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Digitizing material passport for sustainable construction projects using BIM

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ABSTRACT

Several aspects hinder the application sustainability in construction industry. The most prominent problems are related to the conservation of natural resources and the generation of construction and demolition wastes. Previous studies indicated that these problems are due to lack of information available to construction projects stakeholders on the proper handling of building materials in their different lifecycle stages. This paper presents Material Passport (MP) tool that provides information on how to handle building materials at the construction stage and how to benefit from them at their end-of-life stage through different recovery opportunities. This tool provides three quantitative indicators that assess building's sustainability: 1) deconstructability score; 2) recovery score; and 3) environmental score. These indicators help stakeholders to choose more sustainable solutions to building elements in the initial stages of the project. The paper introduces a framework that incorporate MP within Building Information Modeling (BIM). Such incorporation automates sustainability assessment as well as facilitating the documentation and sharing of building's information for future needs. A case study of a traditional residential building is presented to illustrate the concept of the material passport. Also, new alternatives of modular building concept are presented to validate the sustainability indicators, allowing a comparison with traditional building to reach more sustainable solutions. The results reveal that modular buildings are preferred as expected, demonstrating the effectiveness of the presented tools in evaluating alternatives. The results also show the influence of the parameters used in calculating the presented indicators, such as the connection type and the material used. The research provides a methodology that solves the problem of the of insufficient information in order to achieve sustainability for buildings by including quantitative and qualitative information. The provided information covers all lifecycle stages of the building, making it more comprehensive compared to other tools.

1. Introduction

Building new urban communities and development of old ones are necessary to meet human requirements. As a result of the inescapable construction, renovation and demolition activities, huge amounts of waste are generated annually. These wastes cause environmental impacts, affect human health and damage landscape. The massive quantities of construction and demolition wastes (CDW) is a big problem in many parts of the world. In Europe, CDW is estimated to be more than 800 million tons annually [20]. While it exceeded 500 million tons in US in 2017 [74]. Therefore, intergovernmental organizations made extensive efforts to solve this problem. For example, United Nations released the holistic action plan, Agenda 21, to confront the challenges of the twenty-first century. It includes several goals for achieving the sustainability of resources, preservation of the environment and protection of human health [73].

The increasing trend towards sustainability in construction industry led to the emergence of 3Rs rule. 3Rs rule is a concept that prioritize waste management strategies according to their sustainability degree to reduce, reuse and recycle. Despite several studies addressing the economic and environmental benefits of implementing these strategies [59,61], their implementation at the building level is still limited. Several researches attributed this limitation to the lack of information available to construction project stakeholders on how to exploit building materials at their different lifecycle stages [34,57,72].

Several tools have been developed to address the problem of

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providing information. Energy performance certificate (EPC), safety data sheet (SDS) and technical data sheet (TDS) are all examples of data provisioning tools. EPC is only specialized in giving recommendations to improve energy consumption of a building. TDS and SDS are tools that guide workers in carrying out construction work [49]. Besides the previous tools, there is also the material passport (MP) which is described as a material stock document that contains information about building materials composition. This tool has been developed under different terms, such as "Nutrient certificate". An earlier version of the MP was developed in 1997 in Germany. This version included information about operational costs, quality of use, building services and technical properties. With the passage of time, the scope of information included in MP broadens to cover new requirements [35,67].

Despite many MP tools have been developed, they provide information that is limited to only one stage of the building's life cycle such as the design stage or the end-of-life stage. Also, most of the developed tools focus on providing quantitative information such as the environmental performance, without considering other qualitative perspectives such as sustainability guidelines. Therefore, this paper seeks to answer the question of what is required to build an effective and sustainable material passport.

The aim of this paper is to develop the material passport to become more comprehensive than previous tools. Three drivers were identified in the literature motivated this research: 1) the significance of including all lifecycle stages in the sustainability supporting tools; 2) providing both qualitative and quantitative information has a crucial role in achieving sustainability and; 3) the importance of digitizing sustainability supporting tools.

In order to achieve more sustainability, all project phases must be included. The 3 R strategies are not limited to a single stage, as the reduction strategy is more associated to the pre-construction and construction stages, whilst the reuse and recycling strategies are more tied to the post-construction stage [77]. This attitude is also reinforced by Debacker et al. [19] who highlighted the necessity of involving all construction project phases and their actors when developing sustainability protocols and tools such as material passports. The author indicated that the actors responsible for the design phase can facilitate the implementation of circular practices for products if they are concerned by their requirements at the end-of-life phase and vice versa.

In a related context, several studies have shown that lack of knowledge and awareness about sustainable practices is a key impediment to sustainable building [43,44]. Hence, there was a need for information defining sustainable practices and guiding stakeholders on how to use the building's materials at different lifecycle phases. In addition, thousands of indicators are being developed to measure sustainability at different levels due to their importance in evaluation, optimization and decision-making [2,48]. Accordingly, it is of utmost importance to include both quantitative and qualitative information for the development of a comprehensive material passport [39,55].

The reliance on digitalization in industries is becoming one of the aspects recognized to enhance the circular economy. Jabbour et al. [18] indicated that the means of sharing and gathering of information provided by Industry 4 technologies can contribute significantly to managing the sustainability of operations. The same trend is recommended by Wijewickrama et al. [76] who pointed out that digital platforms can be used as a broker of information in order to improve communication, collaboration and sharing. All of these trends drive the proposed research towards digitizing the tool to be developed. The following literature review explores the previous tools and identifies their strengths and weaknesses in order to set a framework for developing a sustainable material passport.

2. Literature review

Several researches investigated on the type of information needed to achieve sustainability. Technical information is considered as one of the most important of this information. Examples of such technical information include the quality of the used materials, their density and their compliance with standards. In a recent study, Da Trindade et al. [17] confirmed that the lack of technological know-how is a significant hindrance to achieving sustainability in construction industry. They also found that inadequate material managing, stacking and storage are main causes of wastes generation. Kurdve [46] indicated the importance of assembly instructions in achieving safety, improving learning and raising efficiency of unskilled workers. In addition, safety information has its importance in improving quality of life and supporting social sustainability [27]. Akadiri et al. [1] emphasized that providing healthy and safe working environment and appreciating the working stuff were among principles that required to achieve social sustainability. Besides, Gorgolewski [33] mentioned the significance of the disassembly guide in allowing third parties who are interested in the second-hand building component to separate and use it in a way that preserves it. This is in line with Sanchez and Haas [64] who recommended that disassembly be accompanied by a plan to improve reusability, indicating the different approaches followed such as deconstruction and selective demolition. In the same context, lack of information about circularity opportunities for building materials at their end-of-life stage is frequently reported as a main reason for the limited application of sustainability concept at the building level [29,47]. A recent research by Kabirifar et al. [43] confirmed the persistence of this issue, emphasizing the necessity of developing a tool that suggest such reusing/recycling information to construction project stakeholders.

