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Visualisation of KPIs in zero emission neighbourhoods for improved stakeholder participation using Virtual Reality

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Abstract. This paper addresses the role of virtual reality in addressing the specific challenge of the increasing complexity and decreasing usability when dealing with the level of detail required to model a zero emission neighbourhood (ZEN).[1] In such neighbourhoods, there is a need to handle both ‘top down’ neighbourhood level data with ‘bottom up’ building and material level data. This can quickly become overwhelming particularly when dealing with non expert users such as planners, architects, researchers and citizens who play a key part in the design process of future ZENs. Visualisation is an invaluable means to communicate complex data in an interactive way that makes it easier for diverse stakeholders to engage in decision making early and throughout the design process. The main purpose of this work has been to make ZEN key performance indicators (KPIs) more easily comprehensible to a diverse set of stakeholders who need to be involved in the early design phase. The paper investigates how existing extended reality (XR) technologies, such as virtual reality, can be integrated with an existing dynamic LCA method in order to provide visualise feedback on KPIs in early phase design of sustainable neighbourhoods. This existing method provides a dynamic link between the REVIT Bim and the ZEB Tool using a Dynamo plugin.[2] The results presented in this paper demonstrate how virtual reality can help to improve stakeholder participation in the early design phase and more easily integrate science-based knowledge on GHG emissions and other KPIs into the further development of the user-centered architectural and urban ZEN toolbox for the design and planning, operation and monitoring of ZENs. [3]

1. Introduction

In the future, municipalities must handle a completely different level of complexity in society. In order to have well-functioning cities, cities must improve how they utilise their resources and how they engage with technologies in different ways. A smart city will use digital technologies to enhance performance and wellbeing, to reduce costs and resource consumption and to engage more effectively and actively with its citizens. In this context, the



objective of this work is to investigate how visualisation methods, such as, Virtual reality (VR), can support the evaluation of zero emission neighborhood (ZEN) and zero emission building (ZEB) design concepts with respect to key performance indicators, such as, greenhouse gas emissions and other potential environmental impacts. [4, 5] The aim is to evaluate how virtual reality can help communicate, involve and improve participation from diverse stakeholders involved in the ZEN design process including politicians, municipality planners, design/planning practitioners, and citizens.

Current methods for visualizing semantic information are mostly limited to coloured map overlays, 2d and 3d-graphs or values spread across maps. The potential of using Immersive technologies, such as VR to enable users to explore and interact with real design projects is investigated in this paper, as well as, the extent to which it can be used for the planning of complex infrastructures and the visualisation of multiple key performance indicators (ZEN KPIs). This VR approach is particularly of interest to diverse experts and decision-makers in order to provides them with the means to explore results early in the design phase and on-site. Full details related to the research presented in this paper can be found in Løvhaug and Mathiesen. [6]

1.1. ZEN Definition, KPIs and pilot project

1.1.1. ZEN Definition and ZEN KPIs

The vision of the ZEN Research Centre, together with its industrial partners, is to create zero emission neighbourhood in smart cities (ZEN). [1] In the ZEN Research Centre, a neighbourhood is defined as a group of interconnected buildings with associated infrastructure, located within a confined geographical area. A ZEN aims to reduce its direct and indirect greenhouse gas (GHG) emissions towards zero over an analysis period typically of 60 years, in line with a chosen ZEN ambition level with respect to which life cycle modules, buildings, and infrastructure elements to include. The ZEN assessment criteria and key performance indicators are divided into seven categories (GHG emissions, energy, power/load, mobility, economy, and spatial qualities), and each of these categories is divided into several assessment criteria. [4] The assessment criteria are then divided into several key performance indicators (KPIs) which are listed in Appendix A.

