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Manuscript title: Quantification of building performance to evaluate novel design methods

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Abstract

A framework is proposed to characterize in a holistic and quantitative manner the performance of buildings. This framework aims at using continuous performance assessment, from the design conception through the life of a building. The quantitative assessment will allow designers to move away from thinking of buildings a prototype that provides no feedback loop to designers towards analysing buildings as living laboratories that inform novel design approaches. To understand the value of the framework and any factors limiting its application a biomimicry approach was used as an example. Biomimicry principles capitalize on evolution to deliver continuous quality improvement and therefore these principles were found to be consistent with modern design objectives. A series of high-profile buildings were analysed based on publicly available data. Six buildings were shortlisted for a more in-dept analysis, nevertheless it became evident that for all these buildings there was insufficient data analysis, against the design objectives, to enable a holistic assessment of performance. To illustrate the weaknesses in the data set, the best documented building, the Council House Building (CH2) in Melbourne, Australia was analysed and areas where data was missing were established.

Keywords: buildings, structures & design, biomimicry, codes of practice & standards, social impact, environmental impact, UN SDG 11

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Introduction

The construction industry is complex and has enormous social, economic, and environmental impact (Aanuoluwapo-Oguntona and Aigbavboa, 2017). Its ‘products’ are necessary to fulfil the fundamental needs of any society, like shelter, transportation, clean energy, and water supply (Institution of Civil Engineers, 2020). Hence, prioritizing high-quality of construction projects becomes crucial to ensure prosperity and sustainability.

In contrast, there is much evidence suggesting that engineering projects are lacking quality. This can be observed through multiple occurrences of building collapses. In Lagos, several structural failures have been reported in recent years, resulting in deaths and injuries, all due to unregulated construction practices (Okunola, 2022). In 2021, a collapse of a Mexico City Metro overpass led to the death of 26 people, attributed to structural and technical issues (Kitroeff et al., 2021). The Surfside Condominium collapse in Miami resulted in the tragic loss of 98 lives. The 12-story structure failed due to the corrosion of the steel rebar within the concrete, caused by water penetration (Del Rey, 2024). Although the structural issues had been identified and plans for remedial work had been made and funded, the collapse occurred before any action could be taken. The Grenfell Tower fire in London (Moore-Bick, 2019), which resulted in 72 deaths, led to a review of the UK building regulations that described the construction industry as following a “race to the bottom” (Hackitt, 2018).

The prevalence of poor-quality engineering projects extends beyond specific instances of high profile building failures and is observed on various levels across different locations. Even in the most economically developed countries, poor-quality is widespread. A study conducted in the UK showed that the majority of participants believed older homes to be of better quality than new ones, with 32% specifically describing new builds as 'poor quality’ (Lago, 2024). The World Health Organization has estimated that 10-50% of households in Europe face issues related to dampness and mould, therefore increasing the risk of developing “respiratory symptoms, respiratory infections, allergic rhinitis and asthma” (World Health Organization Europe, 2009). Additionally, over a quarter of the structures in Sydney built between 2010 and 2017 were estimated to have

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defects (Crommelin et al., 2021). However, when actual quality assessment was conducted, as much as 51% showed signs of faults. Consequently, defects may be more common in modern construction than previously believed as many go undocumented, with water issues, cracking and fire safety issues being the most common (Kurmelovs, 2021).

The recurrent issues with building performance indicate a lack of explicit metrics against which quality can be benchmarked and deficiencies corrected. This highlights a fundamental gap in the understanding of the specific areas where shortcomings occur, hindering the implementation of effective corrective measures and hence the achievement of the intended quality. Given the typical complexity and the multiple objectives of construction products, it is very difficult to establish what is a high-quality project and how to measure it (Page and Gordon, 2017).

In general, the term quality refers to a “degree of excellence” (‘quality’, 2022) or a product’s ability to satisfy the customer (Kärnä, 2004). However, In the construction industry, quality is usually not measured but instead it is associated with meeting certain requirements, either regulatory or set by a client. It has been previously defined as “meeting legal, aesthetic and functional requirements in a project” (Mallawaarachchi and Senaratne, 2015) or by assessing the manner in which a project (or some specific feature that is desirable) is delivered, for example, the quality of a project can be linked to the quality of the workmanship or the presence of user comfort-enhancing features (Page and Gordon, 2017). As a result, the complexity and true representation of quality are overlooked. Unfortunately, there is a lack of agreement of what characterises an ‘excellent project’ that includes social, environmental, and economic factors (Alwaer and Clements-Croome, 2010). Nevertheless, for the civil engineering industry to deliver exceptional projects, it is essential to establish quantifiable criteria for assessing engineering excellence.

Quality control as a field is still a developing discipline across most parts of the world. In recent years there have been attempts to implement Total Quality Management in Europe, Japan, and North America (Hoonakker et al., 2010). TQM can be defined as ‘prioritizing quality, flexibility, and services rather than the cost and presumes that profits follow the quality’ (Patel, 2020). Thus, TQM’s primary advantage is prioritising quality over profits. Nevertheless, the lack of standardization within the construction industry makes the effective implementing of TQM very difficult (Hoonakker et al., 2010). Furthermore, TQM still primarily associates high quality with meeting the specifications set by a client or designer, rather than considering the quality of the structure itself for its inhabitants or society at large. Consequently, current building performance assessment methods remain arbitrary, failing to capture the complex nature of what it means to attain a high quality of a civil engineering project.

Numerous studies have been published presenting attempts to develop building assessment methodologies that could adequality represent the true quality of a project (Alwaer and Clements-Croome, 2010; Suratkon and Jusoh, 2015). These studies use expert-based opinion and engagement of all stakeholders in identifying quality indicators. However, there is still a pervasive lack of consensus regarding the essential criteria that should be employed to holistically evaluate buildings or how they should be established (Alwaer and Clements-Croome, 2010). Therefore, before identifying the factors that are tied to a project of high quality, the process of determining and testing those factors should be carefully examined.

Acknowledging the complexity of building quality, biomimicry draws inspiration from nature to improve quality through positive evolution. It is based on the recognition that nature has evolved over the last four million years and has created systems and strategies that are more efficient than the ones created by humans (Aanuoluwapo-Oguntona and Aigbavboa, 2020). It is believed that biomimicry can provide solutions to many human challenges. By incorporating principles inspired by nature into building developments, it can significantly enhance sustainability, particularly in areas such as energy efficiency and material optimization (Silva et al. 2024), therefore important areas of building quality. Consequently, the field offers the potential to be a model for creating quality standards that adequately mirror the complex technical, social, and environmental balance that a civil engineering project must achieve to positively serve society and the planet.

There have been many attempts to translate the solutions from nature into engineering specifications following both “bottom-up” or “top-down” approaches (Imani and Vale, 2022). The first identifies potentially beneficial features in natural organisms and tries to apply them in human design. In the latter approach, a design problem is identified first, and subsequently natural solutions that can serve to solve the problem are explored. Independent of the approach, it has not been possible to model or test the developed systems, so it is not possible to establish if indeed the methods can help to optimise quality in buildings (Garcia-Holguera et al., 2015). Nevertheless, existing studies provide further confirmation of the existing gap between research and practice in the civil engineering field.

In 2021, the Biomimicry 3.8 Institute, a bio-inspired consultancy, published the Biomimicry Life Principles, a collection of design lessons derived from nature. These principles embody the rules followed by all biological organisms and ecosystems. The six main principles include Evolve to Survive, Adapt to Changing Conditions, Be Locally Attuned and Responsive, Be Resource Efficient, Integrate Development with Growth, and Utilize Life-Friendly Chemistry. By adhering to these principles, a design has the potential to attain a quality comparable to that of natural systems and organisms (Baumeister et al., 2014). However, these rules currently remain arbitrary and have not yet been translated into the realm of building environments. This presents an opportunity to explore the main challenges associated with developing a quality assessment framework for buildings.

In this study the Biomimicry Life Principles will be used to establish a roadmap for the assessment of building quality. The objective is not to characterize the quality of the specific buildings used as examples, but to use the process by which quality is quantified as an attempt to devise a methodology that allows to quantify building quality as a function of these principles. The study uses publicly available data but acknowledges that additional proprietary data must exist but is not available to the authors.

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Methodology- Introduction

The current methodologies used for developing quality assessment criteria within the construction industry are prone to subjectivity and lack of ability to adequately capture the complexity of a building development. To address those shortcomings, biomimicry has been proposed in this study as foundation for establishing a new assessment framework. Consequently, a two-step methodology has been put forward, involving development of assessment criteria followed by their evaluation using publicly available information on high profile buildings. The summary of the procedure has been outlined below.

