Indoor environmental quality (IEQ) assessment using laser-assisted data acquisition (LADA) of building geometry

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Abstract
A new IEQ (indoor environmental quality) assessment tool, called IEQCompass, has been developed to perform inexpensive evaluations of IEQ performance and result dissemination that is understandable for all stakeholders. The current study tested a laser-assisted data acquisition (LADA) process, facilitating the measuring and registration of building geometries and building information, exportable in a format, which is compatible with IEQCompass. Three apartments were tested in two phases, firstly, an evaluation of the LADA tool’s ability to facilitate data acquisition for IEQCompass, and secondly, an evaluation of the complete process of using LADA and the IEQCompass. Testing showed that it can be feasible to use LADA for the acquisition of geometrical data with limited manual input. Testing also showed that LADA can be used to gather other building information, such as surface material, external geometry and construction component information, based on manual input, stored in a structured schema and in a CAD model.

Key Innovations
- Automation of the measuring of internal building geometries, based on usage of handheld laser-meters and data processing software.
- Aiding the registration and documentation of construction components and external geometries needed for the IEQCompass.
- Limiting the amount of manual input with respect to the generation of CAD and information schemas.

Practical Implications
The proposed combined workflow of handheld laser-meters and data processing and modelling software can reduce the workload of building registration tasks, e.g. assessment of building energy and indoor environmental performance. The methodology improves the availability, reliability and consistency of the acquired information, which benefit building professionals that rely on the collected data, such as indoor environmental and energy engineers.

Introduction
Since 2010 Danish legislation has demanded that all private buildings with a size of more than 50 m² and public buildings above 250 m² must be energy-labelled before a permit is given to live in a building and before a building can be sold (Energistyrelsen, 2021). Such energy assessment is based on a fixed set of information found in a Computer Aided Design (CAD) or Building Information Model (BIM). In the case of renovation, information is usually acquired through the registration and measuring of an existing building. This information acquisition often takes place before a building is built or renovated to guide design choices. This mandatory labelling has led to improved building design in Denmark concerning energy consumption. However, research indicates that energy efficiency improvements may compromise the performance of the indoor environment (IE) (Larsen, 2011; Rohde et al., 2019).

To facilitate the design of buildings with a better indoor environment, a new IEQ assessment tool has been developed. The tool delivers fast and inexpensive IEQ evaluation and performance dissemination of a building (Larsen et al., 2020), based on most of the same data used for the mandatory energy labelling. The purpose of the tool includes improving IEQ performance in new and renovated buildings by providing design decision support and creating a strong incentive to invest in IEQ by quantifying and disseminating the performance before and after a potential investment.

The IEQCompass tool is the result of the REBUS project (Renovating Buildings Sustainably) (REBUS, 2016), which is a dedicated R&D partnership that consists of various stakeholders from the building industry. The development team includes a wide range of building professionals such as researchers, consultant engineers, architects, manufacturers and professional building owners. The current version of the tool is for multifamily residential projects in Denmark, which has a temperate climate (relatively cool summers, moderately cold winters, large seasonal variations in daylight).

The IEQCompass facilitates IEQ improvements in the early design stages of renovations proposals or new building designs by providing simultaneous performance simulation based on simple input data. The tool promotes a holistic IEQ focus from the beginning of the project, where the potential for influence is highest.
To assess potential IEQ performance in the early design phases, assessments are made without physical IEQ measurements or occupant surveys, as they are not available until after building completion. Instead, the tool assesses potential IEQ based on calculations using a wide range of available physical building characteristics such as geometry, context, components, systems and constructions.

This potential IEQ performance assessment is based on building geometry, climate data sets and available information on building context, constructions and components. The assessment consists of 40 IEQ criteria split across four main areas: acoustics (ACOU), indoor air quality (IAQ), thermal (THER) and visual (VIS). The tool automatically simulates and assesses the performance of all 40 criteria and scores them on a 0-10 scale (Larsen et al., 2020). For instance, the risk of cold down-draft is assessed through the number of hours that air speeds exceed a dissatisfaction threshold according to standards for local thermal discomfort. Down-draft airspeeds are calculated using window height and the difference between outdoor and indoor surface temperatures of the window based on climate data and information about the building envelope.