1.1.2. ZEN Pilot projects

In the context of the ZEN Research Centre, pilot projects are geographically limited (primarily urban) areas in Norway and serve as innovation hubs where researchers, building professionals, property developers, municipalities, energy companies, building owners and users, test new solutions for the construction, operation, and use of neighbourhoods in order to reduce the greenhouse gas emissions to zero on a neighbourhood scale [4]. Various stakeholders will have different influences on a ZEN pilot area at different times during the development of the area. In this case, key stakeholders include Trondheim municipality and the project owner NTNU, as well as, other stakeholders. The pilot site at Nidavoll Skole [7] in Sluppen is located in the larger ZEN pilot project called The Knowledge Axis [8] and culminates in Sluppen, a mainly commercial area that is planned to be developed into a multi-functional neighbourhood.[9]

1.2. Virtual Reality

There exists a variety of techniques, tools and technologies for displaying data using diverse media. Examples includes 2D-based screens like traditional desktop applications, tablets or interactive multitouch solutions. On the other hand, there are more immersive tools which are covered by the term Extended Reality (XR), which is an umbrella term to refer to all real-to-virtual combined environments such as Augmented Reality (AR) and Virtual Reality (VR). While more traditional user interfaces like desktop applications which are more advantageous when displaying and navigating through large quantities of text-based data, whereas XR is more suited to creating an experience for the user. Solutions span from showing information on a tablet, to strapping the user into a haptic suit with a head mounted display. Due to the immersive effect of head-mounted displays, the user can interact with the data in a way that is limited in desktop-applications. For this project, it was decided to further explore the possibilities of visualizing data using VR. In recent years, the main focus for VR has been centred around the entertainment industry. This focus has driven the innovation in the field where different manufacturers are promising better and cheaper solutions, and has also made the technology available for consumers. There has been a large increase in technologies allowing for users to interact and alter a virtual environment, and technologies suited for immersive experiences.

Virtual Reality is a computer-generated experience which takes place in an virtual environment. Normally the user wears a head mounted display (HDM) with two individual images for both eyes, creating a depth perception. The HMD is tracked by either itself (inside-out) or sensors in the room (outside-in). This allows the application to mirror the position of the user in the real world, in the virtual world. The user can interact with the environment by using speech, hand-tracking, eye-tracking or input devices, where the most common is a form of controller which is tracked in all directions, mimicking the user's movements. VR technologies are potentially groundbreaking for visualising data and creating an experience for the user. It is now possible to not only showcase the data and environment on a 2D screen, but also put the user in the actual environment itself. Combined with different techniques of data visualisation, the overall aim is to leave an impression on the user, as found in a study from University of Maryland where their results showed that participants remembered on average 8.8% more of information presented in VR.[10] By using existing floor plans one has the ability to create a digital twin of the buildings. With this 3D-model one have the ability to re-create a realistic replication of the environment with connected information displayed on and around the 3D-model. In addition to the data visualisation, it is also possible to display the building in a realistic way before the building is even constructed. This use case can make it easier to communicate data and engage diverse stakeholders early in the design process. There are several VR products available, all in different price-ranges which can be defined in two sub-categories; low- and high-end.

The focus of this paper is on the results using high-end VR involving the development of the HTC Vive [11] for use in our application using the Unity 3D software[12] which works well with all known VR headsets and controllers supporting OpenVR. The reason for choosing the HTC Vive was also because of its availability and ease of use. As opposed to the low-end sub category, this kind of equipment is in general more expensive. While the application relying on the low-end equipment can be tried at home, the high-end solutions often needs to be made available for user at for example stands or promotional events. The technology needed to fulfill the requirements in the high-end sub category varies depending on the application. For less intensive tasks, it can suffice to use with a mid-range desktop computer, but for applications which demand more processing power, it is recommended to use a top of the line GPUs. VR head mounted devices (HMDs) have seen rapid development, which initially was mostly driven by the fast hardware iterations of the smartphone industry. The current wave of VR devices began with the Oculus Rift Kickstarter campaign in 2013 accumulating close to 2.5 US dollars in pledges.