On the other hand, many studies indicated to the importance of providing quantitative indicators to evaluate buildings in order to achieve sustainability in the early stage of the project. The developed tools can be divided into three categories [14]: 1) based on building certification or rating; 2) based on Life Cycle Assessment (LCA); and 3) based on building performance. It is important to obtain differences between these methods before approving the suitable method for this study. BREEAM and LEED are among the most popular building certification tools for assessing sustainability. LEED is a tool that tends more towards environmental aspect and used for evaluating sustainability of projects using a rating system. Many versions have been developed to cover all types of buildings and different construction phases [75]. Despite the wide range of buildings covered by the many versions of this tool, it does not completely address sustainability concerns, since it focuses primarily on assessing the project's environmental impact and its conformity with the green building standards. BREEAM is another well-known method that depends on ten assessment categories: energy, innovation, health, land use, management, materials, pollution, transport, waste and water [15]. This large number of categories is one of the advantages of this system, making it more thorough than other methods. However, the certification process does not cover all phases of the project and focuses only on the planning and project completion phases. In general, building certification/rating methods are criticized as that they are country-specific or represent regional scales because they are developed depending on local conditions [14]. This limitation has been confirmed by Hazem et al. [37] who indicated that environmental and cultural differences can hinder the application of these tools in different regions. Thus, this category of tools lacks the property of generality, as it cannot be used in all conditions.

Regarding LCA-based methods, Mateus and Bragança [53] developed a sustainability assessment tool (SBTool^{PT}) to assess existing and new residential buildings in Portugal. Indicators were chosen to represent environmental, economic and social aspects. Each of the indicators were represented by several parameters with a total of twenty-five indicators that are measured based on multiple LCA methods. Bakhoum and Brown [8] developed the sustainability scoring system (SSS). The system provides five-point scores for ten impact categories that represent environmental, social, economic and technological aspects. These impact categories were determined based on grouping and aggregation of indicators from the same aspect. The tool was later redeveloped to support automation and multi-criteria decision-making [9]. Marzouk and El-hawary [52] used system dynamics to simulate building activities and predict building's lifecycle sustainability performance. The sustainability performance is measured in terms of energy consumption, water use, reduced wastes and material reuse. All of these parameters were selected by benchmarking different rating systems such as LEED, BREEAM, GPRS and Pearl to take international and regional scales into consideration. Eberhardt et al. [22] reported a shortcoming of the current LCA methods regarding their thoroughness in assessing buildings that depend on the circular economy concept such as design-for-deconstruction (DfD) buildings. The researchers proposed to integrate the number of uses of reclaimed materials within the assessment method, whereby the environmental impacts of the stages of production, use and end-of-life are divided by the number of using cycles of the material. Despite the comprehensiveness of LCA-based methods, they might be challenging to be applied since they necessitate a significant amount of data, which may not be available in many processes. This type of data is represented in a form of lifecycle inventory databases, which are available for a charge from some organizations.

Performance-based design provides solutions to reach outcomes that meet requirements [14]. One of the most efficient sustainability solutions is the design-for-deconstruction (DfD) approach. Material recovery is considered as one of the important features that supports implementation of DfD building. Tam [71] presented a simplified equation whereby material recovery is determined based on the ratio of recyclable and reusable materials with respect to the whole generated wastes. This concept has been redeveloped and expanded by Akinade et al. [4] who found that other factors could be considered to support material recovery, such as using non-toxic materials and uncoated building elements. In addition to resorting to prefabricated and demountable building components. In the same context, Gao et al. [30] mentioned various benefits of prefabricating building components, including reduced production and delivery time, reduced waste generation, quality control, as well as reduced costs. Disassembly, aka deconstructability, is another sustainability indicator that is rarely considered by researchers despite its importance in evaluating building systems. Durmisevic et al. [21] developed a model that evaluates building disassembly depending on two indicators: independence and exchangeability. Independence refers to the parts that can be separated according their function. Whereas, exchangeability refers to the ability of the building part to be deconstructed. Furthermore, several researches investigated the circularity indicators for measuring sustainability at different levels. One of the most obvious shortcomings of the previous-mentioned methods is that they focus on assessing the building's sustainability using indicators related to the project's end-of-life stage and ignore the rest of the stages. Despite simplicity provided by these methods, they only rely on one or two attributes and neglect others. For example, Giama and Papadopoulos [32] focused on carbon emissions when assessing circularity for different building insulation materials. However, Elia et al. [24] indicated the possibility of mitigating this shortcoming by resorting to LCA-based circularity indicators to involve more attributes for the assessment method.

Besides the aforementioned methods, several researches investigated the use of BIM technology for sustainability assessment. Marzouk et al. [51] developed a BIM-based model for estimating lifecycle emissions including greenhouse gases of construction projects by combining impact assessment tools and building model with the help of C# and SQL tools. Akanbi et al. [2] used Application Programming interface (API), C# programming and visual studio to integrate a mathematical assessment model into BIM tool. The model depends on aging and design factors that are extracted from the building under assessment. Jalaei et al. [41] used API to develop a plugin that integrates LEED certification credits into BIM in order to evaluate sustainability of buildings at conceptual stage. The abovementioned tools employed text-based programming languages to integrate between the presented indicators and BIM, which is sometimes complex and time-consuming.

Röck et al. [62] used the dynamo tool to link materials takeoff that is extracted from the BIM model and a LCA database of different building materials for the purpose of quantifying environmental impact of the building. A study by Basta et al. [12] focused on assessing deconstructability of steel buildings. Dynamo visual programming was used to build a deconstructability assessment tool for steel structures. The tool is designed on counting factors that support deconstructability of building elements such as bolted connection type and hot-rolled manufactured elements. The recently mentioned tools used visual programming languages in order to integrate the proposed tools with BIM. This method, despite its simplicity, may require the use of add-ons that are not built-in the original tool and may not be free of charge.

