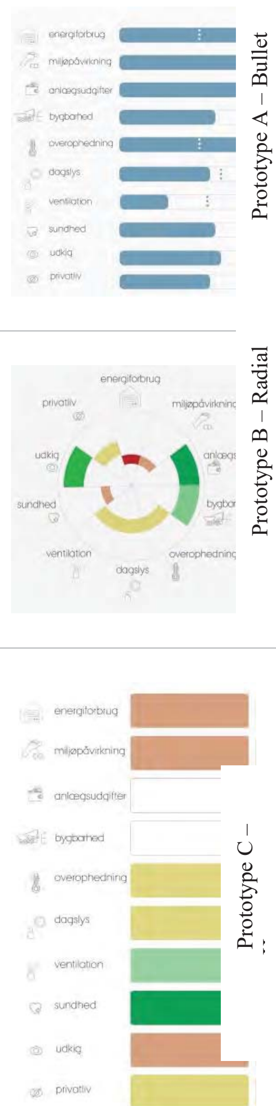

Figure 7. PARDIS visualization prototypes

4. Conclusion

This paper presented an overview of a BIM-based DSS named PARDIS for rapid generation and evaluation of the holistic renovation scenarios. PARDIS can specifically be exploited during the early design stages of renovation projects where a decision has a strong impact throughout the rest of the process and thus the final decision-making. As such, it increases the likelihood that the owners' project goals will be met and streamlines the stakeholders' communication, collaboration, and cohesion, towards facilitation and development of holistic, optimal, and sustainable renovation solutions in a shorter period. Although the tool has been developed for the renovation of dwellings or residential buildings, the flexible employed database can be extended further to include extra renovation approaches and parameters to be applied for other building types, i.e. offices or commercial buildings.

PARDIS is a significant departure from existing optimization approaches in renovation design. Existing approaches and systems tend to deliver a small number of similar, optimal designs with no intermediate layers of abstraction, and no support in analyzing and exploring the diversity of the design space. In future work we will extend PARDIS to support renovations that change the building morphology under constraints (Kondyli et al. 2017; Schultz et al. 2017) and spatial reasoning (Walega et al. 2017; Bhatt et al. 2012; Bhatt et al. 2011).

An important limitation of this research is that the tool has only been tested on a few renovation cases, and regarding the Danish context, and this is a certain aim in the future research work. In addition, the future research work concerns examination, studying, and surveying of the actual renovation context improving the PARDIS user interface especially the demonstration and presentation of the generated and evaluated renovation scenarios where the involved stakeholders and on the top of that design team is enabled to read, understand, and use the outcomes sophistically and appropriately.

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