Table 1 Development of of VR devices based on popular HMDs

Date	Description	Resolution per Eye	Horizontal View	Features
3.2013	Oculus Rift DK1	640x800	90	only 3 DoF tracking
7.2014	Oculus Rift DK2	960x1080	90	
4.2016	Oculus Rift CV1, HTC Vive	1080x1200	90	
10.2017	WMR Lineup	1440x1440	90	inside-out tracking
4.2018	HTC Vive Pro	1440x1600	90	
2.2019	Pimax 8k	3840x2160	170	

2. Method

2.1. Research Method

The Design Science Research [13] has been used in this research and focuses on three different cycles, as explained by Hevner [14]. This includes the *relevance* cycle, *rigor* cycle and *design* cycle. In short, the *relevance* cycle ensures that the result of the research fits into the intended usage area. The *rigor* cycle aims to ensure that the research is representative of the 'state-of-the-art' in the application domain. Finally, the *design* cycle facilitates a development process which consists of several iterations with rapid evaluation.

The prototype used in this research is the ZEN pilot project at Nidarvoll Skole [7] as the main design project, and gives the user the ability to view the pilot project from both a building- and neighbourhood perspective. The embodied carbon data is gathered from an Excel based tool called The ZEB Tool [15]. The pilot project is in a very early stage of design and since there is limited available data, the data used in the prototype is based on another school named Østensjø School in Oslo. There are also limitations regarding to the availability of a 3D model, however, by using existing building plans, an initial Revit model of the main building has been created. New models will be added to the system in the coming months. By using this project for the ZEN VR application, the results from retrofitting and new buildings with data from early phase design can be compared to data from different stages of design to visualise how different design or materials changes impacts the different KPIs in a design project.

2.2. *Data Source and LCA Method*

This work builds upon the work already developed by Houlihan Wiberg together with students to develop a visual LCA method, using a user interface in the form of a dashboard, connected to an integrated dynamic Revit 3D and the ZEB Tool [16, 17]. In this initial version of the developed VR software, the focus is on visualizing the KPIs related to carbon embodied in the production, transport, and replacements of building materials. The embodied carbon data from the ZEBTool [15] is stored together with data from other sources in a MySQL database which is specifically developed for the purpose of structuring and storing building LCA studies in a comparable and accessible format [18], so that the data can be used in applications such as the one presented in this paper. This solution allows easy online access and ensures that the user is always presented the most up to date information and that it is easy to add new information relevant for the application. Furthermore, the database has a set of additional building LCAs which are used to set reference values when benchmarking the results of the case study. In order to be able to run the application offline, the application has a local copy of the database which it used when there is no database connection.

2.3. *User study and questionnaire*

The VR application and its potential was evaluated through the use of semi-structured expert interviews and its usability, through a questionnaire. The participants of these two methods of data collection test the application on the same terms, with a set of predefined tasks. These were conducted in order to answer the research questions. The strategy for obtaining informants used was primarily the snowball technique. To evaluate the user interface and ascertain the degree of usability when using the system, a questionnaire was designed. The questionnaire was designed after the principles of a Likert scale. The general methodology used when conducting the user study has been semi-structured expert interviews which allows one to get the chance to ask the informant specific questions, but it also allows for unexpected turns. There were three participants in each of the interviews including the informant and two of the authors of this paper which allowed for one to lead the interview and the other to take notes on essential parts of the interview. However, the main collection of data were audio recordings that were later transcribed. A detailed description of the user study and questionnaire methodology may be found in Løvhaug and Mathiesen [6].

2.4. *3D Model – Unity Software - VR*

For the visualisations to be as realistic as possible, the buildings are exported from the BIM software Revit [19]. The models are then converted Autodesk Maya [20] before importing them into the Unity 3D, because when Revit exports 3D models, it does not use a naming convention resulting in some building elements end up being unnecessarily detailed, making the app run slow. The choice of using BIM models in the application ensures that the building models are directly linked to the work of the architects, and visualisations can therefore be part of an iterative design process.

3. **Results**

The preliminary results in this paper describe the application prototype, and the informal and rapid feedback from user testing in order to visualise ZEN KPIs and improve stakeholder participation early and throughout the design process. The results provide a way to visualise a selection of KPIs from the actual ZEN pilot projects at different levels of detail. Non-expert users of the application can see how this neighbourhood is performing compared to

other projects in the vicinity. It is also possible to walk around the neighbourhood, inspect individual buildings and identify which building components and materials are the highest driver of emissions. The application also has the flexibility to add new KPIs when more data becomes available for each pilot.