The tool visualizes both non-aggregated (e.g. draft: 0-10 score), partially aggregated (e.g. thermal: 0-100%), and fully aggregated results (overall IEQ: A to G scale) to provide nuanced assessments while accommodating the needs of different stakeholders.

In addition to IEQ assessment and labelling, the automatic performance simulation and result visualisation provide design teams with early-stage design decision support (through design alternative comparisons and known trade-offs) without compromising the flexibility and pace of the early design process.

At least five different types of information are necessary to collect to allow energy assessment and use of the IEQCompass, as shown in figure 1. When evaluating the design of new buildings, all of said information should be present in the design model and design description. However, concerning the evaluation of design for renovation projects, very little information is available in the public building databases and in many cases, such data have not been recorded. Tools used to collect building information before energy assessment, and use of IEQCompass must be able to acquire and store as many of the five categories of information as possible to conclude if a set of tools or a method for using said tools is feasible.

Collecting information can be time-consuming and expensive with respect to modelling and storing building information in a data repository, e.g. spreadsheet schema or in a building information model (BIM). The current registration and building measuring process on renovation projects used in the Danish building industry are often based on visual registration of building components and condition of constructions, as well as measuring of room geometry. Such measuring is usually conducted using a traditional measuring tape or a handheld laser-meter used as an advanced measuring tape. The gathered information are then typically entered into a schedule or used to generate a CAD or BIM model manually. Building models generated based on a manual input process, however, often lack consistency and reliability (Gerrish et al., 2016). The process of making data acquisition should, therefore, be as automated as possible.

It is important to emphasise that IEQCompass is not a substitute for energy assessment, but an add-on to it. The combination of both energy consumption and IEQ parameters enables better informed building designs without affecting the final building cost.

**Laser-Assisted Data Acquisition**

In renovation design projects, data collection is typically split into two parts. Firstly, information collection from existing building documentation such as drawings, building permits and photos. Such existing documentation are often limited, fragmented or scattered over multiple databases or physical locations. Secondly, information gathered through on-site building registration. Most building registration includes measuring geometry, either the entire building, or enough to validate the geometry documented in existing building drawings.

Measuring geometries can be done in at least three ways. Firstly, using a measuring tape and manually drawing or modelling the geometry on paper or using CAD. Secondly, using photogrammetry, which includes capturing thousands or millions of data points using camera technology, resulting in a documentation of geometry. Using the proper CAD-processing tool furthermore allow automatic or semi-automatic building modelling (Ordóñez et al., 2010), based on such documentation. Thirdly, using a handheld laser-meter as an advanced measuring tape, after which information is

1. **Internal Geometries**
   - Length, width and height of rooms, windows, doors, windowsills and other internal room geometries.

2. **External Geometries**
   - Length, width and height of neighbouring buildings. Eaves, balconies, flora etc. allowing analysis of shadowing and view in/ out.

3. **Construction Components**
   - Parameters of specific layers of construction types.

4. **Surface Materials**
   - Parameters of surface materials such as flooring, walls and ceilings.

5. **Locational Data**
   - Orientation, GPS position and wind, pollution, etc. maps.

Figure 1 Five types of building information.
written, drawn and modelled on paper or using CAD. Alternatively, it is possible to connect the laser-meter to data processing and modelling software to exchange the registration of measurements taken with a handheld laser, allowing semi- or full automatic generation of geometrical representation of the building in schemas, 2D and 3D.

The first way of performing data acquisition of building geometry is based on manual input of data to generate CAD and schemas. Such manual data input is often time consuming and lacks consistency and reliability (El-Omari and Moselhi, 2011; Gerrish et al., 2016).

Much research has already been done for using photogrammetry (Armesto et al., 2009; Barazzetti, 2016; Ottoni, Freddi and Zerbi, 2017); however, most of said research also recognise that the vast amount of data collected using photogrammetry can be hard to filter and condense into a functioning model.