1. **Developing Assessment Criteria**

   Key to the assessment of quality is the development of adequate assessment criteria. These criteria should represent the societal expectations and be comprehensive in nature. Furthermore, should enable to weigh the importance of each criterion. Below a set of principles that enable generation of such performance criteria based on biomimetic objectives:

   1.1. **Identification of natural characteristics that contribute to efficiency of biomimetic design:** to establish effective assessment criteria, the primary objective of this methodology is to identify what are the characteristics of natural organisms that are shared on a holistic level.

   1.2. **Translating the identified natural characteristics into analogous building properties:** taking examples and case studies from the industry, the step involves finding the most adequate similarities between the principles found in nature and their equivalent application in building systems. The result will be a set of categories under which a building can be assessed.

   1.3. **Quantification of translated building characteristics:** proposing quantitative performance metrics for each of the categories to allow comparison across different building projects. It is recognized that this will lead to a subjective outcome, nevertheless, the purpose of this study is to deliver the methodology, but the quantification of the specific criteria will require an extensive consultation that is beyond the scope of this work.

Testing the assessment criteria

The assessment criteria will then be tested against a set of high-profile buildings. These buildings projects have all explicitly stated strong building quality drivers. This assessment will enable to characterize the way this methodology can be applied but also will allow to establish any shortcomings on the methodology but also on the availability of necessary information.

2.1 **Selection of a project to be assessed-** a project that serves as a representation of current utilisation of biomimicry in the construction industry is to be selected. The selection will be based on the availability and quality of data, so that the criteria can be tested to the highest extent possible.

2.2 **Application of the selected criteria to the chosen project-** this step aims to assess the extent to which a typical design of a biomimetic building aligns with the established assessment methodology. Simultaneously, it will be evaluated how well the available data on buildings fit into the developed categories.

Methodology- Implementation

1. Developing Assessment Criteria

1.1. **Identification of natural characteristics that contribute to efficiency of biomimetic design:**

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After comprehensive literature review, the Life Principles developed by the Biomimicry 3.8 Institute (see Figure 1) were selected as a foundation for the criteria development. These general principles, rooted in the embodied characteristics of biological organisms and ecosystems, are suited to translate into human design, aiming to mimic natural systems' performance and offer a holistic approach to building quality.

1.2 Translating the identified natural characteristics into analogous building properties:

A series of analogies between the Life Principles and building performance characteristics have been identified and the results have been summarised in Figure 2. The first column to the left shows the objectives or general virtues of the organism/building, establishing the main goals that buildings should be striving for. The second column shows the mechanism by which the goal is achieved, and the final column presents the quality consequence that closes the performance loop. To establish if a system is evolving in a manner that allows it to improve the effectiveness in which it fulfils its function, data needs to be gathered. This data, together with the modelling of the function, establishes the performance at each point in time. The evolution of this performance then allows to assess whether the effectiveness of the system is improving in time (third column from the left). For many of the objectives the mechanism by which the goal is achieved is the quality consequence, therefore in these cases there is no third column. A good example is how the use of life-friendly chemistry directly leads to the reduction of embodied carbon.

1.3 Quantification of translated building characteristics

Based on review industry performance reporting standards (Alwaer and Clements-Croome, 2010; Suratkon and Jusoh, 2015; BRE Global Ltd, 2009; LETI, 2020; International WELL Building Institute, 2022) the categories were developed into a scoring system that incorporates tangible performance requirements. The specific benchmark that a building must obtain in each of the categories has been also outlined. By establishing clear and measurable performance criteria, this approach ensures a comprehensive assessment of a building's performance across all relevant categories. If data in a certain category is not available, no points shall be awarded. The final score for an engineering project constitutes the sum of the points achieved in each category and aims to represent to what extent the application of biomimicry principles has improved its performance.

Performance is quantified using a scale of 5, commonly employed as a rating system (Yu et al., 2016), thus enhancing stakeholders' ability to intuitively judge and compare performance. Before score weighting, each category feature can achieve a maximum of one point. Quantitative criteria are described for each category to determine the performance benchmark, with 3-5 distinct score values selected to optimize the criteria's efficiency and analysis performance. Lastly, weighting is assigned to each category within each Life Principle to adequately reflect their importance, ensuring that the sum of points within each Life Principle equals 5. All scores are then aggregated to allow comparison across projects.

It's important to emphasize that while the scoring system is based on stakeholder perception and is arbitrary, it aims to be comprehensive. A holistic performance assessment requires evaluating all relevant categories. The paper’s goal is not to define an ideal scoring system but to present a methodology and identify areas for improvement. Therefore, the actual quantitative performance is not fundamental to the conclusions.

The first step to develop a series of categories that can be allocated quantitative values requires to identify the relationships between the individual objectives and the mechanisms that are used to achieve them. In many cases the same mechanism can be used to establish several objectives, in this case all these objectives are amalgamated into a category. The attainment of an objective is not a binary process, but the objectives can be fulfilled at different levels of success. The qualitative characterization of the level of success is labelled here a feature. Despite the continuous nature of the level of success, it must be categorized in a quantitative manner. The quantitative categorization of success is defined here as a score. Finally, the stakeholders can grant a certain category different importance to another category, thus scores must be weighted. A summary of these four different processes is presented in Table 1.

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Construction projects are defined by physical variables that are associated to their functionality. These physical variables are integrated into systems and will have an unavoidable impact on one or more of the different categories. For a complex project, the number of critical variables can be very large and can be arranged in complex systems with multiple interdependencies. However, for this study, only a small set of physical variables will be considered and structured around systems with minimal interdependencies. While, the chosen variables/systems have been defined, through review of the literature (Li et al., 2020; LETI, 2020; BRE Global Ltd, 2009), as being the commonly referred to by the construction industry, the final choice of variables was defined by the authors. These variables are listed in Table 2.

The different categories are structured in the series of tables below. Some categories require systems to be assessed independently, with individual system scores averaged. However, in other categories such as "Biodegradable materials," development is evaluated holistically, as there are no separate mechanisms to achieve specific performance functions. An evaluation method is specified under each category table. In each table there are five columns, the first column shows the principle as established by Figure 2 and summarized into the relevant categories.; the second provided a tangible assessment method; the third gives a quantitative score. Each category has been broken down into a range of discrete performance objectives. The fourth column informs about the relevant weightings. The final column provides a commentary on the reasoning behind the specific choices.

Table 3 outlines the data quality metrics used to evaluate a building's ability to collect performance data, determined solely by reporting rates. While other indicators were considered, the analysis was limited to this basic metric due to the lack of necessary data. In this category, each system listed in Table 2 should be assessed individually.

The way in which data is reported is an important aspect of any evaluation, thus it is essential to characterize the data before any of the principles gets evaluated. Table 3 provides an approach towards qualifying the quality of the data available for a specific building. For simplicity, this approach is limited to the rate of reporting, nevertheless, other quality indicators such as type of data, data density, precision of instrumentation, etc. could have been included.

Table 5 outlines the objectives or general virtues of the organism/building related to its capacity to recover from stressors, thereby preventing failure. In this category, each system listed in Table 2 should be evaluated individually.

Table 6 outlines the objectives or general virtues of the organism/building that demonstrate its local integration and responsiveness. In this Life Principle, each category should be evaluated separately, and the scores summed. In the Sourcing Distance category, assess the proximity of material, water, and energy resources, as these are essential for civil engineering projects. In the System Integration Interval category, evaluate each system listed in Table 2 individually. The remaining category should consider the development as a whole, assessing its characteristics against the values in Table 7.

Table 8 outlines the objectives or general virtues of the organism/building regarding Resource Efficiency in material and energy use. In the System Efficiency category, each building system should be evaluated separately against the standard performance values summarized in Table 9. In the Resource Circularity category, systems should also be assessed individually, with the exception of the structural system, as it does not apply to this category.

The percentages in the System Efficiency category are established against a specific benchmark. Table 9 summarises all the systems evaluated, and the benchmark performance used as the basis for the comparison.

Table 10 outlines the objectives or general virtues of the organism/building related to its integrated development and growth. In this category, the development should be assessed holistically.

Table 11 outlines the objectives or general virtues of the organism/building concerning its user-friendly chemistry. In this category, the development should be assessed holistically.