Sandberg et al. [65] urged to include neutral file format in the design optimization framework to enhance cooperation and data exchange between different disciplines in the design process and to enable accepting parametric information of building materials from other systems like MySQL. Figueiredo et al. [28] suggested a framework integrating LCA, fuzzy-AHP and BIM to select more sustainable building materials. GaBi LCI database was used for environmental assessment. BIM has been used to model the building with different construction materials. Whereas, the fuzzy-AHP method has been used to aid in the selection of the best building materials alternatives based on environmental, social and economic aspects. Bapat et al. [10] integrated both fuzzy factor method (FCM) and internet of things (IoT) technology into BIM for developing a sustainable material selection methodology. FCM was used as a multi-criteria decision-making technique for trading off between different materials based on many parameters such as safety, aesthetics, carbon emissions and others. BIM was used to model the building under investigation and the material alternatives. While, temperature sensors were used as IoT tools for efficient energy management. Although tools employing IoT technology are distinctive, their availability may be dubious, which might prohibit this technique from being used. Despite the numerous techniques for integrating BIM technology with sustainability practices, its implementation confronts a number of challenges, including opposition to changing conventional practices and a lack of awareness of the procedures necessary to combine sustainability with BIM [58].

Gathering such amount of information gave rise to the term Material Passport (MP). Kovacic et al. [45] proposed to use LCA-based indicators in the development of the MP such as the green warming potential, acidification potential and potential energy intensity. Schützenhofer et al. [66] considered other indicators including building costs and recycling potential. Bertin et al. [13] focused on other perspectives by including technical parameters for building components such as Young's modulus, deflection and bending moment to enable performing structural analysis for the sake of evaluating reusability of deconstructed load-bearing elements. Honic et al. [38] proposed a technique for generating MP for existing buildings using both laser scanner, laser penetrating radar and BIM tools. Laser tools were used to extract both physical and geometric properties. Whereas, BIM is used to combine them.

In order to identify the gaps in the previous tools in literature, it is necessary to define the current state and the target state. Then, an action plan should be adopted to develop a sustainable material passport. Considering the studies shown in Table 1, most of the developed MP tools are limited to providing quantitative indicators. This type of information is not sufficient to solve the sustainability application issue since they do not provide construction project stakeholders with a guidance on how to handle and benefit from the building elements during their different lifecycle stages. Furthermore, there is no clear criteria for selecting indicators. The significance of each indicator is not justified. Some of the indicators provided in the previous tools, such as Acidification Potential, are difficult to understand for non-specialists. Some of the previous tools only provide environmental performance indicators and neglect practicability indicators such as reusability and deconstructability of buildings. Relying just on environmental

Table 1
Contributions of recent MP researches.

Concept/ References	Considered lifecycle stage	Provided qualitative information	Provided quantitative information	BIM-based
Design optimization and material documentation [45]	Design stage		✓	✓
Providing sustainability guidelines [56]	All stages	✓	✓	
Design optimization [66]	Design stage		✓	✓
Assessing existing building for reusing/recycling [38]	End-of-life		✓	✓
Facilitating reuse/ recycle of old components [13, 16]	End-of-life		✓	✓

indicators is insufficient for interpreting the outcomes. The previous tools failed to consider the whole lifecycle stage of building. Munaro et al. [56] proposed adding both qualitative and quantitative information in the MP, however the type of quantitative information was not specified and the BIM technology was not relied on in their proposal despite its importance in documenting and sharing information. The gap can be summarized as the previous MP tools lack a combination of quantitative and qualitative information and the insufficient of indicators provided to achieve building sustainability. This paper developed a material passport tool that supports the achievement of sustainability in construction projects. The tool provides instructions on how to exploit building materials at their different lifecycle stages. It also provides a set of quantitative indicators that assess the sustainability of buildings to help the architectures/engineers to evaluate different alternatives. The next section sets the action plan to fill this gap by proposing a framework for developing a sustainable material passport.

3. Framework and methods

The aim of this research is to redevelop the material passport in order to support the achievement of sustainability. This could be accomplished by exploring the gaps left by earlier tools. In line with Hart [36]; establishing a framework for the study requires differentiating between what has been done and what is required to be done. Accordingly, the literature review method was the first to be applied in the paper. Based on the literature study, it became obvious that the design of the material passport must include two categories of information: qualitative and quantitative. The instruction guide is the considered form for providing qualitative information. According to Mack et al. [50]; the qualitative method is effective in obtaining and expressing information about values and social concerns. Thus, the elements of this guide have been selected to serve the environmental and social aspects. Section 4 describes the scope and relevance of each element of the guide.

On the other hand, choices of tools adopted for quantitative assessment of sustainability are based on three concepts. First, the indicators should be characterized by simplicity and ease of interpretation. Besides, the tools should include both of material recovery and LCA indicators to comply with as many standards as possible such as EN 15804 [40]. Finally, sustainability assessment tools must express both of environmental performance and human health to conform with the sustainable development plan, Agenda 21 [73]. The foregoing considerations were taken into account in adopting three indicators for this study, namely: deconstructability score, recovery score and environmental score. Each of these indicators are based on several parameters as depicted in Fig. 1. The parameters employed in the production of these indicators are addressed in depth in Section 5.

The final step in the design stage of the material passport is the digitization of the proposed tools. According to Shirowzhan et al. [69]; compatibility is a main factor in the diffusion of innovation (DOI) theory. BIM, as a widely used technology in the building industry, is mainly intended to create a digital twin for buildings and their characteristics [3]. Hence, there is an obvious compatibility between the MP's digitizing step and the usage of BIM. Furthermore, the ease of sharing, time saving and error mitigation are considered as relative advantages that support tools adoption according DOI theory. All of these considerations argue in favor of using BIM technology to digitize the proposed material passport.

In order to validate the proposed framework, the case study method is used. The case study is designed to serve two purposes: to test the quantitative sustainability indicators and to illustrate the features of the developed material passport. For the sake of achieving the first purpose, a comparative study approach is followed to validate the parameters of the proposed indicators. The comparative study between dissimilar cases provides a chance to trace and analyze the influencing factors [11]. A case study of a residential building with traditional and modular alternatives were used in this study. The same case is exploited to illustrate final form and features of the material passport. Section 6 describes the case study in further depth and its appropriateness for the validation is shown. Fig. 1 summarizes the framework used to develop the material passport.

4. Defining qualitative information

Instruction guide is the first type of information that represent the qualitative aspect. It is required to guide construction projects stakeholders on how to manage building materials in a sustainable manner. Instruction guide involves four parts: technical, safety, circularity and disassembly information. This section illustrates the scope of each part of the instruction guide, how it will be included in the proposed material passport, and how it contributes to the building's sustainability.

Determining the correct quantity of material needed for building elements is a crucial matter in the construction projects. Besides its importance in cost estimation, it is also necessary for the environmental evaluation. This research adopts using BIM-based quantity takeoff. Based on the fact that most building materials are measured in terms of mass (in kilograms), the quantities are estimated using the volume and density of each material. Volumes of the used materials were extracted using Autodesk Revit® software. Whereas, technical information such as densities of building materials are obtained from relevant building codes. Besides, the proper assembling method and handling of construction materials should be mentioned in the technical data of the material passport as it serves one of the main objectives which is to avoid construction wastes that may result from implementation errors.