Using a handheld laser-meter as an advanced measuring tape is an approach energy consultants often take when collecting data for energy assessment of a building. Using a handheld laser together with data processing software for generating a CAD and schematic representation of a building is, however, not common practice in the Danish building industry. This paper explores how handheld laser-meters can be used to acquire geometric building data, as well as other relevant data needed for IEQ assessment, using the IEQCompass.

As shown in figure 2, many laser-meters can be used in two ways. Firstly, as a centralised measuring tool on a tripod, capable of taking measurement from a fixed location. Secondly, as an advanced measuring tape, able of measuring distances between surfaces. In this paper, we focus on using the handheld laser as an advanced measuring tape, as this approach is most similar to the way laser-meters are already used for energy assessment.

In addition to providing accurate measurements, which can be written down and used for manual processes, many handheld lasers today, allow interoperability between the laser-meter and data processing and modelling software, such as Orthograph, Magicplan or software developed by the individual laser-meter vendors. Such interoperability makes it possible to send measurement from a laser-meter to a handheld unit, such as a mobile phone or tablet using Bluetooth or Wi-Fi, and manipulate the measurements into geometric models as well as data schemas, in real-time.

Handheld lasers and data processing software for geometrical modelling and building registration are available in various prices, quality and with divergent levels of exportability, interoperability and usability. However, only a few of the available tools and software fulfils the needs of automated data acquisition for energy assessment and IEQ assessment using IEQCompass. We have named the use of handheld laser-meters in unison with data processing and modelling software Laser-Assisted Data Acquisition (LADA).

The use of LADA makes it possible to export building data acquired using the handheld laser and data processing software in various digital formats, each containing variable types and amount of information.
Many different handheld laser-meters facilitates an automated data acquisition; however, only a few allow documentation of more than geometry. In addition, not all tool-combinations, which can be described as LADA, allow export of information that can support both energy and IEQ assessment.

In this paper, we describe the testing of LADA to conclude if the use of handheld laser and data processing software in unison are feasible for use with IEQ Compass, to a degree that allows a reliable and accurate assessment and to disclose limitations in LADA usage for IEQ Compass.

**Methodology**

The handheld laser-meter used for LADA, tested in this study, was the Leica Disto S910. The data processing software used was the Construction and Floor planning App Magicplan, installed on an iPad Air Wi-Fi tablet. The selection of the specific tools was based on the selection-framework for Laser-Assisted Data Acquisition described by Wyke et al. (2019). The selection framework focuses explicitly on exportability, connectability, interoperability between laser-meters and data processing software and an average calculation of usability based on user-evaluation of handheld laser-meters and data processing software.

The testing of LADA for IEQ Compass was conducted in 2019 and was divided into two phases. Firstly examining the feasibility of using LADA in real test cases, and secondly exploring compatibility and identification of the limitations of LADA usage for IEQ Compass.

For the first testing phase, two apartment buildings were submitted to registration using LADA. The first test case is an apartment of 83 m², built in 1986, located in Northern Denmark. The second test case is a 67 m² apartment in a single story building in Central Denmark, built in 1967.

In the second testing phase, focussing on LADA use for IEQ Compass, an apartment building was submitted to registration using LADA. The test apartment has the size of 84 m², was built in 1986, and is located in Northern Denmark.

Two test persons took part in the first testing phase. One with specialised knowledge regarding the IEQ Compass, collecting construction component information manually and one with specialised knowledge regarding LADA. Three researchers participated in the second test phase, two researchers focused on manual registration of data for IEQ Compass, whilst one participant used LADA.

The IEQ Compass assessment tool specifies the data required for the assessments, and thus defines which data to collect using LADA. However, the accuracy of the data is dependent on the person using LADA, and her/ his judgement with respect to how precise measurements must be. Common practise tolerances for IE and IEQ assessment must, however, be applied, as a minimum, ensuring that the data acquired using LADA are reliable and accurate to a degree which allows reliable and accurate assessment of the IEQ.

