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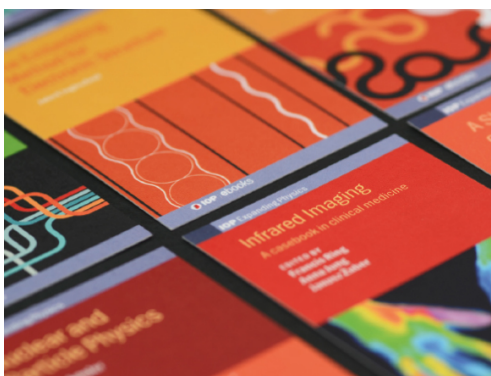
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Status assessment of buildings using existing data and identifying gaps in data from performance indicators

Jan Mandinec¹ and Pär Johansson¹

¹ Department of Architecture and Civil Engineering, Chalmers University of Technology, 412 96 Gothenburg, Sweden

jan.mandinec@chalmers.se

Abstract. In past decades, several performance indicators have been developed allowing to objectively assess current status or predict failures of material, components and other factors like moisture safety. However, each performance indicator requires its unique sets of data, which are often difficult to obtain. It is therefore of interest whether a combination of several indicators is applicable in older buildings which often lack readily available documentation. The aim of this study is to identify data gaps preventing the use of indicators and to ascertain whether missing data can be filled by combining visual inspections and non-destructive testing. The first part of the paper summarizes known building envelope related indicators and arrange them into three groups: general, hygrothermal and service life performance indicators. The second part is a case study where the applicability of selected performance indicators is tested against an in-house database consisting information about 610 buildings in Gothenburg. It was found that the use of performance indicators is limited as the gaps in the available data are present for all types of performance indicators. The material composition of buildings envelope was identified as the most substantial gap. This limited the use of hygrothermal performance indicators in 58.5% of the buildings.

1. Introduction

In recent years the maintenance planning of buildings is moving from subjective status assessment methods to more performance-based evaluations. This changing paradigm of how to extend the building service life is changing quite considerably. This shift is driven by the development of smart and cheap sensor technologies, which find applications especially in newly built constructions, allowing to continuously measure various building's aspects like indoor climate, ventilation rate, moisture content of walls etc.

To assess a performance of a building one may use a metric called performance indicator. This metric tells how well a building fulfils its designated purpose (current status assessment) or how efficiently this purpose will be achieved in a future (future risk assessment). However, the applicability of performance indicators is highly dependable on not only measurement itself, but also on other data sets of building information. These could be the material composition of walls, the year of construction, etc. In many cases, these data sets are not readily available. In Sweden, this is especially the case for older buildings (built before 1945) where it is estimated that 40% [1] lacks a readily available documentation for performance metric evaluations. Consequently, making the performance indicators difficult to apply

This study is the first part of a PhD project with the aim to develop a tool allowing to predict potential performance failures and assessing possible renovation strategies in buildings with lack of



technical documentation. This research paper aims to identify and highlight gaps in data sets by applying performance indicators related to the building envelope to an in-house database with information on 610 buildings in Gothenburg, Sweden, constructed before the year 1945.

In the first part of the study, performance indicators were collected in a literature review focusing on answering the following research questions: (1) Which performance indicators exist that can be used to assess the current status of the building envelope? (2) Which performance indicators can be used to predict the future risk for damage?

The second part of the paper is a case study where firstly the in-house database is introduced according to this research question: (3) What data are available to make performance indicators useful? The in-house database contains general information about 610 buildings (address, number of storeys, type of buildings, etc.) as well as the description of the type of façade and its state. The database also contains data from EPC (e.g. Energy performance, Energy index, built year), information about the type of ventilation (natural, mechanical, whether a heat exchanger is present, etc.) and also important dates like year of construction from real estate register (may be different from built year from EPC), reconstruction year and value year.

In the final part of the paper, data from the database was connected with data from non-destructive in-situ measurements to identify gaps in data to answer the following question: (4) Can existing information in building databases be combined with non-destructive in-situ measurements to make use of performance indicators? Finally, the conclusions of the possibilities to close the gaps in data and highlight what type of data is still missing.

2. Performance indicators

Based on a literature review, performance indicators are structured in three subsections: General and high-level indicators, Hygrothermal indicators and Service life indicators. Note that none of the indicators presented below indicate the performance as a binary option (0 – no failure, 1 – failure), but rather shows building performance on a sliding scale. Therefore, the state when a failure occurs is a highly subjective matter making a building envelope current status assessment an ambiguous process.