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2. Testing the assessment criteria

2.1 Selection of a project to be assessed

To test the proposed criteria a series of existing developments was analysed. Based on the reviewed project literature (Biju, 2020; Ali, 2016; Bligh and Glasby, 2013; Coffman, 2018; Dahl, 2013; Hes and Walker-Morrison, 2012; Klimke, 2002; The Overview, 2023), a set of projects was shortlisted as well documented examples of biomimicry in the building environment. These projects were qualitatively assessed in terms of which presents the biggest potential to provide relevant analysis outcomes. An important variable for this initial assessment was the date of completion. It was necessary for the date of completion to allow for the assessment of the evolution of the building in time. The shortlist of selected projects and their brief description was summarised in Table 11. The complete list of projects evaluated is presented in Appendix A.

2.2 Application of the Selected Criteria to a chosen Project

An assessment of data quality and accessibility was conducted for each of the shortlisted projects. Publicly available data is essential for a transparent assessment of performance. After an exhaustive analysis of all the available data, it can be generally ascertained that there is a dearth of publicly available high-quality data pertaining to these developments. The result is that none of the buildings shortlisted in Table 12 allowed for a comprehensive assessment of all the relevant areas described in the previous section. It needs to be noted, that most of the publicly accessible information serves commercial objectives rather than serving as reliable data suitable for the purposes of this analysis.

To illustrate the data deficiencies, this study analyses the shortlisted building with the most comprehensive set of publicly available data. The Council House Building in Melbourne (CH2) was chosen as the primary case study, owning to the City of Melbourne's publication of "Design Snapshots," which includes technical and design information about the building. Notably, the term “biomimicry” was not explicitly invoked in the designers’ assertions. Nevertheless, the high-level environmental strategies applied by the CH2 building are directly aligned with the Biomimicry Life Principles, which shape the framework for this analysis. Hence, this development stands out as the most suitable subject of study within the current research context. Figure 3 illustrates the completed Council House Building (CH2).

CH2, a fully operational office building in Melbourne, Australia, was completed in 2006 with the purpose of addressing the issue of outdated office structures nearing the end of their service life (Hes and Walker-Morrison, 2012). Designed as an innovative space, it aimed to pioneer green technology adoption, focusing on energy efficiency and creating a high-quality environment for its occupants.

A key aspect of the building's functionality is its ability to adapt to diverse climatic conditions through the utilization of physical phenomena rather than relying solely on electrical devices. This allowed for effective day and night, as well as summer and winter modes. Local environmental characteristics also significantly enhance energy efficiency (Stewart et al., 2012).

Additional features that make the structure especially suitable for this analysis include water and energy conservation, strategic material selection, and on-site electricity generation. This on-site generation was achieved through a combination of photovoltaic cells and a gas-fired microturbine, with the waste products being utilized in other building systems (Chung, 2015).

Distinguished in its field, the development's strategies not only prioritize energy efficiency but also focus on encompassing social aspects and aligning with local conditions. This positions CH2 as a compelling case study, amenable to the examination of a diverse array of data against established metrics.

Results

Council House 2 in Melbourne has been comprehensively evaluated using the established criteria derived from all available public data. The summarized overall scores are presented in Table 13. A detailed breakdown of the scores awarded, along with justifications for these scores, can be in

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the Appendix B. However, it was generally challenging to assign specific points using direct, concrete measures and quality performance data values, as the level of information provided in the design details did not reach such specificity. When feasible, the data has either been extrapolated or translated into suitable metrics. These instances have been noted and reported within the score breakdown and can also be found in Appendix B.

It would have been the objective of the present study to conduct a detail comparison of a few buildings showing their performance in the different areas as well the comparison between their aggregate performance. Nevertheless, from the overall score of 6.65/30 (Table 13) obtained by the best documented building, this comparison is not possible. More detail perusal of the scores and of the data breakdown presented in Appendix B, will show that many areas were awarded a zero because the data was not available. Even in cases like energy consumption, where model predictions were conducted as part of the design, no data was collected and analysed in a manner that those prediction were validated through the time evolution of the building.

Discussion

It has been a long tradition to design and construct building projects as prototypes. No two buildings are the same and therefore it is unclear how lessons learnt from one project can translate to a different project. As a result, performance assessment of a building finalizes with the final inspections associated to handover. The evolution of the performance of a building in time is therefore not monitored with enough detail to establish whether the building is preforming as designed or if its evolution in time is one leading to better or worse performance. Deterioration is often considered a natural part of this evolution.

This study attempts to establish a comprehensive set of variables to understand building performance in line with current societal goals (United Nations, 2015). The objective was to develop a framework around the principles of biomimicry accepting that natural evolution leads to continuous performance improvement. This framework is comprehensive in nature to account for the full complexity of these systems and the interactions between the different building characteristics. The framework was simplified to what was considered the minimum set of variables, dependencies, and interactions. Any further simplification would have most likely led to omissions that will limit the value of the quantification process.

Less emphasis was given to the quantitative scoring in that this aspect of the framework needs to evolve as a function of expert opinion from a broad range of stakeholders as well as the continuous use of the framework. The continuous assessment of buildings will enable the refinement of the scores with the consequent improvement of the framework outcome.

An observation that clearly emerged from this study is that despite the explicit performance objectives currently set for building projects, they are still being treated as prototypes that offer no learning values. The evidence is the lack of data collected, the poor processing of the data and the limited relationship between the information collected and the design objectives. Data collection is so poor that none of the long list of projects studied offered a set of adequate data that enabled a comprehensive study. In the cases where any data was collected in time, this was very narrow focused and thus promoting tunnel vision in the way performance objectives have been defined. This tunnel vision has a clear relationship with the identified failures. An excellent example is the Grenfell Tower where the primary focus was on the reduction of energy consumption to the detriment of many other performance metrics such as safety.

The example of the Council House 2 in Melbourne used in this study can therefore not be treated as a benchmark of the quality of information that is necessary for such a comprehensive analysis. Instead, it should be treated as the best that is available and therefore used to establish what additional data needs to be collected. Detailed analysis of Appendix B will show that the data collected for this building focuses on energy, water, and lighting, nevertheless, this data is not used to establish the evolution of performance of the building, nor it is used to benchmark the building against the design objectives. Thus, the evolution of the building in time cannot be established. Areas that are regulated, such as structural performance, ventilation or fire safety are not assessed at all. For these performance categories no data is collected and therefore they are simply assumed to perform as intended. In addition, the design approaches and safety factors used in design are never validated and as a result there is no information that enables the designer to learn lessons that can lead to improvements and optimization in future designs.

Particularly important is the fact that there is no study being performed indicating post occupancy user engagement, no data has been found about the exact number and types of facilities currently being used in the building or the level of stakeholders' engagement throughout the building's operation. While there was significant stakeholder's engagement during the design stage, no information has been found about how the community has influenced the direction of the building evolution and direction after handover. Hence, no points could be awarded in any of these categories. The approach to data is to highlight some key features that make the building attractive but still treats the building as a prototype from which very few lessons can be learnt.

Conclusions

Biomimicry principles provide a comprehensive assessment of performance for buildings that covers key societal goals for buildings and infrastructure. This study presents a framework that has the potential of using these principles to assess the quality of a building in time. However, the study demonstrates that to utilize this framework, buildings must be designed, constructed, and managed in a way that allows for the collection of appropriate data and performance models necessary for analysis. Without such information, buildings will continue to be treated as prototypes, offering no lessons to enhance design and construction. This framework explicitly provides indication of the necessary data for future projects. Traditional frameworks introduce subjective criteria, and how to quantify these criteria must be carefully considered. Stakeholder engagement methods, such as expert opinions, can continuously inform and improve performance quantification; however, for this to evolve verifiably, appropriate data must be collected and aggregated to inform stakeholders about building performance at each stage over time. This study establishes that there is currently a lack of appropriate publicly available data for comprehensive building performance assessment. his deficiency correlates strongly with the increasing number of reported failures and poor performance in buildings, making it impossible to establish an adequate framework for performance assessment.

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Appendix A

The complete list of projects evaluated for testing the assessment criteria. A preliminary set of scores was awarded for each of the life principle to all these projects nevertheless some were discarded because of lack of available information.

Project Name	Location	Year of completion
Eastgate Centre	Harare, Zimbabwe	1996
Council House Building (CH2)	Melbourne, Australia	2006
Sinosteel International Plaza	Fuzhou, China	2006
Esplanade Art Centre Singapore	Singapore	2002
Benin National Assembly	Porto Novo, Republic of Benin	2019
Bosco Verticale	Milan, Italy	2014
BIQ House	Hamburg, Germany	2013
The University of Queensland Global Change Institute	Brisbane, Australia	2013
Gardens by the Bay	Singapore	2012
National Aquatic Centre	Nejing, China	2003

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Appendix B

Assessment tables including a justification for scores awarded in the process of CH2 evaluation.