Lack of understanding the difference between several terms such as demolition, deconstruction, and design for deconstruction (DfD) is considered as one of the main causes of waste generation. Hence, instructions of disassembling or demolition of the system/building part is an essential part that is provided in this framework. Instructions of disassembly techniques guide for the proper direction of the disassembled parts for either disposing to the nearest dump or further treatment. In a related context, the demolished/separated parts should follow the strategies of recycling/reusing to be handled in a sustainable manner. Hence, information about circularity opportunities is provided in the proposed framework as it addresses one of the most common issues, which is knowing how to benefit from construction waste.

Moreover, safety instructions are provided to support the social sustainability aspect. This part includes instructions related to stacking, storage and handling of the supplied building materials. Also, it indicates the personal protective equipment that all site workers should

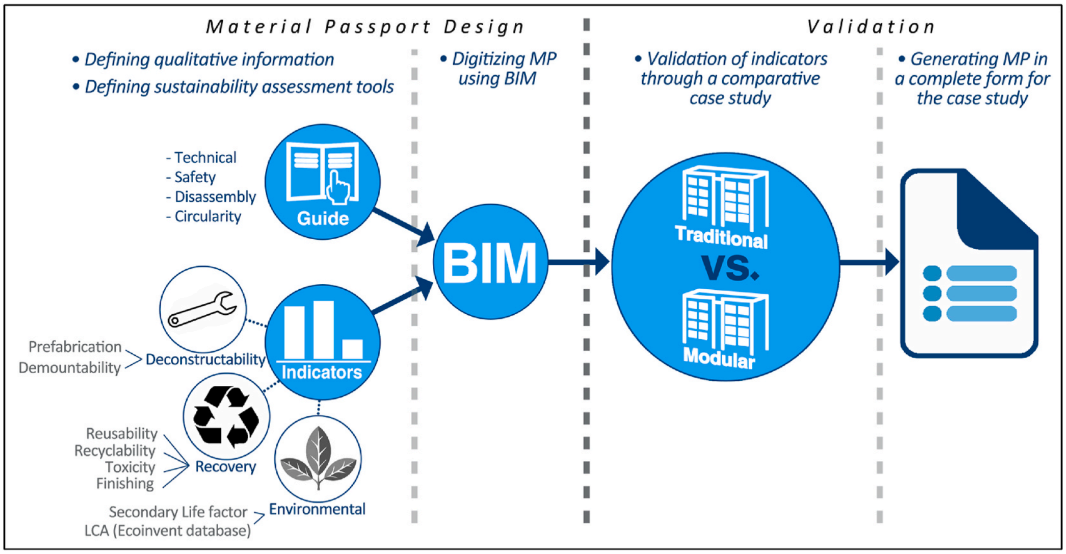

Fig. 1. Proposed framework of developing a digital material Passport.

wear according to the activity and the material used. Adherence to these instructions ensures the health of workers dealing with these materials.

5. Sustainability assessment tools

Existence of sustainability assessment tools in the material passport is of a great importance. Availability of such tools allows stakeholder to evaluate different building alternatives and compare them before construction. Furthermore, they indicate the potential of using the construction elements for those who are interested in purchasing second hand components. Also, it can be used by authorities or environmental affairs to bring additional perspectives to green building and sustainability certification systems. In this study, three indicators are used based on the concepts stated in section 3: 1) deconstructability score, 2) recovery score, and 3) environmental score. The following sub-sections explain roles and parameters of each of these indicators and conclude them.

5.1. Deconstructability score

Building deconstructability score expresses the ability of the building parts to be dismantled. It is based on two factors: ratio of demountable connections and ratio of prefabricated building elements. Demountable connections stimulate a sustainable end-of-life scenario for building components, providing a circular building that can be dismantled and reused. Whereas, conventional fixed connections allow only a demolition scenario in order to separate its components.

Bolts, interlock and dowels are all considered as demountable connections in this study. Whereas, welds, binder and nails are considered as fixed connections. Depending on the specified connection type for each building element, ratio of demountable connections (Dc) can be calculated as shown in Equation (1).

$$Dc = \frac{\sum Demountable\ Connections}{\sum All\ Connections} \quad (1)$$

Ratio of prefabricated elements (Rp) is the second factor that enhances deconstructability. Applying prefabrication concept significantly reduces waste generation resulting from implementation errors as standard molds are used in manufacturing instead of traditional equipment. Ratio of prefabricated elements can be estimated using Equation (2).

$$Rp = \frac{\sum Prefabricated\ elements}{\sum All\ elements} \quad (2)$$

Hence, deconstructability score (D-score) can be calculated based on the abovementioned key factors as follow [4]:

$$Dscore = \frac{Dc + Rp}{2} \quad (3)$$

where, D-score ranges from 0 to 1, with a greater value indicating higher deconstructability.

5.2. Recovery score

Recovery score (R-score) expresses the percentage of recoverable building components and materials. The score depends on the ratio of reusable components and recyclable materials. Uncoated building elements and nontoxic materials are considered as key factors that support material recovery. Equation (4) is used to calculate recovery score [12]:

$$Rscore = \frac{Rc + Ru + Nx + Ns}{4} \quad (4)$$

where, Rc, Ru, Nx and Ns are the ratios of the building elements that are recyclable, reusable, non-toxic and uncoated, respectively. The score ranges between 0 and 1 as the higher score, the higher material recovery.

5.3. Environmental score

This paper adopts using LCA-based indicator for the environmental indicator. The indicator depends on normalizing LCA results of the comparable building materials. It also takes into consideration secondary life chances of building elements. In order to normalize LCA results of building materials, they should be categorized according to their function. Six categories were considered in this study as shown in Table 2. It is worth noting that more categories can be considered if other alternatives and systems are available. Thereafter, LCA is performed for each of them.

IMPACT2002+ method is chosen to estimate the basic environmental LCA results for each of building materials. This is due to the wide range of mid-point indicators it contains. These indicators are categorized into four damage categories [42]: ecosystem quality, climate change, resources and human health. The damage categories were

Table 2
Building material categories and options.