3.1. VR Application Overview

The Research Centre on Zero Emission Neighbourhoods in Smart Cities have defined a set of assessment criterias and key performance indicators which are used to track, evaluate and validate the progress of ZEN pilot areas. The developed prototype builds upon existing work conducted at the Fraunhofer Research Centre in Singapore, where several different VR and AR-applications have been developed, one of which is used to assist the Housing and Development Board in Singapore. [21] This application utilizes VR in a way that correlates with the vision of the end product of our research. The application aims to visualize data for the Nidarvoll site in light of a selection of these predefined criterias. In order to achieve different levels of detail, a three layered model with the following views which were developed in the VR application as shown in table below:

1. Full

view

This view displays all available projects in the Sluppen area. The map of the neighbourhood and surrounding area are put on a table-surface and the user have the ability to get an overview of the whole area. Relevant KPIs for this view would be aggregated values from all buildings and other high level high level KPIs such as mobility, economy and energy efficiency.

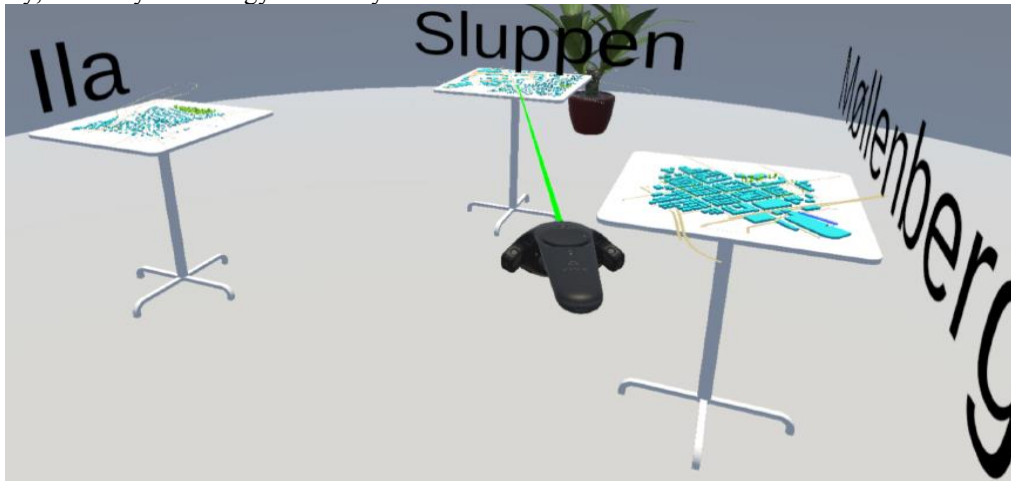


Figure 1. Full View of the Sluppen area Using VR

2. ZEN-view

When selecting a specific pilot project in the full view the user gets transported down one layer, and is presented with the ZEN view. In this view the user stands in a small scale model of the environment and have a ability to teleport around and inspect each part of the neighbourhood. The user can, to begin with toggling between two different KPIs i.e. GHG emissions and energy consumption/generation. Emission values are presented as either a colorisation of the buildings or a column visualisation, both of which have a possibility to be further developed in the future. For comparing the score of the buildings in the neighbourhood, the user has two options: 1) evaluate the buildings total CO_2eq/m^2 compared to the total CO_2eq/m^2 for all buildings present in the pilot area. 2) Evaluate the buildings total CO_2eq/m^2 compared to the total CO_2eq/m^2 for all buildings that are present in the database. To put these numbers into context and to engage the user, it is possible to visualise the weight of the CO_2eq emissions in terms of vehicles most users are familiar with using images of airplanes and cars. In addition, it is possible to get an explanation as to what the emission equals in kilometers driven in cars and round world trips in airplanes. This is shown on the left in Figure 2. Energy is visualized as a bar which displays energy consumption versus energy production for each building. The user will also be able to see the sum of consumption and generation. In the next stage of development, when the energy KPI has actual data, the user would be able to get examples of feedback for energy usage.