**Results**

**The first test-phase**

The first testing phase showed that using LADA allows fast and accurate documentation of room geometry. It allowed instant modelling of measured geometry in the data processing and modelling software (software) based on measurements taken with a handheld laser, in real time. The tools further allowed photo documentation of rooms, building components and other important visual aspects of the test cases.

Using the “parameter” function in the used software, positioning, condition of a building component and other factors were documented as a note to a geometric object. Documentation of HVAC and electronic equipment and parameters regarding these objects was done in the same way, by attaching information to a surface, hosting HVAC or electronic equipment, using the note-function in the application. This text-based documentation was in the testing sessions supplied with photo documentation.

1. **.PDF** Portable Document Format. For exchange and view of electronic documents, represented as text and graphics in a independent manner (Ag, 2005).


5. **.CSV** Comma-Separated Values. A text file using comma separated values, able to store large amounts of numbers and text. Easily editable using spreadsheet applications (Smith, 2018, CSVReader, 2018, Super-CSV, 2018).

Figure 3 Exportable formats for the used data processing and modelling software.
Using the selected handheld laser-meter and software for LADA, data-export was made possible in six formats, as shown in figure 3. For the IEQ Compass, the Comma Separated Values (.CSV) format was used, in combination with the JPEG format, in which photodocumentation was exported, and the Drawing Exchange Format (.DXF) showing the documented floorplans.

The exports from the two test cases were analysed based on their content. The DXF and the .CSV format were found to be the most feasible for further data manipulation for energy and IEQ assessment, as they included both CAD and text based information. This included building geometry and documented construction components, surface materials and locational data. Figure 4 shows an excerpt from the data exchange, including the .CSV and .DXF floorplan generated from LADA.

The second test-phase

The second test phase included the use of the IEQ Compass, based on exported data from LADA. Figure 5 shows the exported .CSV information after initial manipulation, allowing information transfer to the IEQ Compass.

When transferring the information to the IEQ Compass, it became evident that most of the geometric information were available from LADA. However, external geometries were not included as they could not be acquired feasibly during registration. Shadows, shadowing elements to the focal test case and view in and out, could therefore not be calculated in the IEQ Compass, without additional data acquisition.

In both test-phases, a PDF report was generated from LADA automatically, which included GPS coordinates of the building, registered using Google Earth. This made it possible to easily access locational data and include such in the IEQ Compass. The report further contained photodocumentation aiding the manual data entrance in the IEQ Compass. The use of photodocumentation, furthermore allowed registration of construction components and external geometries, however without measurements included. This photo-documentation also included documentation of HVAC and electronic equipment.

In the second test-phase the “parameter” function in the software was used, which allowed some automation in documenting HVAC and electronic equipment, making it possible to indicate if a radiator was placed underneath a window or if an exhaust hood was placed above a stove and similar information. However, the type, size and function of HVAC and electronic equipment remained a manual and/ or photo-documented task using LADA.

Utilising the acquired data, the IEQ Compass performed automated calculation, assessment, weighting, scoring and result dissemination of the indoor environment. Figure 6 shows a graphical representation of the assessment results for the apartment of the second test-phase. Each main area is split into four categories, of which the fourth is always concerned with the degree of the occupants’ possibilities to adjust the IEQ within the given category (if applicable). The 16 categories cover a total of 40 IEQ parameters under the following headlines;

Figure 4 .CSV and .DXF export based on LADA. The highlighted area shows the initial data manipulation allowing information-transfer to IEQ Compass. The manipulation is based on the information shown in the top of the figure.

Figure 5 CSV export from LADA after initial data manipulation.
ACOU1 (Noise from surroundings), ACOU2 (Noise from neighbouring dwellings), ACOU3 (Noise from within the dwelling), IAQ1 (Impact of outdoor air), IAQ2 (Building ventilation and materials), IAQ3 (Impact of household activities), THER1 (Temperature, summer), THER2 (Temperature, winter), THER3 (Draught risk), VIS1 (Daylight), VIS2 (Direct sunlight) and VIS3 (Views). Note that the assessed performance and the relative weight of each category are indicated using the number and width of the coloured bars, while the partially aggregated (%) and fully-aggregated (letter/label) results are indicated in the centre of the compass.