Category/Subcategory	Building Material options
Structure	RC - Steel - Wood
Walls/Core	Clay bricks - Cement bricks
Walls/Interior Finish	Mortar and putty - Plasterboard - Ceramic tiles
Walls/Exterior Finish	Dry mix - Fiber cement tiles
Flooring	Ceramic tiles - Cement tiles - Laminated timber - HDF
Paints	Acrylic paints - Alkyd paints
Binder	Cement mortar - Lime mortar - adhesive mortar
Doors & Windows/Trim &Frame	Pine beech - Aluminum - Steel - MDF
Doors & Windows/Panels	Glass - Polycarbonates

normalized using characterization factors in order to obtain the single score. The characterization factors that were suggested by the developers of this method is adopted [42]. The single score is expressed in Pers/yr which indicates the number of affected persons per year. This process requires a Lifecycle inventory (LCI) database for building materials. Ecoinvent 3.5 LCI database has been relied on for this purpose [23]. As well, OpenLCA 1.9 software is used to perform the LCA process.

Results of single scores within each building category are normalized using Equation (5) to get the normalized environmental performance (E_i) for each building material.

$$E_i = 1 - \frac{S_i}{S_{max}} \quad (5)$$

where.

The minimum environmental impact is considered 0. S_i is the environmental impact of the material i within each category in Person/yr. S_{max} is the maximum environmental impact of the material i extracted from available options within each category in Pers/yr. The score of the environmental performance E_i is considered to be 100% for the best material option and 10% for the worst result.

The environmental score indicator considers the secondary life factor (w) that distinguishes reusable elements. This is based on the fact that reusing second-hand materials has a lower environmental impact compared to manufacturing new ones. Thus, the ratio of reusable elements is relied upon to determine this factor is estimated using Equation (6).

$$w = R * (R_{max} - R_{min}) + R_{min} \quad (6)$$

where.

R is the ratio of reusable building components. R_{max} and R_{min} are the maximum and minimum value assumed for this factor, respectively. The secondary life factor is assumed to be within the limits 0.5 and 1. The maximum value for this factor is 1 for full reusable building components and 0.5 for the minimum value of the factor. This assumption is to avoid the overstated influence of this factor on the value of E-score.

Both of normalized environmental performance (Equation (5)) and secondary life factor (Equation (6)) can be substituted to determine final environmental score (E-score) using Equation (7).

$$Escore = \frac{w^* \sum m_i {}^* E_i}{\sum m_i} \quad (7)$$

where.

w is the secondary life factor for the building. m_i is the mass of material i in kg.E_i is the normalized environmental performance of the building material i. The result of this indicator ranges from 0 to 1. The highest E-score indicates the better environmental performance.

6. BIM-based material passport

Integration between material passport and BIM provides several advantages such as mitigation of errors, saving time and efforts and sharing sustainability information. Autodesk Revit® software is used as a BIM tool for digitizing the sustainability instructions for the building materials, allowing to couple geometric designs with sustainability information. Also, it is used to model the aforementioned sustainability indicators taking advantage of automation feature.

Creation of shared parameters is one of the most beneficial features of Autodesk Revit® that used to represent the sustainability instruction. This feature enables user to add new information that is not exist in the project parts. Also, it can be shared with other projects once created. Fig. 2 shows some of the modeled instruction include technical, safety, circularity information.

In order to automate sustainability assessment process, two main steps are implemented. The first step is to create shared parameters that help in calculating and displaying scores. Twelve parameters are created in Autodesk Revit®. Four parameters were created to describe the condition of the building elements, namely: reusable, recyclable, uncoated and non-toxic. Five parameters are considered to represent connection types, namely: bolted, fixed, nailed, interlocked and doweled. In addition, a prefabrication parameter is created to represent offsite manufactured elements. Also, material density and basic environmental performance are two created parameters that belong to materials properties. The next step is to use dynamo visual programming tool to model the sustainability indicators.

The dynamo model is composed of four main parts. The first part is used to select the considered building elements within each building category. A sample of the dynamo script that is used to implement this part is depicted in Fig. 3. Whereas, parts 2, 3 and 4 are used to calculate environmental score (E-score), deconstructability score (D-score) and recovery score (R-score), respectively. The E-score part depends on retrieving information of environmental performance of building materials (E_i), mass of each material in the model (m_i) and the secondary life factor (w). The mass is calculated based on the volume and density of each building material. Whereas, the secondary life factor is calculated by counting the reusable building components and determining the reusability ratio. The R-score part of the model depends on determining the ratios of both reusable (Ru), recyclable (Rc), nontoxic (Nx) and uncoated (Ns) building components by retrieving the properties of each building element of the model. Using the same concept, the D-score part determines the ratios of prefabricated and demountable elements by counting both of bolted, interlocked and doweled connections.

7. Case study

In the preceding sections, a set of indicators was provided to assess a building's sustainability based on many parameters such as

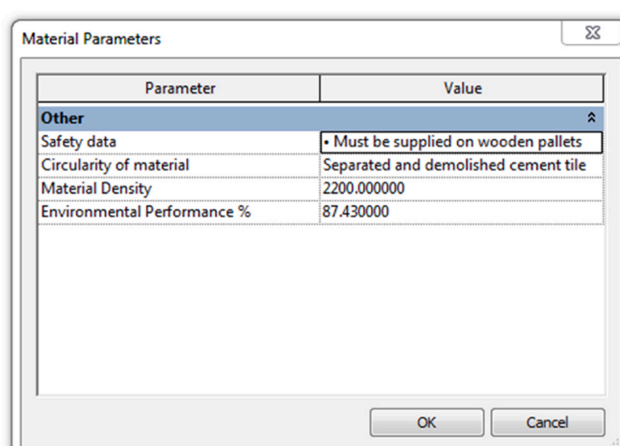

Fig. 2. Example of the modeled instructions for a building material.