2.1. General and high-level indicators

The high-level indicators describe the overall performance of a building envelope rather than its individual aspects. Following three indicators presented in this subsection may be used to assess the current status of the building envelope.

The value year is a parameter commonly used by the Swedish tax agency (Skatteverket) which helps to estimate the general state of a building, indicating its expected remaining service life. Newly built houses or buildings which did not undergo major renovation measures have value year equal to the year of construction. Value year is changed only following larger renovation measures, i.e. when the costs for renovation exceeds 70% the costs for a new comparable building, or based on the calculation including the year of construction [2].

The second high-level performance indicator is the Energy Performance (kWh/m^2). This is commonly a calculated value derived from the Energy Performance Certificates (EPC). This indicator shows the overall performance of a building as indirectly describing many of a building's features like the quality of the building envelope, airtightness, and its state. Note that in Swedish context, the concept of primary energy was not embedded in EPCs' energy performance calculation up until 2019. Therefore, Energy Index (kWh) and Heated surface area (m^2), which are obtainable in new EPCs, need to be used for the purpose of keeping EPCs from different eras fully comparable.

Airtightness, or the level of leakages through the building envelope, is another indicator which suggests energy performance of a building. Airtightness is measured at a pressure difference 50 Pa as a leakage rate through area of building envelope ($\text{l/s}\cdot\text{m}^2$).

Overall thermal transmittance (U-value, $\text{W}/(\text{m}^2\cdot\text{K})$) is another performance indicator implying energy performance of a building as it describes how well is a building envelope insulated. The U-value is usually derivable from the structural composition.

2.2. *Hygrothermal indicators*

This section presents performance indicators which may be used to assess the current status of the building envelope and future risks from the hygrothermal (building physics) perspective.

A common performance indicator for moisture is to investigate the risk for mould growth. The most advanced indicator is the Mould Growth Index. This was developed by Hukka and Viitanen in 1999 [3] who firstly presented a mould growth model for pine sapwood and spruce. The applicability of the original model was extended further to other materials as well, and it is also possible to model the mould decay development (mass loss process) for pine and spruce sapwood. The mould growth potential is a slightly modified version of the mould growth index, based on counting the favourable conditions for mould growth where the relative humidity exceeds the critical relative humidity [4]. Note that, the exceedance of the critical relative humidity of materials may be considered as general hygrothermal performance indicator as it may also suggest the freeze/thaw damage as well as the risk of condensation. All mould growth performance indicators need temperatures and relative humidity of the air in the structure which is rarely readily available.

The risk of freeze/thaw damage can be estimated by the Freeze-Thaw Damage Risk (FTDR) index which was developed by Zhou [5]. FTDR index sums up the difference between highest and lowest saturation degree of ice content in each complete or incomplete freeze/thaw cycle. As for the mould growth index, this method needs a hygrothermal model that simulates the heat and moisture transport across e.g. a wall. Therefore, the knowledge of the wall composition and material properties of each layer, as well as weather data and moisture/thermal conditions inside a building, are necessary to obtain.

Also, the performance indicator to estimate the risk of condensation need hygrothermal models and/or measurements. All condensation methods are based on comparing the surface temperature with the associated dewpoint temperature. Risk of condensation may be also indicated by the surface temperature factor (f_{rsi}), which is used to assess thermal bridges. The indicator proposed by Cho [6] can quantify the risk of condensation by counting the number of occurrences of condensation. This can be used to estimate the level of microbial growth, potential reduction of thermal performance, visual and structural deterioration.

2.3. *Service life indicators*

The indicators presented below are used to estimate the current status of a building envelope forming a base for the remaining service life prediction. The methods are usually based on data from visual inspections, comparing the area of degradation with the area of the investigated component. The simplest method applicable for façades is the metric 'Area and Extension of Degradation' which forms a ratio of degraded and undegraded façade. This indicator has its limitations as it does not contain information about the type of damage and its severity.

Another more advanced method is called the 'Severity of Degradation' allowing one to specify the type of deterioration (e.g. staining, cracks) and its extension by applying defect multiplying factors and weighting coefficients. Note that factors and coefficients are available only for specific façades with cementitious render, external thermal insulation composite systems (ETICS), ceramic tile cladding and stone cladding. Another very similar method allowing to assess any rendered façade is the 'Overall Degradation Level' (ODL) [7].

2.4. *Performance indicators summary*

All performance indicators, data they need and whether they can be used for current status assessment of building envelope and risk assessment are listed in the Table 1.

3. **Case study of the applicability of the performance indicators**

To evaluate the different performance indicators, introduced above, a case study of an in-house database is used to investigate their applicability and what data are missing today.