1. Evolve to survive.

System	**Category**	**Score Awarded**	**Comments**	**Source**
Structural	Performance Reporting	0	No evidence has been found that there is a system put in place capable of tracking building's structural performance.	NA
	Quality and Performance Evolution	0	No evidence has been found proving that the building's structural performance has been improved since the beginning if its operation. However, significant challenges have been encountered during preparation of the concrete mix that were resolved through experimentations and maintenance actions. This could potentially indicate an evolution of the structural material. However, as the criteria refer to an evolution of the system throughout its operation stage,	(Hes et al., 2005)

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			no points could be awarded in this category.	
Thermal	Performance Reporting	1 * 2 = 2	Temperature sensors are present in the building. They are in concrete elements on each floor and outside of the building, at the rooftop station, to assess the outdoor conditions. Information about the model of the device and system used has not been found. Comparing typical systems available on the market continuous recording provides outputs in intervals less than one second. The Microchip Technology TC72 was assumed for the study, that records temperature every 150 ms. Heat loss is not directly measured in the building. However, points have been awarded in this category as it can be calculated based on recorded temperature variations and amount of thermal energy supplied to the building.	(Architecture & Design, n.d.; Microchip Technology Inc., 2002)
	Quality and Performance Evolution	0	No evidence has been found proving that building's temperature performance has	NA

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			been reviewed since the beginning of its operation, neither by a professional nor by a digital system, and that alternations to the building have been made as a result, so that he thermal performance is improved. Hence, no points have been awarded in this category.	
Water	Performance Reporting	1 * 2 = 2	Based on Australian Plumbing and Drainage Act 2018, every building must include a water meter that is „pattern-approved" and put in place by a designated professional. Due to Australian Standard 7474, the meters must be connected to a local intelligence device. It has been indicated that in CH2 the water meter is connected to the cooling, heating and irrigation system and allows for remote data access and continuous monitoring. There is however no evidence that the building tracks the number of its occupants, which is necessary for obtaining performance data indicated by	(City of Melbourne, n.d.; NSW Government, 2022; Smartvatten, n.d.; State of Queensland, 2018)

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			this criterion. However, as the building used as an office facility, it has been assumed that it is likely for the number of people present in the building is tracked, e.g. through a sign-in procedure. Additionally, Australian Building Fire Regulations 2008 indicate that there is an obligation to limit the number of people in the building to avoid an unreasonable risk, hence it is likely that the occupancy is monitored. Hence, full scores are going to be awarded in this category. However, based on the assumptions the outcome introduces uncertainty.	
	Quality and Performance Evolution	0	No evidence has been found proving that building's water performance has been reviewed since the beginning of its operation, neither by a professional nor by a digital system, and that alternations to the building have been made as a result, so that the water	NA

			performance is improved. Hence, no points have been awarded in this category.	
Ventilation	Performance Reporting	0	No evidence has been found about the device or system that is used to monitor the ventilation performance. However, in its design snapshots it has specified that a goal to provide 22 l of fresh air per second per person of fresh air has been set. Providing optimal Indoor Environmental Quality conditions has been mentioned as the design driver by many sources It was therefore assumed that standard methods are utilised to measure the ventilation performance within the building. However, it can't be assumed with enough certainty how often those measurements are performed, hence no points have been awarded in this category. No information has been found proving that there are sensors monitoring the CO2 level in the	(City of Melbourne, n.d; Paevere and Brown, 2008)

			building. However, a post occupancy study has been conducted that performed CO2 levels measurements. Nevertheless, it was a onetime study, and there is no evidence that the performance recording is done in more regular basis. Hence, no points overall could be awarded in this category.	
	Quality and Performanc e Evolutiom	0	No evidence has been found proving that building's ventilation performance has been reviewed since the beginning of its operation, neither by a professional nor by a digital system, and that alternations to the building have been made as a result, so that the ventilation performance is improved. Hence, no points have been awarded in this category.	NA
Lighting	Performanc e Reporting	1*2 = 2	There are sensors present in the building recording the sunlight coming in and adjusting the system accordingly. The sensors record the luminosity in different parts of the building. Ambient	(Ada et al., n.d; City of Melbourne, n.d)

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			environmental controllers are used for that purpose; the exact device and system has not been specified. A generic light sensor has a capacity of generating outputs every several ms. For the study an output every 100ms has been assumed. Hence, full points have been awarded in this category.	
	Quality and Performance Evolution	0	No evidence has been found proving that building's lighting performance has been reviewed since the beginning of its operation, neither by a professional nor by a digital system, and that alternations to the building have been made as a result, so that the lighting performance is improved. Hence, no points have been awarded in this category.	NA
Energy	Performance Reporting	1 * 2 = 2	Due to Australian National Measurement Act 1960, every development is required to install necessary meters. On that basis it was assumed that the data is being continuously	(AEMO Markets in consultation with the National

			recorded. The assumption however introduces uncertainties as the exact information about utility measuring system has not been found.	Measurement Institute, 2021)
	Quality and Performance Evolution	0	No evidence has been found proving that building's energy performance has been reviewed since the beginning of its operation, neither by a professional nor by a digital system, and that alternations to the building have been made as a result, so that the energy performance is improved. Hence, no points have been awarded in this category.	NA

2. Adopt to Changing conditions

System	Category	Score Awarded	Justification	Source
Structural	Self-healing properties	0	No evidence has been found that the system has self-healing properties.	NA

	System failure detection	0	No evidence has been found that the building utilises a structural failure detection system, e.g. through Structural Health Monitoring.	NA
	Back-up potential	0	There is little available information about the structural design and strategies related to the development of CH2. No evidence has been found that strategies have been developed in case of structural failure of the building.	NA
Thermal	Self-healing properties	0	No evidence has been found that the system has self-healing properties.	NA
	System failure detection	0	No evidence has been found that there is a system put in place allowing to recongnise a failure within the thermal system.	NA
	Back-up potential	0.5 * 2 = 1	The cooling and heating system within the building has many components that work independently to provide optimal conditions. It has been assumed that if one of those systems fail, the operation of others can partially restore the performance of the building. There is however no evidence that the full performance can be restored of one of the elements fail.	(City of Melbourne, n.d.)

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			Hence, only partial points have been awarded in this category. The thermal system elements include chilled ceiling panels, chilled beams, a shower tower, phase change thermal energy cooling storage and a night purging process.	
Water	Self-healing properties	0	No evidence has been found that the system has self-healing properties.	NA
	System failure detection	1*1 = 1	Evidence has been found that the meters installed in the building allow for „greater ability to detect leaks and key water area inefficiencies". The second point indicates that the system is able to detect inefficiencies and faults in the system before that failure happens, therefore full points were awarded in this category.	(City of Melbourne, n.d.)
	Back-up potential	0.5 * 2 = 1	Evidence has been found proving decentralisation of the water system within the building. The water is obtained in two ways: through rain-water harvesting and through treating municipal sewage water. It has been assumed that if one of those systems fails, the performance can be restored through utilisation on the second one.	(City of Melbourne, n.d.)

			Additionally, a significant proportion of the water within the building is recirculated, therefor in case of water system failure, the pressure of the system will be reduced. There is however no evidence indicating that full performance can be fully restored once one of those systems fails. Hence, partial points have been awarded in this category.	
Ventilation	Self-healing properties	0	No evidence has been found that the system has self-healing properties.	NA
	System failure detection	0	There is no evidence indicating that there is a mechanism in place that allows for ventilation failure detection system.	NA
	Back-up potential	0	Information has been found that the ventilation in the building has been provided by use of mechanical system. No information has been found that the system is decentralised and that the performance of the system can be restored once the system, or its part, fails. From the user perspective, the airflow can be operated at the level of every workspace. In this case, in case one of those mechanisms fails, the	(City of Melbourne, n.d.)

			performance can be restored by use of remaining vents. However, it has been decided that this is too small proportion of the system to award points in this category.	
Lighting	Self-healing properties	0	No evidence has been found that the system has self-healing properties.	NA
	System failure detection	0	There is no evidence that there is a failure detection system for the lighting installation.	NA
	Back-up potential	0.5*2 =1	As the building has an adequate access to natural light, it can be argued that is the lighting system fails, throughout the day it performance can be restored by sunlight. However, this cannot be applied during the night hours, so the argument did not contribute to allocation of points. Additionally, as every working desk has an lighting installation, it can be argued that if one of them fails, other workspaces will provide and alternative utility. The building also is separated into individual lighting zones of no more than 100 m^2, which implies decentralised design. As a result,	(City of Melbourne, n.d)

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			partial points have been awarded in this category.	
Energy	Self-healing properties	0	No evidence has been found that the system has self-healing properties.	NA
	System failure detection	0	No evidence has been found suggesting that there is a failure detection system in terms for the energy installation.	NA
	Back-up potential	0.5*2 = 1	Evidence has been found proving decentralisation of the energy system within the building. The energy is partially produced by use of solar panels and partially through utilisation of wind cowls. The remaining energy requirement is met through utilisation of a „gas-fired co-generation plant". Additionally many energy saving appliances and passive house principles have been used, so that if the system fails the pressure on the energy system will be smaller. It has been assumed that in case one of the energy system fails, the performance can be partially restored by the utilisation of remaining alternatives. However, there is no evidence suggesting that in case of system	(Hes et al., n.d.)

			failure, full performance can be restored, hence partial points have been awarded in this category.	