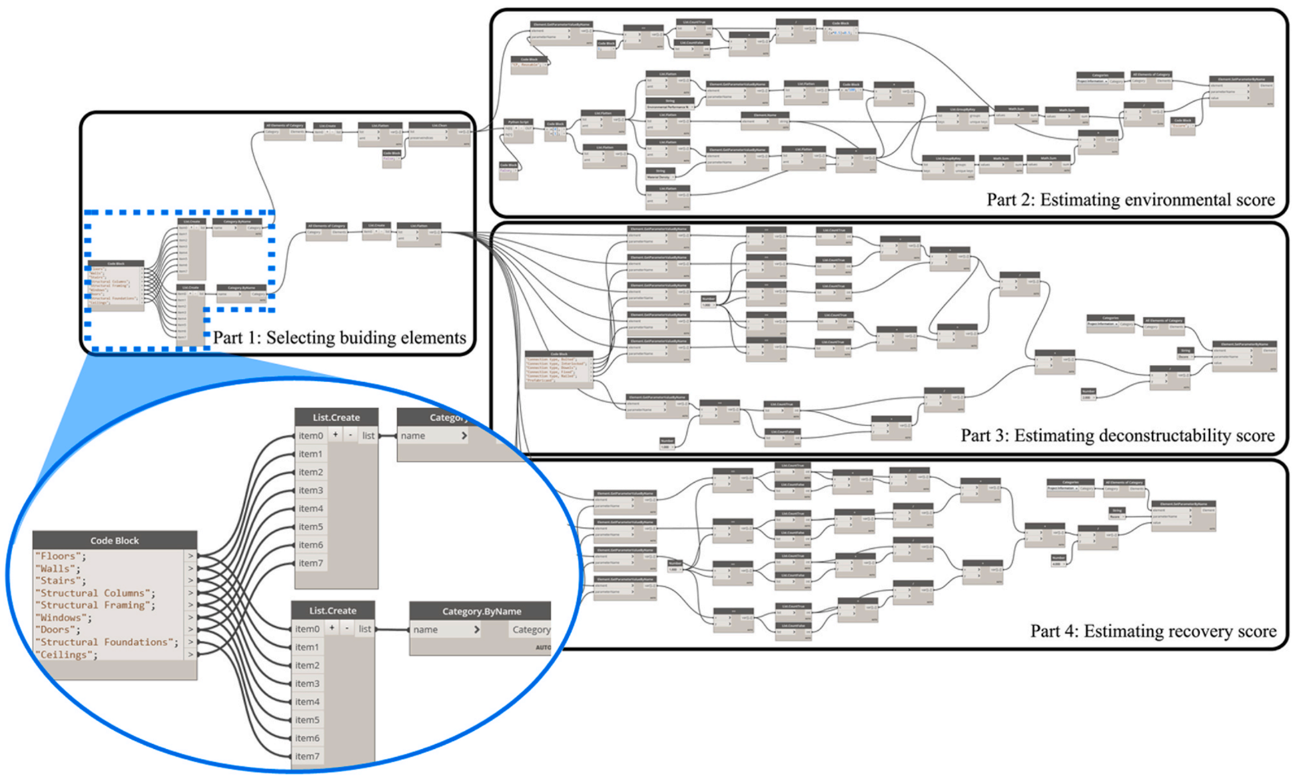

Fig. 3. Sample of the dynamo model for sustainability assessment indicators.

demountability, prefabrication, recyclability, reusability, and others. In order to validate these indicators, cases that are directly influenced by the aforementioned parameters were selected. Traditional cast-in-place buildings (base case) and modular buildings are the cases studied. Modular buildings are prefabricated and their parts can be assembled using demountable or fixed connections [6]. Whereas, cast-on-place buildings are usually fixed components. The modeled base case is based on the uniform design of thousands of social housing buildings. As a result, it is regarded as a representative sample of Egyptian traditional buildings. In the case of modular buildings, both forms of connections are included in the study, allowing the samples to cover a wider range of modular buildings. The comparison of the three samples of buildings provides an opportunity to test the efficiency of the provided indicators.

7.1. Alternatives description

This section applies the concept of material passport on a real case of a residential building of the social housing project in Egypt, named "Ebny Baitak 6" in 6th of October city. The base case consists of a ground floor and five typical floors. Materials used for this building represents most of traditional residential buildings in Egypt. The building structural system depending on the skeletal concept that made of cast-in-place concrete as shown in Fig. 4. Walls are made of clay bricks and cement bricks. Whereas, ceramic tiles and cement tiles are used in the flooring items.

Two modular building alternatives are presented in this study to compare their results with the base case. Non-volumetric type is considered to keep the original architectural design of the case study. Floors and walls are reconsidered in modular alternatives. Prefabricated concrete panels are used for walls instead of bricks [63]. Moreover, high density fiberboards (HDF) that are connected by interlock are used in living rooms flooring instead of ceramic tiles. Whereas, ceramic floors for bathrooms and kitchens are considered to be unchanged. The structural elements of the modular alternative consists of precast columns along with beams of L-section for external type and inverted T-beams internal ones [25]. These types of beams are more applicable for the prefabrication concept as it provides ledgers for supporting slabs. Hollow-core slabs are used due to their high structural efficiency and light weight that makes it suitable for transporting, lifting and installation.

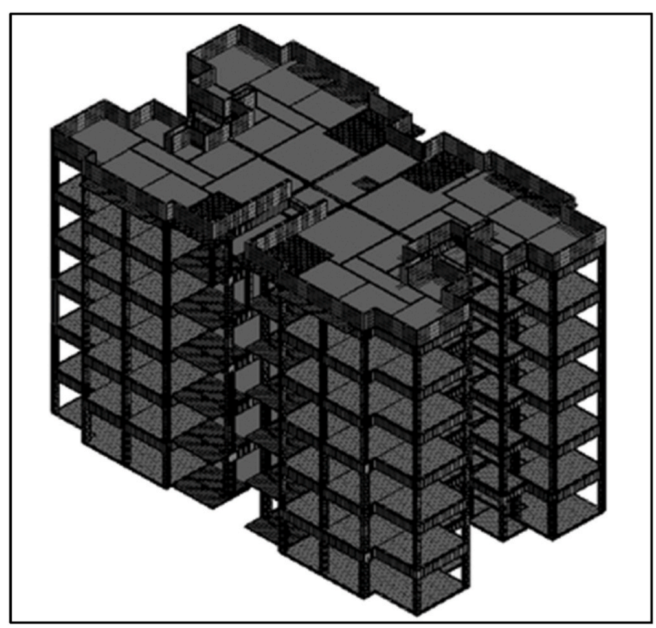

Fig. 4. Cast-in-place structure of the base case.

Two types of connections were assumed to represent the modular alternatives: dry connections and wet connections. Dry connections are demountable parts that enable connected building elements to be dismantled and reused. These connections are assumed to be bolts or rods that connect steel plates [6,7]. Fig. 5 illustrates examples of the dry connections of the modular building case. Whereas, wet connections do not support reusability of dismantled elements due to the required demolition process that damages the connected building elements.

7.2. Defining case parameters

This section presents the different parameters assumed in the case study to determine sustainability scores. Ratios of demountable connections and prefabricated elements are required to estimate deconstructability score. Whereas, ratios of reusable, recyclable, non-toxic and uncoated building elements are needed to determine recovery score. All of these variables are defined by assigning values for each of building elements in the form of true/false Boolean statements in Autodesk Revit® parameters that previously created. Table 2 summarizes values of these parameters for the considered three case study alternatives.