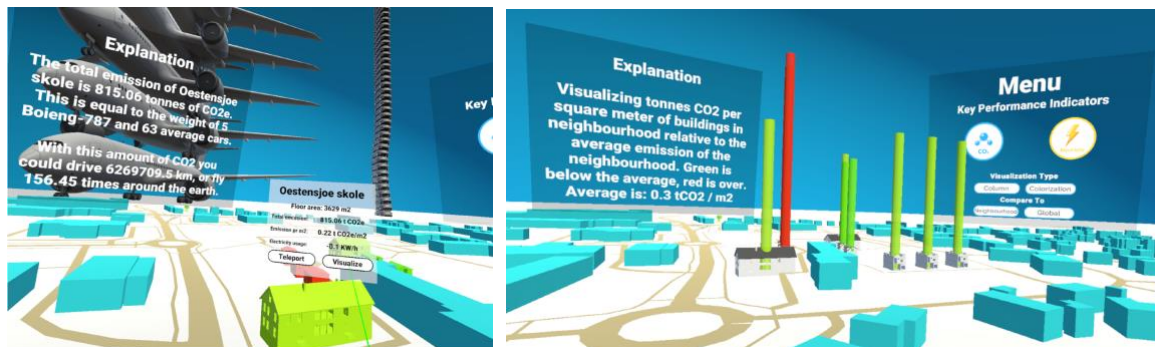


Figure 2. Snapshot in ZEN View of the Sluppen area using VR to visualise emissions of buildings

3. ZEB-view

If the user selects one specific building in the ZEN view, they teleport down to the ZEB-level (Building level). This view focuses on one particular building, and serves the purpose of communicating the KPI GHG-emissions for both each building part and every material in said building part. This view has two models; one 1:1 model where the user can teleport inside and experience/inspect the building. The other is a “dollhouse”-model where the user can inspect and interact with the building by clicking on building parts. The user is also presented with a menu for toggling between different building parts. The KPI score is visualised using colourisation similar to the ZEN-view. The user can choose two different approaches; the first compares the performance of each building part to the total emission of the building. The second approach weights the building mass as part of the equation and returns a score based on both the emission and building part mass compared to total building mass. If the user selects one specific part, they get presented with material information in tabular form for the selected element. In addition to the tabular form, the materials used will be visualised in actual size and weight so the user can put the quantity of materials into context. The intensity of the emission is visualized by using the same columns from ZEN-View. The purpose again is to give the user a more immersive experience and to put the numbers into context.

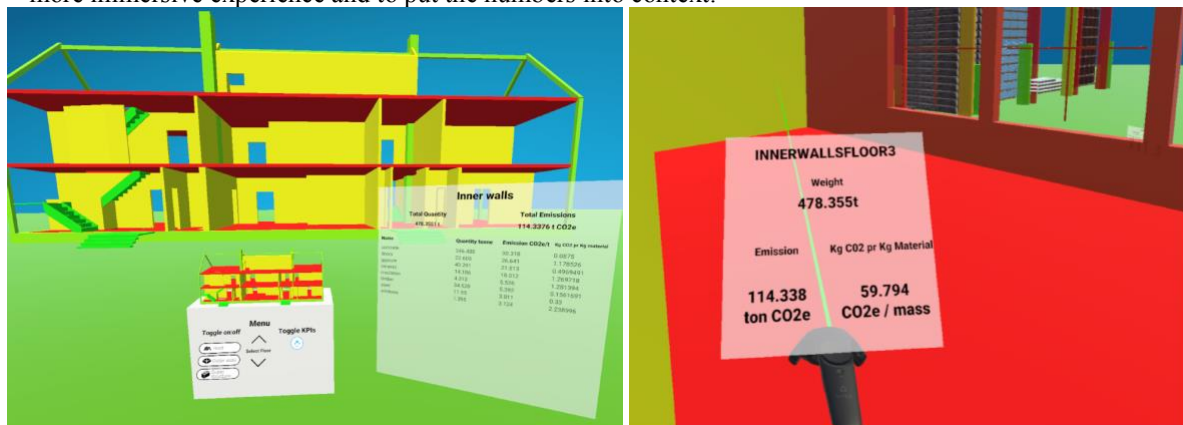


Figure 3. ZEB View of a building using VR to visualise emissions and by listing materials in tabular form