3. Be locally attuned and responsive

System	Category	Score Awarded	Justification	Source
Energy	Sourcing Distance	1 * 2 = 2	All the energy in the building is sourced on site. Solar panels and wind cowls are utilised to generate energy. Additionally, an on-site electricity co-generator is used for meeting remaining energy requirements. Hence, full points were awarded in this category.	(City of Melbourne, n.d.)
Material		0	The two most significant materials mentioned in the literature in relation to CH2, are steel, concrete, timber, and PVC. Therefore, they were assessed in this category. It has been stated that 100% of steel for the construction was imported from Thailand, which in terms of distance far exceed 1000 km. No information was found in regards of where the concrete constituents were sourced. It was stated that timber used in the	(Gillian, 2010)

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			facade came from old housing frames. Although it can be assumed that the frames come from Australia, this information cannot be confirmed based on the existing literature. As a result, no points could be awarded in this category.	
Water		1*2 = 2	25% of the building's potable water requirements is provided through rainwater harvesting within the building's boundaries. The remaining demand is met through on-site grey water and black water treatment. Hence, maximum points were awarded in this category.	(City of Melbourne, n.d.)
Structural	System adaptation interval	0	There is no evidence that the structural system adjusts based on daily and seasonal patterns.	NA
Thermal		(0.35+0.35) * 1 = 0.7	There is evidence suggesting that the thermal comfort in the building is ensured by utilising both daily and seasonal cyclic processes. There are several mechanisms utilised to achieve that, among others, using thermal mass of concrete elements to regulate the internal temperature. Through review of the design considerations in the building it	(City of Melbourne, n.d.)

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			cannot be stated that the building will be able to adapt if the annual temperature patterns will significantly change in the future. Hence, partial points were awarded in this category.	
Water		0.35 * 1 = 0.35	There is no direct evidence that the water system is attuned to daily and seasonal changes in the local environment. However, some cyclic processes were utilised in the design, like the irrigation system for the vertical garden. It utilises water crystals, which physical behaviour controls the water supplied. Additionally, utilisation of a water harvesting system can be interpreted as a seasonal adaptation, as it stores more water in the wet seasons and utilises it in the dry season. As those solutions compromise only a proportion of the water system, partial points were awarded in this category.	(City of Melbourne, n.d.)
Ventillation		0.35 * 1 = 0.35	There is evidence suggesting that the ventilation system within the building incorporated daily cyclic processes, like opening windows at	(City of Melbourne, n.d.)

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			night to allow for „purging with fresh-air ventilation”. However, no information has been found proving that the system is adjusting seasonally or have a capacity to adjust with changing climate. Therefore, partial points were awarded in this category.	
Lighting		0.35 * 1 = 0.35	Evidence has been found that the timber shutters on the Western Facade adjust on daily basis to accommodate for the position of the sun and provide optimal lighting conditions. There is no evidence that the system changes on seasonal basis or includes mechanism that will allow it to adjust to changing climate. As a result, only partial points were awarded in this category.	(City of Melbourne, n.d.)
Energy		0	There is no evidence proving that the energy harvesting systems, i.e. solar panels and wind vowels change their operation characteristics on daily or seasonal basis or were designed to accommodate for changing climate conditions. Hence, no points were awarded in this category.	(City of Melbourne, n.d.)

Contribution to the local area	Outdoor air quality	0	Even though the presence of vertical gardens and green rooftop of the building suggests that the outdoor air quality might be improved, no studies or data has been found that analyse the influence of the building on the local area's air quality. Hence, no points were awarded in this category.	NA
	Green Space	1*2 = 2	Evidence has been found stating that CH2 provides at least the same amount of space covered in greenery as it occupies. This is achieved by utilising both green rooftop and vertical green panels. No information has been found about the exact area the greenery covers. However, before the development another building used to exist there. Based in visual analysis and archive photographs, it was assumed that it did not provide green space. It was further assumed that the green areas introduced by CH2 can be counted as the net green areas added to the surrounding. Hence, full points have been awarded in this category.	(Gillian, 2010; The Hidden Panorama, 2017)

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	Energy Generation	0	Within the building, the energy is partially harvested and partially provided by an onsite energy co-generation system. That indicates that it harvests less energy than its demand, hence no points were awarded in this category.	(City of Melbourne, n.d.)
	Water harvesting	1 * 2 = 2	"The entire system will have the capacity to provide 100,000L per day, 45,000 of which will be used in CH2 and 55 000L for other Council purposes such as CH1, street cleaning and garden irrigation". Evidence has been found that the building harvests significantly more water than its demand. It has been stated that the system has the capacity to provide 100 000 l of water per day. Its demand has been estimated at 45 000 l per day. The remaining 55 000 l is intended to be utilised by City Council Purposes. As the building donated more water to the local area than it uses itself, full points were awarded in this category.	(City of Melbourne, n.d.)

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	Urban wind reduction	0	There is no evidence suggesting that the building positively contributes to the urban air patterns in the local area. Hence no points could be awarded in this category.	NA

4. Be resource Efficient- material and Energy

System	Category	Score Awarded	Justification	Source
Structural	System Efficiency	0	No evidence has been found related to the efficiency of the structural system, therefore no points were awarded in this category.	NA
	Resource Circularity	0	There is no evidence suggesting that the building is recycling resource in terms of its structural performance.	NA
Thermal	System Efficiency	0	Even though careful estimations and modelling have been performed at the design stage, the data about the obtained heat loss parameters within the building have not been found. The design brief of the building states that the building design was driven by passive house principles. However, the building is not certified by the Passivhaus Standard. It cannot be therefore confirmed that actual Passivhaus performance levels have been	(City of Melbourne, n.d.)

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			obtained. Hence, no points could be awarded in this category.	
	Resource Circularity	0	It is approximated that around 100 kW of energy generated by the building will be recovered and used for direct heating. However no information has been found about the energy required to operate heating and cooling systems in the building, thus it is impossible to calculate what percentage of energy is recirculated. As a result, no points could be awarded in this category.	(City of Melbourne, n.d.)
Water	System Efficiency	1 * 2 = 2	It is stated that the water consumption in the building is 31 l per day and per person which far exceeds the standard requirements by more than 100%. Hence full points were awarded in this category.	(City of Melbourne, n.d.)
	Resource Circularity	0.5 * 2 = 1	It is stated that 72% of water demand is provided through recycled means, by treating grey and black water. Hence, corresponding amount of points	(City of Melbourne, n.d.)

			have been awarded in this category.	
Ventilation	System Efficiency	1*2 = 2	The ventilation system in the building was designed to provide 22 l of fresh air per second per person, which far exceeds the assumed standards. Hence a maximum amount of scores have been awarded in this category.	(Gillian, 2010)
	Resource Circularity	0	One of the design goals for the building was not to recycle the air within the building, but provide fresh air access for the occupants at all times. Hence no points have been awarded in this category.	(City of Melbourne, n.d.)
Lighting	System Efficiency	0	Evidence has been found that only low-intensity lighting utilities are installed in the building that have lighting power density of no more than 2.5 Watts per 100 lux. Translating this value into comparable units, that accounts to 40 Lm/W, which is far less than European regulatory standards. Hence, no points have been awarded in this category.	(Gillian, 2010)

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	Resource Circularity	0	There is no evidence that circularity principles were used in lighting system design. Hence no points have been awarded in this category.	NA
Energy	System Efficiency	0.25 * 3 = 0.75	The energy consumption data for the building after the commencement of its operation has not been found. However information about the predicted energy consumption through modelling at the design stage has been established. After further analysis it has been decided that the data is not accurate enough to be used for the analysis, e.g. the Net Lettable area is significantly smaller than the actual outcome (7488 m^2 in the analysis and 9373 m^2 actual). A statement has been however found claiming that the building uses 50% less energy than a benchmark for Australian offices. Based on information provided by Australian government bodies, this value lies between 30-40 kW per m^2	(The Hidden Panorama, 2017; City of Melbourne, n.d.)