Table 1. Summary of performance indicators for status assessment and future risk assessment.

Performance indicator	Data needed	Status assessment	Future risk assessment
Value year	Year of construction and renovation, renovation costs	Yes	No
Energy performance	Energy index (kWh), Heated surface area (m ²)	Yes	No
Airtightness	Leakage rate (l/s·m ²)	Yes	No
Thermal transmittance	U-value	Yes	No
Mould index, Mould growth potential	RH, Air temperature	Yes	Yes
Exceedance of critical moisture content	RH, Air temperature	Yes	Yes
FTDR index	Freeze/Thaw cycles, Saturation degree of ice content	Yes	Yes
Surface temperature factor (frsi)	Outdoor & indoor temperature, Surface temperature	Yes	Yes
Condensation risk	Dewpoint temperature, Surface temperature	Yes	Yes
Service life indicators	Area of component, Area of degradation	Yes	Yes

3.1. Description of the database

The in-house database is based on an inventory of selected buildings constructed before the year 1945 in Gothenburg, Sweden. Data from various sources like municipality agencies, governmental offices (Swedish Tax Office) and EPCs were augmented with data from building inspections forming a database which consists 610 unique properties with 663 buildings in total. Each property consists of one record in the database containing information only for the main (largest) building.

The general information about the buildings contains information on the property name, street, number of buildings on the property and the basic information contains the construction such as number of floors, number of attic floors, whether the building has an elevator, if courtyard is accessible, living area in m², premises in m², whether a building is self-standing or not. The buildings are also divided into 8 distinct buildings groups according to their construction type and whether a building is under an architectural or historical protection.

For most of the buildings, the envelope's characteristics is different for the street side and from the backside (another main façade or from courtyard side). Each façade is then divided into upper part (façade up) and its lower part (façade down) and described in terms of façade material, thickness of added insulation (if any), percentual coverage of insulation and the state of a façade. However, the database does not contain information about the exact composition of the walls, neither the thickness of its individual components.

In the database, a description of the façade material is incomplete for 5.6% of the façades. This is because the courtyard side was not accessible in several cases. Note that only in 25 instances in total (4.1%), inner façade is completely unidentified as only the lower part of the inner façade is predominantly missing with 112 cases (18.4%). See Figure 1 for the distribution of individual façade materials over the different parts. The database also contains information about other parts of the building envelope such as the type of windows and, more specifically, the number of panes and the material in the window frame [8].

3.2. Applicability of performance indicators to the database

As presented above, the database describes the buildings from a rather general perspective. The applicability of performance indicators is therefore very limited as they need more specific sets of data for each individual building. The only exception represents high-level performance indicators (Value year, Energy performance) which are presented in the database for the majority of buildings. However,

there are missing data for these parameters as well, as shown in Figure 2. Value year is accessible for 498 building (81.64%) whereas EPC data are present in 532 cases (87.21%).