During the testing, connectivity-issues were experienced by the test-persons concerning paring and signal quality between the handheld laser and handheld unit the software was installed on. These issues were usually resolved by resetting the Bluetooth setting on all devices. Low battery on devices also caused issues when paring units for LADA.

Both test-cases showed that the benefit of using LADA was primarily concerning the registration of room geometries, improving the acquisition of accurate measurements and an automated process of generating CAD representation of said geometries.

Discussion

The results from the tests show that LADA can be used to automate the registration of building geometry, but regarding the data required for IEQCompass, it is limited to internal geometry and surface materials. In addition, LADA can be used to store information and photo-documentation of construction components and external geometry. The latter part of the benefits of LADA, cannot be described as an automated process, compared to how information are already acquired for energy and IEQ assessment. The ability to store information in one application and export it as a single report, however, seems to improve the workflow of energy and IE data acquisition. Compared to the current data acquisition workflow of IE and IEQ consultants, the LADA process automates some of the steps required when going from measurements to geometric modelling as well as how acquired data are structured and stored, which might solve some of the known issues related to data reliability and consistency (Gerrish et al., 2016)

It is currently not possible to transfer data directly from LADA to the IEQCompass, however, as shown in figure 4, only a limited manipulation of the exported data from LADA is needed, to allow data transfer from the data processing software to IEQCompass.

As most of the information needed for the IEQCompass calculations overlap what is already acquired to perform energy assessment, using the IEQCompass will not increase cost on a design or renovation project significantly. It can, on the other hand, provide design decision support, enable design variation comparison, and ensure a better balance between residential comfort and energy efficiency. In addition to the listed early design stage benefits, the IEQCompass combines all relevant IEQ assessments in a single tool, which is a significant improvement compared to existing methods.

Using LADA furthermore allow a central structure and storage of information that benefits the person performing data acquisition for IEQ assessment, even though some of the data acquired and stored using LADA are based on manual input and photo-documentation.

Figure 6 Visualisation of the IEQ assessment score as generated by the IEQCompass (for the case building in the second test-phase)
Investing in the tools needed for LADA and implementing LADA in an architectural or engineering company will involve some costs and changes in work processes. The combined benefits of using LADA, automating the modelling of building geometry and centralising the information storage for energy and IEQ assessment is nonetheless expected to outweigh the cost of the tools. However, more research in this regard is needed.

Conclusion
An IEQ assessment tool called the IEQCompass was developed to assess the indoor environmental quality as an indoor environmental counterpart to the mandatory energy assessment in Denmark. Laser-Assisted Data Acquisition (LADA) is a methodology utilising a handheld laser-meter and data processing and modelling software in unison to automate data acquisition of room geometries and other building information.

Testing LADA for the IEQCompass showed that it is possible to acquire internal building geometries using a handheld laser-meters and data processing software. Testing also concluded that registration and documentation of construction component and external geometries needed for the IEQCompass can be facilitated using LADA. However, this part is not yet automated. The testing furthermore revealed that it is possible to limit the amount of manual input for generating CAD and information schemas, thereby improving the reliability and consistency of the acquired information. Manual input is however, not eliminated using LADA.

The use of LADA for IEQCompass showed that LADA can automate the acquisition of building information stored in the same processing software, allowing structured documentation of building information. Testing, however, showed that LADA could not facilitate the acquisition of all information needed for the IEQCompass.

It is important to stress that LADA is not meant to facilitate automatic data acquisition nor data transfer. It is designed to ensure registration and measuring in an automated way, relying on accurate handheld laser-meters and data processing and modelling software, to ease the workload in doing building registration, allowing not only registration needed for doing energy assessment as demanded by Danish legislation but also facilitating the assessment of the IEQ using the IEQCompass.

References


Super-CSV (2018). Available at: http://super-