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			calculated on annual basis. A more rigorous value of 30 kW has been assumed. Therefore it has been estimated that the building energy consumption is less than 15 kW per m^2. Hence partial points have been awarded in this category.	
	Resource Circularity	0	No evidence have been found that there are energy recirculation mechanisms used within the building. Hence, no points have been awarded in this category.	NA

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5. Integrate development with growth

Category	Score Awarded	Justification	Source
Change in user occupancy	0	There is no study being performed indicating post occupancy user engagement, hence no points have been awarded in this category.	NA
Number of facilities	0	No data has been found about the exact number and types of facilities currently being used in the building or the level of stakeholders’ engagement throughout the building’s operation.	NA
Community Involvement	0	There have been strategy in terms of stakeholder’s engagement during the design stage, but no information has been found about community influence of the direction of building evolution and direction. Hence, no points were awarded in this category.	(Jones, 2008)

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6. Use life-friendly chemistry

System	Category	Score Awarded	Justification	Source
The Building	Biodegradable Materials	0	The main materials used for the construction in CH2, mentioned in the Assessment and Selection of materials for Melbourne City Council House 2 are concrete, steel, timber and PVC. Even though glass has not been taken under consideration in the document, another source states that there is a 50:50 ration of façade to glass area in the building. Hence, it was assumed that the significant amount of glass has been additionally utilised in the building. Out of the mentioned materials only timber can be classifies as biodegradable. Even though the information about the exact volumes of materials used for the construction, it has been identified that the proportion of timber by volume constitutes to 25%, which is the benchmark in this category. It is due to the fact that it has been utilised as a façade element and not in the structural system. Hence, no points have been awarded in this category.	(Heset al., 2005; City of Melbourne, n.d.)
Embodied Carbon	Steel	0	It has been specified that only recycled steel is going to be utilised in the design. However, the exact embodied carbon has not been specified. Therefore, a standard value	(City of Melbourne, n.d.)

			has been assumed. Embodied carbon of steel made from scrap is approximately 80 gCO2/kg. Transportation of the material must be additionally accounted for. On average the distance between Melbourne and Thailand is 7500 km is straight line. Assuming sea transport a distance of 1000 km has been assumed. The emission of a very large container vessels can be quantified as 3.0 g CO2 eq/tkm. Transferring it into value relevant for this category this is equivalent to 30 gCo2eq/kg. Therefore the total EC of the recycled steel is 110 gCO2 eq/kg. Hence, no points have been awarded in this category.	
	Glass	0	The glass used was not specified however due to the nature of the building a standard value of laminated glass has been assumed. The raw material production stage is responsible for approximately 1,900 gCO2 eq/kg whilst the glass manufacturing stage is responsible for 7,300 gCO2 eq/kg. Road transport consumes 200 gCO2 eq/kg per 1000 km with an estimated 3000km traveled across the life cycle of the glass the emissions equate to 600 gCO2 eq/kg therefore the estimated total EC of laminated glass is 9,800 gCO2 eq/kg. No points will be awarded this category.	(City of Melbourne, n.d.)

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	Timber	0.25	The timber used with the structure was reclaimed timber, as the exact embodied carbon was not specified an estimate will be made using standard values. The salvage and processing of reclaimed timber has an EC of approximately 35 gCO2 eq/kg whilst transportation carried out by diesel lorry accounts for approximately 20 gCO2 eq/kg. The total embodied carbon for using reclaimed timber is 55 gCO2 eq/kg.	(Energy Efficiency Council, 2021; City of Melbourne, n.d.)
	Concrete	0	The embodied carbon of the concrete was not specified as such the embodied carbon of the concrete was estimated based on a standard value. The extraction of raw materials contributes 540 gCO2 eq/kg towards the EC whilst the manufacturing stage contributes a further 260 gCO2 eq/kg. The embodied carbon in the transport stage includes the transportation of raw materials and the transport of the concrete to site, the EC is 35 gCO2 eq/kg. The total embodied carbon is therefore 835 gCO2 eq/kg. Therefore, no points have been awarded in his category	(Energy Efficiency Council, 2021)

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Tables

Table 1- Structure that is used to restructure the objectives of Figure 2 into quantifiable categories.

Category	Feature	Score	Weighing
A certain Life Principle can correspond to more than one performance mechanism. Therefore, categories reflect the areas of building performance relevant to a certain Life Principle.	Features reflect different levels to which a building succeeds in a specific category. Each feature has an associated qualitative indicator that provides the basis for systematic assessment.	Score are awarded based on which benchmark the building or its system achieves. For each feature, the building can achieve a maximum score of 1 depending on how it meets the stated criteria.	Each of the categories is weighed depending on what is its relevance in improving building's performance.

Table 2- Systems and physical variables used to characterise a building.

System	Classification	Performance indicator	Unit	Reference
Structural	S.E.C.S – Structural Efficiency Classification System	Percentage Ratio between the weight of the structural system and the load it can withstand	NA	(think tank engineering SL, n.d.)

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Thermal	Build Test Solution	Heat Loss Parameter	W/m^2K	(Jack, 2021)
Lighting	EU 2019/2020 Single Lighting Regulations	Luminous Efficiency	Lm/W	(The European Commission, 2019)
Water	Wales Regulations	Water Usage per occupant	l/person/day	(Welsh Government, 2018)
Ventilation	UK government recommendation	Air supply per person per unit time	l/person/s	(Health and Safety Executive, n.d.)
Energy	Passivhaus Requirements	Energy demand per area	KWh/m^2	(Passivhaus Trust, 2021)

Table 3- 'Evolve to survive' biomimicry principle- data quality metrics.

	Category	Feature	Scores awarded	Weighing	Explanation
Evolve to survive	**Performance Reporting**	The system reports its performance less frequently than once a month or does not report its performance at all, but reports it less	0	2	In nature evolution is connected to utilising information for improvement (Baumeister et al., 2014). This has been translated into

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		often than weekly intervals			building systems' ability to report their performance. It has been suggested that the frequency at which the information is gathered is a significant factor, as more continuous reporting would allow for more adequate data patterns. As there are already existing systems that can provide life data reporting, it has been set as the highest score target. It has been decided that if a system reports the information less than monthly the data is not useful in terms of identifying performance
		The system reports its performance at least weekly but less frequently than daily.	0.2		
		The system reports its performance at least daily but less frequently than hourly	0.4		
		The system reports its performance at least hourly but less frequently than every minute	0.6		
		The system reports its performance at least every minute but not more frequently than every second	0.8		
		The system reports its performance continuously (at least every second)	1.0		

					patterns. Standard time units have been specified for the intermediate benchmarks.

Table 4- 'Evolve to survive' biomimicry principle- quality and performance objectives.

	Category	Feature	Scores awarded	Weighing	Explanation
Evolve to Survive	**Quality and Performance evolution**	The system worsens or maintained the same performance since it has been installed	0	3	Evolution means to embody information to improve performance (Baumeister et al., 2014). It has been translated into building systems' ability to improve their performance over time based on gathered information. As this is the core principle of
		System's performance has been improved by 1-10% since the beginning in comparison to the previous annum	0.5		

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		System's performance has been improved by more than 10% since the beginnings of the previous annum	1		evolution this the category carries a more significant weight. In the table below the unit of performance for each of the systems has been specified. As it is not an industry standard to design for future improvement, a realistic target of 10% has been set.

Table 5- 'Adapt to changing conditions' biomimicry principle- performance objectives.

	Category	Feature	Scores awarded	Weighing	Explanation
Adapt to changing	**Self-healing properties**	The system does not have self-healing properties	0	2	In nature organisms develop resilience mechanism to prevent failure (Baumeister et al., 2014). For a building it has been translated
		The system can self-heal (fully restore its performance) if no more than 1% of its	0.25		

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		tissue is destroyed per unit volume			into an ability of its systems to restore performance after failure. For simplification, in the assessment a failure is only linked with depletion or deformation of material forming a system. As systems with self-healing characteristics are not common in the industry, a realistic target of 10% has been set. As this is the core principle of adapting to changing conditions this the category carries a more significant weight.
		The system can self-heal (fully restore its performance) if no more than 5% of its tissue is destroyed per unit volume	0.5		
		The system can self-heal (fully restore its performance) if no more than 10% of its tissue is destroyed per unit volume	0.75		
		The system can self-heal (fully restore its performance) if more than 10% of its tissue is destroyed per unit volume	1		
	System failure Detection	The system does not contain failure detection mechanism	0	1	For a building to be able to restore its performance after a failure has occurred, it is fundamental that
		The system has an ability to alert about a	0.5		

		failure once it happens			such a failure is detected so that adequate actions can be taken. It has been suggested that a time instance at which the failure detection occurs is crucial in effectively responding to failure outcomes.
		The system has an ability to alert about a potential failure before it happens	1		
	Back-up potential	If a system fails, there is no back up option to restore its performance	0	2	In nature one of principles of organisms' adaptability is decentralisation of their main systems (Baumeister et al., 2014). This has been translated into presence of backup structures that can prevail buildings properties once one of components fail.
		If a system fails, its performance can be partially restored by a back-up option until its performance can be restored	0.5		
		If the system fails, its whole performance can be restored by a back-up option until	1		

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		its performance can be restored			The level to which performance can be maintained in case of partial failure has been suggested as the basis for the category. As this is the core principle of adapting to changing conditions this the category carries a more significant weight.