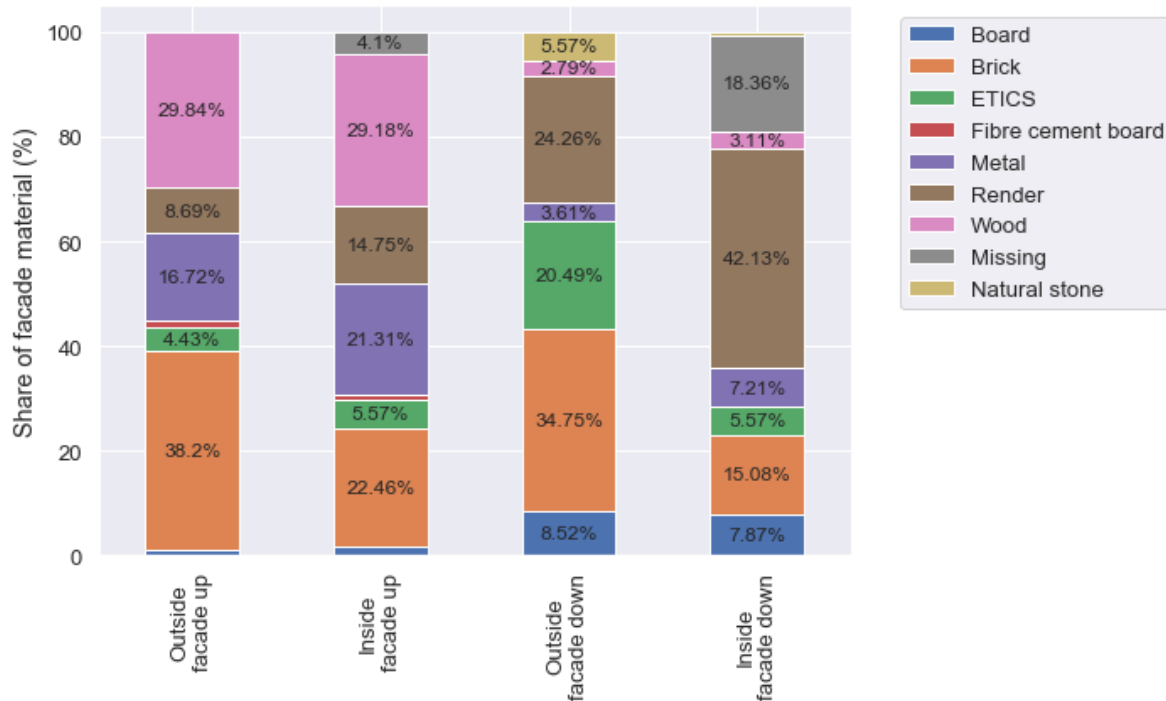


Figure 1. Distribution of façade materials over individual parts of façades of the 610 buildings.

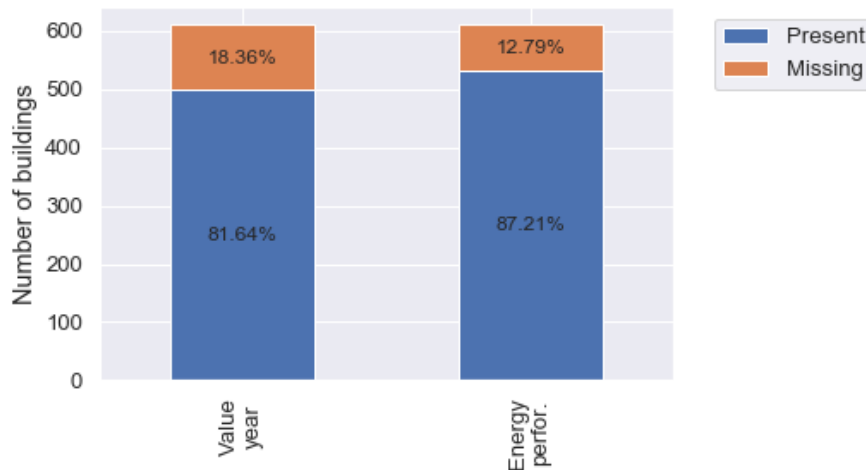


Figure 2. Occurrence of value year and EPC data in the database of the 610 buildings.

3.3. Applicability of performance indicators to the database in combination with non-destructive in-situ measurements

The performance indicators introduced above, can be divided into two distinct group; (1) indicators which parameters can be measured directly by using non-destructive in-situ measurement, and (2) indicators which cannot be instantaneously measured. The first group is represented by e.g.

airtightness which can be measured by blower-door test. Another class of these indicators is all service life indicators which rely on visual inspection of the building envelope, by using e.g. thermography analysis.

It is possible to perform blower-door test in any building from the database. However, in case of service life indicators one must take into consideration material limitations of the selected performance indicator. Table 2 shows to which materials individual service life indicators are applicable to, share of buildings in the database which have at least one façade made of corresponding material and total share of external walls with corresponding material.

Table 2. Overview of service life indicators and their applicability to individual buildings/facades in the database of 610 buildings.

Performance indicator	In database applicable to:	Share of buildings	Share of external walls
Area and Extension of degradation	All façade materials	100%	100%
Severity of degradation	Render, ETICS, Natural stone	61.80%	26.00%
Overall Degradation Level	Render	48.03%	17.58%

The group of performance indicators that cannot be instantaneously measured are e.g. the thermal transmittance (U-value) and hygrothermal performance indicators. For all these indicators, except U-value, rather extensive knowledge of the history of constructions and their related hygrothermal parameters (e.g. temperature, relative humidity) are needed. Thus, to use such an indicator and to perform current status or future risk assessment, one needs to perform a hygrothermal modelling. Ideally one needs to put into proper context data from long-term measurements with structural information of building envelope, combined with weather data.

The database indirectly provides complete weather data by storing the exact location of any building. However, structural information, which can normally be found in technical documentation, may be harder to obtain non-invasively. Many older buildings lack proper documentation such as technical drawings and documentations of previous interventions. The database does not contain any information whether the technical documentation is accessible and its extent. Unfortunately, the database itself provides only an incomplete picture about the building envelope, as it only holds information about façade materials and external insulation. The information on the wall composition is missing which makes the use of history dependable hygrothermal performance indicators rather problematic. Although the U-value is theoretically obtainable using thermographic analysis, the knowledge of the building envelope composition is also considered as vital as the U-value measurement method is reasonably reliable only for homogenous and heterogenous (masonry) constructions [9].