For the sake of calculating the environmental score (E-score), the ratio of reusable elements is defined based on pre-set condition in Table 3. The normalized environmental performance for building materials (*Ei*) is required for calculation. Table A1 lists of the considered materials and their environmental LCA results. Thereafter, Table A2 shows the normalized values of *Ei* for the materials used in both alternatives of the case study. These values are obtained based on normalization of LCA results of the considered building material alternatives. These tables are attached in the supplementary data.

8. Results and discussion

In order to demonstrate the features of the presented material passport, the framework is applied on the case study providing guidelines to reduce wastes at the early stages of the project and to exploit the generated wastes at the end-of-life stage. Quantitative indicators are also provided to allow stakeholders to tradeoff between the different building alternatives. The following sub-sections analyze the results of the sustainability indicators of both alternatives. The results of both deconstructability, recovery and environmental scores were calculated based on Equations (3), (4) and (7), respectively. The final form of the material passport is presented including instructive data. Furthermore, the role of BIM tools is discussed.

8.1. Sustainability scores

The results illustrated in Fig. 6 show the superiority of modular building alternatives over the traditional one. Modular building with dry connections (MBDC) achieved the highest Deconstructability score of 0.825, outperforming both of traditional building and modular building with wet connections (MBWC) which have Deconstructability scores of 0.16 and 0.55, respectively. Results indicate that prefabricated elements and demountable connections play the major role in the superiority modular building alternatives. This is evident from Fig. 7a showing that using demountable connections increased D-score effectively. Moreover, using both prefabricated elements and demountable connections increases D-score in a massive way compared to the base case. The demountable connections that made the difference in favor of MBDC are represented in the dry connections between beams, columns and walls, in addition to the interlock connection between HDF panels.

Regarding recovery score, MBDC achieved the highest score of 0.76 followed by MBWC and traditional building with scores of 0.62 and 0.5, respectively. Compared to base case, R-score achieved an improvement of about 23% and 50% for both MBWC and MBDC, respectively (see

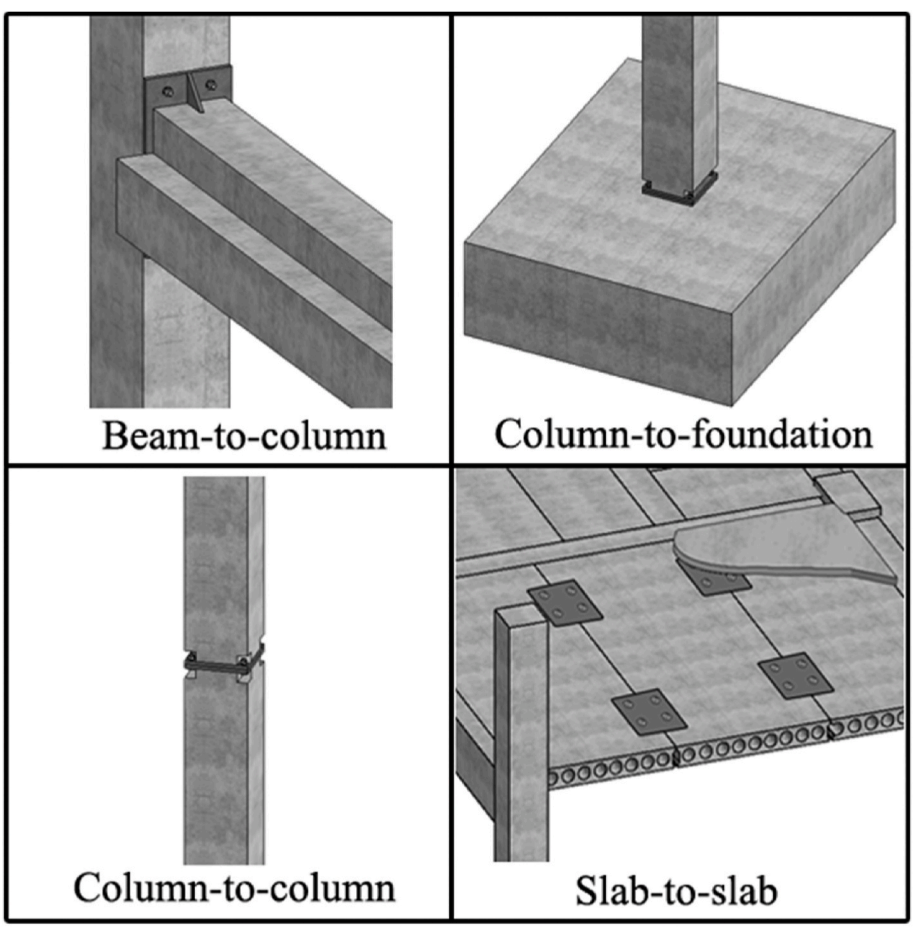

Fig. 5. Examples of dry connections of modular building case.

Table 3
Recovery and deconstructability parameters assumptions for case study.

Building Elements	Connection Type	Prefabricated	Reusable	Recyclable	Non-toxic	Uncoated
Doors						
D1: Wrought iron frame with panel	Fixed	True	True	True	True	False
D2, D3: Wood frame with wood panel	Nailed	True	True	True	True	False
D4: Wood frame with wood and glass panel	Nailed	True	True	True	True	False
D5: Aluminum frame with panel	Bolted	True	True	True	True	True
Flooring						
Ceramic tiles, mortar and sand	Fixed	True	False	True	True	True
Cement tiles, mortar and sand	Fixed	True	False	True	True	True
HDF floor with foam layer	Inter-locked	True	True	True	True	True
Structure						
Cast-in-place Concrete	Fixed	False	False	True	True	False
Precast concrete	Bolted[a]/Fixed[b]	True	True[a] /False[b]	True	True	False
Walls						
Clay bricks	Fixed	False	False	True	True	False
Cement bricks	Fixed	False	False	True	True	False
Precast walls	Bolted[a]/Fixed[b]	True	True[a] /False[b]	True	True	False
Windows						
W1, W3, W4: Aluminum and glass window	Bolted	True	True	True	True	True
W2: Wood and glass window	Nailed	True	True	True	True	False

Note.
[a] "Bolted" and "True" assumptions are belonging to modular building with dry connection alternative.
[b] "Fixed" and "False" assumptions are belonging to modular building with wet connections alternative.

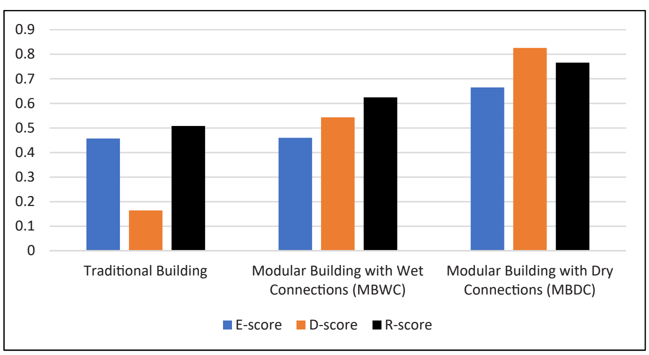

Fig. 6. Sustainability scores of case study alternatives.