Table 6- 'Be locally attuned and responsive' biomimicry principle- performance objectives.

	Category	Feature	Score	Weighting	
Be Locally Attuned and Responsive	**Sourcing distance* This should be rated in 3 categories- material, energy, and water resources.** ***Cumulative scores are awarded in this category**	Most of the resource comes from more than 1000 km radius from the site location	0	2	For a building to follow biomimicry, it should gain its resources from the local environment. Three main types of resources have been identified and put to assessment: materials, energy, and water. It has been suggested that the local area
		Most resources come from a radius	0.25		

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		of more than 500 km but less than 1000 km from the site location			constitutes of 50 km radius relatively to the development.
		Most resources come from a radius of more than 100 km but less than 500 km from the site location	0.5		
		Most resources come from a radius of more than 50 km but less than 100 km from the site location.	0.75		
		Most of the resources comes from less than 50 km radius from the site location	1		
			0.35	1	

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	System Adaptation Interval-	Short Terms Only – daily			A factor that has been identified as important in this category is the building system's ability to respond to periodically changing environmental conditions. It has been proposed that the score should depend on how many cycles a system responds to from within the daily, annual, and long-term climate cycles. As the systems can simultaneously adopt based on different interval cycles, cumulative scores have been awarded in this category.
		Seasonal- based on seasons identified in the local climate	0.35		
		According to changes in climate	0.3		
	Contribution to the local area	The development does not improve the characteristics of the local area	0	2	The building collaboration with the local environment has been translated through quantifying how much

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					the development improves the local area in characteristics summarised in Table 7. As a civil engineering development can have very significant social and environmental impact a 50% of improvement has been set as an ideal target.
		The development improves the characteristics of the local area by at least 5% but less than 10%	0.25		
		The development improves the local characteristics by at least 10% but less than 25%	0.5		
		The development improves the local characteristics by at least 25% but less than 50%	0.75		
		The development improves the local characteristics by at least 50%	1		

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Table 7- Characteristics of a local surrounding that can be potentially improved by a building development. The characteristics are based on case studies.

Local Area Characteristics	Performance Indicator	Unit	Exemplar Case study as Justification for the Criteria	Reference
Outdoor Air Quality	Level or air pollution in 100 m radius quantified by the Daily Air Quality System (DAQS)	No units- scale system- 1-10	Palazzo Italia, Milan, Italy- Example of a building with a façade that absorbs smog and air pollution; potentially leading to improved air quality	(Gray, 2016)
Green Space	Available green area	m^2	The Interlace, Singapore- Example of a development that through optimising geometry and utilising green roof, resulted in more green area that was originally on-site.	(TED, 2016)
Energy Generation	Excess of energy generated in	kW	Heliotrope Rotating House, Freiburg in Breisgau, Germany- Example of a building that	(Gaute, 2018)

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	relation to demand		harvests more energy that its demand.	
Water Harvesting	Volume of wastewater treated in relation to demand	m^3	San Francisco Public Utilities Commission Headquarters, San Francisco, USA - Examples of a building that treats water from the local surrounding.	(Novo, 2023)

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Table 8- 'Be resource efficient' biomimicry principle- performance objectives.

	Category	Feature	Score	Weighting	Explanation
Be Resource Efficient	System efficiency	The system performs worse or the same than a comparable system	0	3	The resource efficiency of a system has been quantified by comparing it to the standard efficiency class of a system within the industry and identifying to what degree the system exceeds that value. A standard performance of different systems has been specified in Table 9.
		The system performs 1-20% better than a standard system	0.25		
		The system performs 21-50% better than a standard system	0.5		
		The system performs 51-70% better than a standard system	0.75		
		The system performs more than 70% better than a standard system	1		
	Resource circularity	The system recycles no more	0		For a building to follow biomimicry

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		than 5% of its resources		2	principles recycling elements within systems is crucial. the degree to which the systems within a building are recycling their expended resources have been quantified according to circularity principles. As there are already projects that utilise circularity mechanisms to a high extend, a 90% circularity has been set as an ideal target.
		The system recycles more than 5% but less than 25% of its resources	0.2		
		The systems recycle more than 25% but less than 50% of its resources	0.4		
		The system recycles more than 50% but less than 75% of its resources	0.6		
		The system recycles more than 75% but less than 90% of its resources	0.8		
		The system recycles more than 90% of its resources	1		

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Table 9- Standard Performance values of building systems serving as Evaluation Criteria- Be Resource Efficient- Material and Energy

System	Classification	Performance indicator	Value	Unit	Reference
Structural	S.E.C.S – Structural Efficiency Classification System	Percentage Ratio between the weight of the structural system and the load it can withstand	10%	NA	(think tank engineering SL, n.d.)
Thermal	Build Test Solution	Heat Loss Parameter	0	W/m^2K	(Build Test Solutions, n.d.)
Lighting	EU 2019/2020 Single Lighting Regulations	Luminous Efficiency	210	Lm/W	(The European Commission, 2019)
Water	Wales Regulations	Water Usage per occupant	100	l/person/day	(Welsh Government, 2018)
Ventilation	UK government recommendation	Air supply per person per unit time	10	l/person/s	(Health and Safety Executive, n.d.)
Energy	Passivhaus Requirements	Energy usage per area	15	KWh/m^2	(Passivhaus Trust, 2021)

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Table 10- 'Integrate development with growth' biomimicry principle- performance objectives.

	Category	Feature	Score	Weighting	Explanation
Integrate Development with Growth	Change in user occupancy	The amount of building stakeholders has declined in the previous annum or didn't change	0	1	For a building to act within a system, it requires organic growth. The development of the project can be measured by the increase in the number of stakeholders that interact with the building following completion. A timeframe of 1 year has been suggested as basis for the measure. A conservative target of 20% growth per annum has been suggested.
		The number of users has increased by at least 5% but less than10% in comparison to previous annum	0.25		
		The amount of building stakeholders increased by 10% but less than 15% in comparison to the previous annum	0.5		
		The amount of building stakeholders increased by at least 15% but less than 20% in comparison to the previous annum	0.75		

		The amount of building stakeholders increased by at least 20% in comparison to the previous annum.	1		
	Number of facilities (function)	The number of facilities in the building has decreased or remained the same	0	1	This criterion measures the number of facilities within a structure and the change in not only the number of physical facilities within the development but also changes in the functionality of the systems to meet the needs of occupants and to improve the current services the occupants receive. A conservative target of 20% growth per annum has been suggested.
		The number of facilities has increased by at least 5% but less than 10% in comparison to the previous annum	0.25		
		The number of facilities has increased by at least 10% but less than 15% in comparison to the previous annum.	0.5		
		The number of facilities in the	0.75		

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		building has increased by at least 15% but less than 20% in comparison to the previous annum.			
		The number of facilities in the building has increased by at least 20% in comparison to the previous annum.	1		
	Community involvement	There was no community involvement in the project.	0	2	The community involvement criterion measures the instances during which the local community had an influence on the project development. It can be assessed by the amount of community engagement initiative that the
		Community involvement resulted in at least one but no more than 2 changes being made to the project.	0.5		
		Community involvement resulted in three or more	1		

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		changes being made to the project.			building management or adequate body has initiated in the last annum relative to the time of the comparison.

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Table 11- 'Use life friendly chemistry' biomimicry principle- performance objectives.