Buildings which are classified as 'brick buildings', and which have at least one part of the façade (either from outside or inside) made fully out of bricks, occurs in the database in 146 instances (37.37%) which corresponds to 22.91% of all façades in the database. Here, one may argue that the whole construction is made from masonry elements making the U-value and hygrothermal modelling available by measuring the thickness of the construction. The U-value is also theoretically verifiable by connecting results with thermography analysis together with energy performance data rejecting walls which may be insulated from the inside or may have other heterogeneity deviations. In case of brick buildings in general, the composition for other types of façades as well as the material properties may be deductible from similar buildings where the wall composition is known, making the calculation of U-value and hygrothermal performance indicators possible. Therefore, the hygrothermal performance indicators are theoretically applicable up to 253 (41.5%) buildings in the database. However, it is still impossible to know the correct wall composition with high degree of certainty for other types of buildings as their building envelope is often made of wood. Table 3 summarizes the individual groups of performance indicators, their applicability, and gaps in data.

Table 3. Summary of performance indicators groups, their applicability to buildings in the database of 610 buildings and gaps in data which prevent the performance indicators to be useful.

Performance indicator group	Data accessible from in-house database/non-invasive testing	Applicable to x % buildings	Gaps in data
General (Value year, Energy performance)	Yes - data in the database	87.21%	Missing values in the database (see Figure 2)
General (Airtightness)	Yes - blower door test	100%	-
General (U-value)	Yes - for brick buildings No - for other buildings	41.50%	Composition of building envelope
Hygrothermal	Yes - for brick buildings No - for other buildings	41.50%	Composition of building envelope
Service life	Yes - Visual inspection	see Table 2	-

3.4. Possible approaches in filling gaps in data

One of the most promising options which may help to fill gaps in data, is to make use of advanced machine learning algorithms. These can take an advantage of large amount of information which are available in a building stock level filling gaps in data or enriching database with new sets of features. For instance, Zeppelzauer [10] and his team was able to predict year of construction using convolutional neural networks and images from real-state agency. Similar technique can be theoretically used for value year prediction (high-level performance indicators). However, no such algorithm was found during the literature review. The energy performance is another high-level performance indicator which may be to some extent deduced as various papers using artificial neural networks and clustering algorithms have been published in the matter. Note that different researchers used different sets of features to make their predictions [11].

The composition of walls, which is vital for obtaining U-value (for majority of buildings) and for many hygrothermal performance indicators unnecessary hygrothermal modelling, represents the biggest gap in available data. No exact methodology which would allow one to determine building envelope composition was found. However, clustering analysis, an unsupervised machine learning algorithm allowing one to find hidden structures within data by grouping mathematically similar buildings close to each other in n-dimensional space, imply to be a promising method for obtaining the approximation of wall composition and also filling other gaps in data.

This method theoretically allows one to draw missing features for any building from its nearest neighbours (or nearest centroid) where the information is known. Different missing features may have linkages to different sets of data. Therefore, one must first determine which features have significant impact on a missing information that he or she is trying to fill. For instance, the feature living area in m² may have large impact in predicting Energy performance while small significance for Value year predictions. Clustering analysis has also its own limitations as it has problems running with incomplete sets of data. Therefore, eventually selected determining features with significant impact on prediction need to be complete.

4. Conclusion

This study has investigated the available performance indicators for status assessment and future risk assessment of buildings exemplified on an in-house database of 610 buildings. Based on a literature survey a number of performance indicators were identified that can be used on the available data.

Furthermore, gaps in the data was investigated combining proposed non-destructive in-situ measurements to make use of the performance indicators. Finally, methods to bridge the remaining gaps in data were discussed to evaluate data that is still missing.

The gaps in accessible data are present in all types of performance indicators. General performance indicators, except airtightness and thermal transmittance, are directly derivable from the database. However, relatively large number of buildings have missing values. Hygrothermal and service life performance indicators cannot be used with just the database at all as hygrothermal indicators heavily rely on the composition of a structure and service life indicators rely solely on visual inspection.

Finally, it is proposed that gaps in data may be overcome by the use of machine learning algorithms. Especially clustering analysis, an unsupervised machine learning algorithm, imply to be a promising method for obtaining any kinds of missing information from a building's mathematically nearest neighbour. Any form of gaps in data may be therefore theoretically filled. However, apart from the Energy Performance prediction, no such an application of clustering analysis has been found during the literature review.

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