3.2. Results of user tests and questionnaires

After conducting some informal user-tests on subjects without prior knowledge regarding sustainable neighbourhood design, the results show that average citizens and other stakeholders do not find it easy to understand what the emission data means in relation to the neighbourhood context, and designers find it difficult to understand how to integrate this data into the design process. As a result, a design has been developed which focuses more on the immersive experience and visual display of data as a means to communicate complex KPI data. An example of this, is the visualisation of the amount of timber used in construction not only as a number, but also as as number of virtual logs stacked. Another example is, that the contribution of transport related emissions is indicated as a number of different vehicles and GHG emissions for travel distance and intensity of pollution is indicated in size and colour.

It was found that when working on the application, that by using high-end VR equipment, a more immersive experience is achieved which results in more engagement from the user and facilitates easier interaction and feedback with the ZEN KPIs. The results also show that users enjoy exploring the novelty of a virtual environment and because of this, it was decided to only implement a small portion of the pilot area, so the user would not get lost in the experience, but rather focus on interacting with the relevant information and specific KPIs for the area. It was also found that the *Unity 3D* software allows for quick prototyping and development for multiple platforms at once in addition to making a high quality result.

Another finding was that size matters. Some of the visualisation methods, first deemed unnecessary, ended up being the most important in making an impression on the user. By using only colour visualisation of the emission data, the user does not fully understand the significance of the emission results. However, it was found if different sizes of columns are used instead to communicate the significance of the level of resulting emissions from the building, it was found that the users more easily understood this data in this more visual context. One of the test-subjects stated when looking at a large, red column that she *"I would not like to live in that house"* due to the associated high emissions.

4. Conclusion and Discussion

The results of this paper show that this ZEN VR approach provides for a new and intuitive way of interacting with and viewing multiple KPIs simultaneously. This approach presents a new way of combining KPI data with BIM models early in the design process. By utilising visualisation methods which inspire and engage diverse stakeholders to explore the environment and learning by putting numbers into context, the ZEN vision of a sustainable neighbourhoods can more easily be communicated by diverse stakeholders. VR is a valuable tool to engage users with no prior knowledge of ZEN or KPIs, to put data into context and to more easily understand the meaning and size of the numbers presented. This VR approach improves communication with and between stakeholders and provides a means to overcome traditional interdisciplinary barriers. It was also found that high end equipment offers a better immersive experience by having better image quality, performance and input possibilities. This makes it easier to engage the user and keep their attention in the application while learning useful information, but with an increased cost and more cumbersome setup.

The research explored the utilization of virtual reality as a tool for engaging and interacting with emission data in new and immersive ways. A VR application, called ZENVR, was developed through several iterations by connecting an existing MYSQL database, containing life cycle assessments of 11 projects in Unity 3D. Furthermore, the application and its potential was evaluated through the use of semi-structured expert interviews and its usability through a survey. The participants of these two methods of data collection all tested the application on the same terms, with a set of predefined tasks. These were conducted in order to answer the objectives of this work which was to investigate how visualisation methods, such as, Virtual reality (VR), can support the evaluation of zero emission neighborhood (ZEN) design concepts with respect to key performance indicators, such as, greenhouse gas emissions and other potential environmental impacts.

The results of this study found that virtual reality is a good platform for communicating and visualising complex data including the KPIs in sustainable neighbourhoods, for not only researchers but also for the general public. ZENVR can be used as a data visualisation tool for presenting data in a understandable format by creating a presence inducing environment which subsequently may result in an emotional experience when interacting with the application. In ZENVR we have shown that these principles can be used to visualize the KPIs from ZEN. These visualisation methods are exemplified through greenhouse gas emissions related to the transport and use of materials, but the principles are transferable to numerical data in general.