	Category	Feature	Score	Weighting	Explanation
Use Life Friendly Chemistry	Biodegradable materials	No materials are biodegradable	0	3	In nature, organisms utilize carbon to construct their structures, and they are inherently biodegradable, thus seamlessly integrating into the carbon cycle (Baumeister et al., 2014). By measuring what proportion of materials by volume within its systems is biodegradable within the whole building instead of the individual systems a better overview of the life-friendly chemistry of the building can be seen.
		At least 25% but less than 50% of materials by volume in the building is biodegradable	0.25		
		At least 50% but less than 75% of materials by volume in the building is biodegradable	0.5		
		At least 75% but less than 100% of materials by volume in the building is biodegradable	0.75		
		100% of materials in the building by volume in the system is biodegradable	1		
		The building uses less than 3 different materials.	1		

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	Category	Feature	Score	Weighting	Explanation
	Embodied Carbon	The capital embodied carbon exceeds 300 kg CO2 eq /m^2	0	2	To account for the current industry challenges and focus the Embodied Carbon equivalent contribution per unit of functional area of a building has been proposed as one of the element of buildings chemistry, and therefore a criterion. The benchmark has been proposed based on Arnold et al. (2020) study that estimates and records capital carbon contribution of various building development.
		The capital embodied carbon is between 200 -300 kg CO2 eq/m^2	0.25		
		The capital embodied carbon is between is higher than 100 kg CO2 eq/m^2 but do not exceed 200 kg CO2 eq/m^2	0.5		
		The capital embodied carbon is between is higher than 0 kg CO2 eq/m^2 but do not exceed 100 kg CO2 eq/m^2	0.75		
		The building sequesters more CO2 than its Embodied Carbon contribution	1		

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Table 12- Shortlist of projects to be assessed.

	Year Built	Description	
Eastgate Centre **Harare, Zimbabwe**	1996	The Eastgate Centre located in the capital of Zimbabwe has a ventilation system and thermal arrangement designed to mimic termite mounds, applied by strategically placing ventilation channels and the application of passive cooling strategies to naturally cool the structure allowing it to maintain optimal temperature and humidity in harsh desert conditions. (Dahl, 2013).	 *Photograph credits: earthbound.report*
Council House Building (CH2) **Melbourne, Australia**	2006	CH2 is an office building focusing on indoor air quality, water conservation, and energy efficiency which opened in 2006. The building features three power sources as well as a rainwater collection system. The thermal and ventilation systems within the building were designed, so that they take advantage of natural	 *Photograph credits: Dianna Snape*

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		cycling and seasonal processes with the windows automatically opening at night to cool down concrete panels inside of the structure. (Hes and Walker-Morrison, 2012).	
Esplanade Art Centre Singapore **Singapore**	2002	Theatres on the Bay also known as the Esplanade Art Centre was created in 2002 with a design inspired by biomimicry. The spiked exterior façade was inspired by the durian fruit skin. The façade also retains the ability to change its degree of transparency based on environmental conditions to make the building more energy efficient. (Klimke, 2002).	 *Photograph credits: DP Architects*
Bosco Verticale **Milan, Italy**	2014	Bosco Verticale is a residential complex consisting of two towers whose focus is the relationship between humans and other vegetation. As such the building has over 800 trees, 5000 shrubs and 15,000 perennials. The project features the equivalent of 30,000 square meters of	 *Photograph credits: Barcelo Experiences*

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		vegetation and undergrowth within an urban plot of 3,000 square meters. The structure benefits from purer air, a reduction in noise pollution and less CO2 because of the trees (Coffman, 2018).	
BIQ House **Hamburg, Germany**	2013	The BIQ house is a structure that features a unique series of algae-filled bioreactors that provide shading and biogas used for powering the building. As sunlight hits the exterior of the structure the algae begin to multiply, providing shade for the building. As the algae grow, it is harvested to create biogas, which helps to power the building. The system's central control is the fully automated energy management centre in which solar thermal heat and harvested algae are used in a closed loop to generate hot water and store energy (Ali, 2016).	 *Photograph credits: Arup*

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The University of Queensland Global Change Institute **Brisbane, Australia**	2013	The University of Queensland Global Change Institute located in Brisbane, Australia is a research institute that was designed with a series of sustainable and environmental features. The institute features a translucent main roof made of lightweight Texlon ETFE material which allows natural light into large parts of the interior. Additional sustainability features include rainwater harvesting and recycling systems (Bligh and Glasby, 2013).	 *Photograph credits: greenroofs.com*

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Figure captions

Figure 1- The Life Principles developed by the Biomimicry 3.8 Institute

Figure 2- Flow diagram showing the objectives and/or virtues of construction projects, the method to achieve them and the desired performance objectives. The objectives are analogous to the Life Principles developed by the Biomimicry 3.8 Institute.

Figure 3- Photograph of the Council House Building in Melbourne (CH2). Photograph credits: George Fethers & Co

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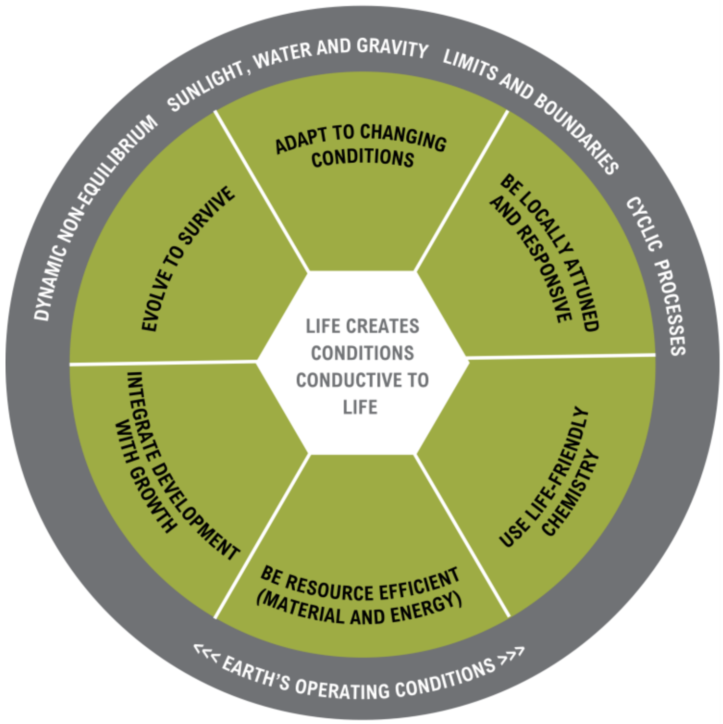

Fig. 1

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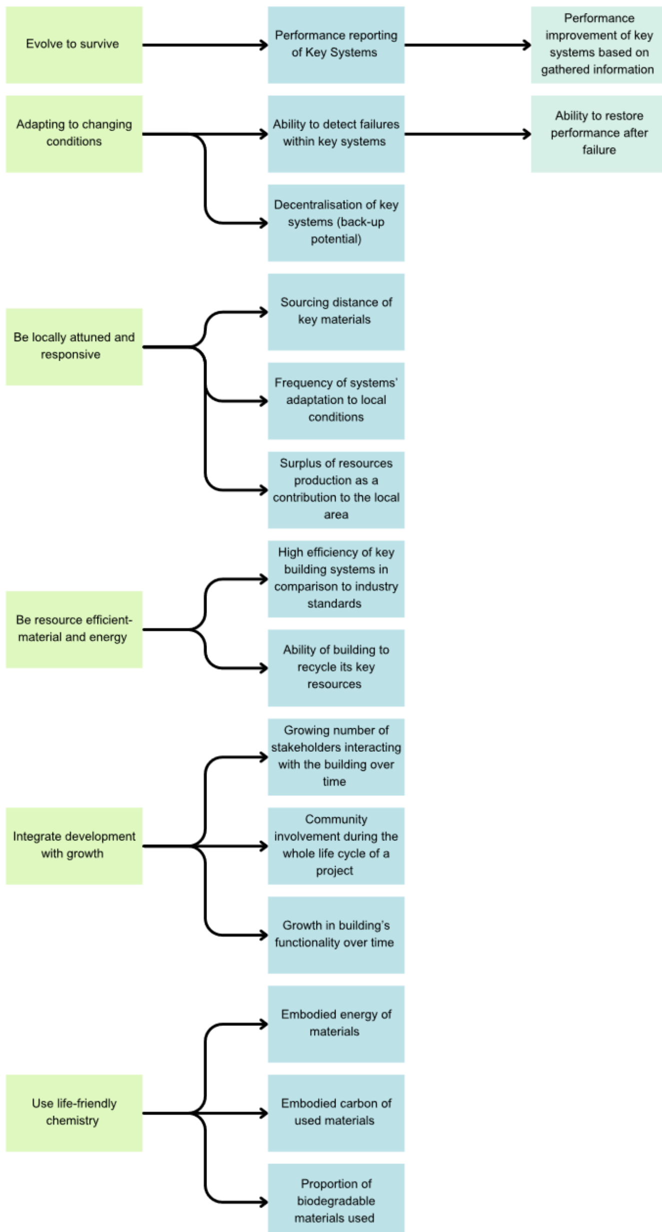

Fig. 2

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Fig. 3