In terms of which form of data visualisation are most beneficial for comprehending the KPIs for different user group, it was found that ZENVR allows for selecting between several forms of data visualisations. Expert interviews revealed that professionals preferred traditional visualisation approach i.e. columns, colors and numbers when looking at KPIs. It was further discovered that in order to make a lasting impression, which ultimately is the goal of ZENVR, one have to use visualisation methods which appeal to the human emotions. This can be achieved by anchoring the visualisations to human factors by using the principles mentioned earlier, for instance using sizes to make the user feel small or movement of objects for dramatic effects. The visualisation type which made the biggest impact on all users was when numbers were put into context by using relatable objects from everyday life.

In relation to how can VR be used to improve stakeholder participation in sustainable neighbourhood projects, the results show potential areas where ZENVR can be used to improve stakeholder participation include citizen engagement, promotion and the advertisement of ZENs, tool for interdisciplinary communication and collaboration between professionals. With its natural immersive properties, VR has proven to be a suitable platform to spark engagement among its users. Through a well designed VR environment, highlighting the beneficial parts of an environmental friendly neighbourhood, all subjects agreed that this has a huge potential to promote sustainable neighbourhoods. In addition, VR allows for displaying data in new perspectives making it understandable for different stakeholders, reducing the barriers of interdisciplinary communication and collaboration.

5. Further work

The application in its current state is experimental and should be viewed more as providing a foundation for further development. Further work should investigate how more KPIs can be included in the application and the associated effect on stakeholders. In addition, when the application is more complete and thorough, user-testing might reveal if the usability improvement suggestions from the latest iteration are indeed useful. From a technical point of view, some alterations and features which might benefit the application arose from conducting user tests and interviews. These mostly centred around the user interface and how it might be changed to better suit the user's needs and understanding. It would be advantageous to test the application with other virtual reality systems to test its compatibility and possible adaptations that may be necessary.

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Appendix A

Category	Assessment criteria	Key performance indicators (KPIs)
GHG emission	<ul style="list-style-type: none"> Total GHG emissions GHG emission reduction 	<ul style="list-style-type: none"> Total GHG emissions in tCO_{2eq}; tCO_{2eq}/m² heated floor area (BRA)/yr; kgCO_{2eq}/m² outdoor space (BAU)/yr; tCO_{2eq}/capita % reduction compared to a base case
Energy	<ul style="list-style-type: none"> Energy efficiency in buildings Energy carriers 	<ul style="list-style-type: none"> Net energy need in kWh/m²BRA/yr; Gross energy need in kWh/m² BRA/yr; Total energy need in kWh/m² BRA/yr Energy use in kWh/yr; Energy generation in kWh/yr; Delivered energy in kWh/yr; Exported energy in kWh/yr; Self-consumption in %; Self-generation in %; Colour coded carpet plot in kWh/yr
Power/Load	<ul style="list-style-type: none"> Power/load performance Power/load Flexibility 	<ul style="list-style-type: none"> Net load yearly profile in kWh; Net load duration curve in kWh; Peak load in kWh; Peak export in kWh; Utilisation factor in % Daily net load profile in kWh
Mobility	<ul style="list-style-type: none"> Mode of transport Access to public transport 	<ul style="list-style-type: none"> % share Meters; Frequency
Economy	<ul style="list-style-type: none"> Life cycle cost (LCC) 	<ul style="list-style-type: none"> NOK; NOK/m² heated floor area (BRA)/yr; NOK/m² outdoor space (BAU)/yr; NOK/capita
Spatial qualities	<ul style="list-style-type: none"> Demographic needs and consultation plan Delivery and proximity to amenities Public Space 	<ul style="list-style-type: none"> Qualitative No. of amenities; Meters (distance from buildings) Qualitative

Table 2. ZEN assessment criteria and KPIs covered in ZEN definition guideline.[2]