Fig. 7b). This can be attributed to the fact that nearly all building elements have the same uncoated, non-toxic and recyclable properties in both alternatives. This makes the reusability ratio the most influential parameter in R-score, knowing that it is highest in MBDC alternative.

As for environmental performance, MBDC achieved the highest E-score of 0.66 with an improvement of 45.5% compared to the base case (see Fig. 7c). Whereas, both MCWC and traditional alternatives achieve roughly the same score of 0.45. These results are clearly referring that demountable connections give modular buildings the advantage over traditional ones. In other words, the higher reusability ratio resulting from the use of demountable connections plays a crucial role in giving preference to MBDC as it is directly influencing the secondary life factor. This is evidenced by the achieved value of secondary life factor (w) that was calculated based on Equation (6), which is 0.89 for MBDC compared to 0.62 and 0.58 for both MBWC and traditional alternatives, respectively. Although it is difficult to compare these results with other studies due to many differences in the scope and methods, they are in line with several studies that found that modular constructions are more sustainable than traditional ones [26,54,60].

8.2. *Building material passport*

Information included in the material passport are categorized into general information, technical guide and circularity instructions. This information is summarized in interactive report for each category. Such information includes description of the building location, structural system type and the usage of the building as well as building's sustainability scores (see Fig. 8).

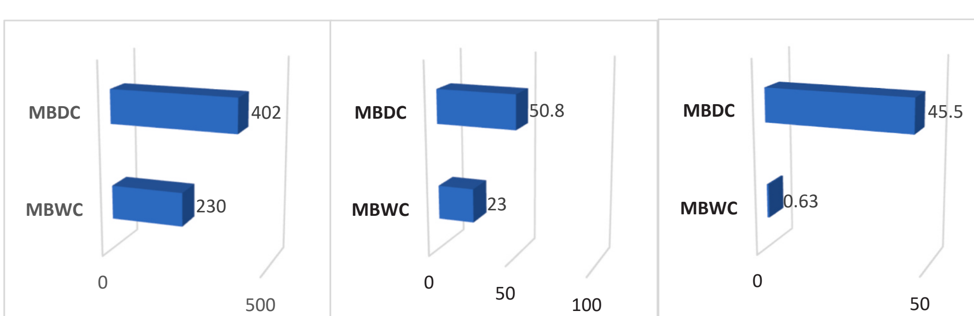

Fig. 7. Improvement of sustainability scores for modular building alternatives compared to the base case.

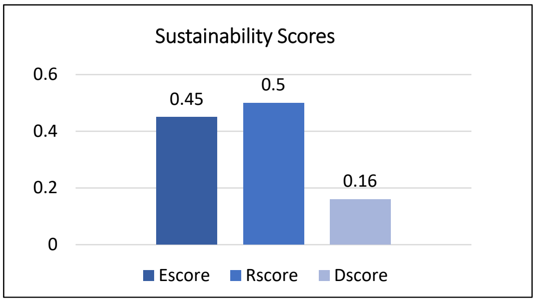

Fig. 8. Sustainability scores for the base case provided by the MP.

Furthermore, tables may involve technical information of the element understudy. For example, Table 4 contains technical information of clay bricks used in the walls. This includes the amount of material needed for constructing the wall, material density and assembling method. This information is extracted either from Egyptian building codes or technical specification released by manufacturers. It also includes safety information regarding the proper handling and stacking of supplied materials as well as the proper disassembly technique. These kinds of information contribute to reducing wastes that may result from wrong practices, whether in construction or end-of-life stages.

Second table includes circularity suggestions for the building materials represented in two parts: potential reuse/recycling of each component separately and potential reuse/recycling of the whole element. For instance, Table 5 includes information on potential use of clay bricks only as well as the potential use of mixed wastes form demolished wall. This division is helpful as it suggests a sustainable solution for the demolished wastes from the building part that is difficult to separate its components. Also, it suggests solutions for each single component that may result from excessive order of materials.

Table 4
Material technical guide (Walls: Clay bricks).

Material	Amount	Technical Data	Safety	Disassembly
1.1 Clay bricks	142894 kg	• Building units are perforated bricks type according to ES 4763/2006 and corresponding to ECP 204–2005. • Dimensions of a single unit is 25 × 12 × 6 cm. • Density ranges from 1200 to 1500 kg/m^3 with an average of 1350 kg/m^3 according to ECP 201–2012. • Units must be connected using mortar with a cement content of 300 kg/m^3 of sand. • Units should be washed by water to remove any contaminants and to avoid absorbing mortar water.	• Lifting crane should be used for lifting over bricks for higher floors. • Height of stacked bricks should not exceed 7 ft (2.1 m).	• Wall should be demolished starting from the top of top to bottom. • Walls should be broken inward as possible. • Unsupported walls should be prevented from falling by any means of support. • The allowable floor loads should not be exceeded by wastes of demolished walls; storage areas must be provided.

Table 5
Material circularity guide (Walls: Clay bricks).

Material	Circularity of the single component	Circularity of the whole part
1.1 Clay bricks	• This material has the potential to partially replace cement in the production of concrete [31]. • Also, it can partially replace silica fume in the production of reactive powder concrete [78].	Demolished walls have the potential to be recycled through loops of crushing and screening to produce recycled aggregates that can be used for: • Replacing natural fine and coarse aggregates in the production of concrete masonry units that meets Egyptian limits [5]. • Partially replacing natural aggregates in the producing paving blocks that meets European standards [70]. • This part of the building includes clay brick walls can be used to produce very fine pozzolanic material according to ASTM [68].

8.3. The role of BIM in developing MP

BIM technology played an important role in this study. It automated the calculations for the three sustainability indicators, contributing to reducing calculation time and avoiding errors. For example, Fig. 9 shows the results of the automated assessment made by Autodesk Revit® software for the base case. Furthermore, the important role of the information preservation feature in the BIM tools appears, as it has been exploited in storing technical information, as well as safety guidelines and a circularity guide. The user can control and retrieve the required data and can organize and customize it by exporting it to other programs such as Microsoft Excel®.

8.4. Contributions and limitations

The outputs provided by the developed material passport, whether quantitative or qualitative, contribute to the implementation of sustainability by helping designers, environmental affairs agencies and

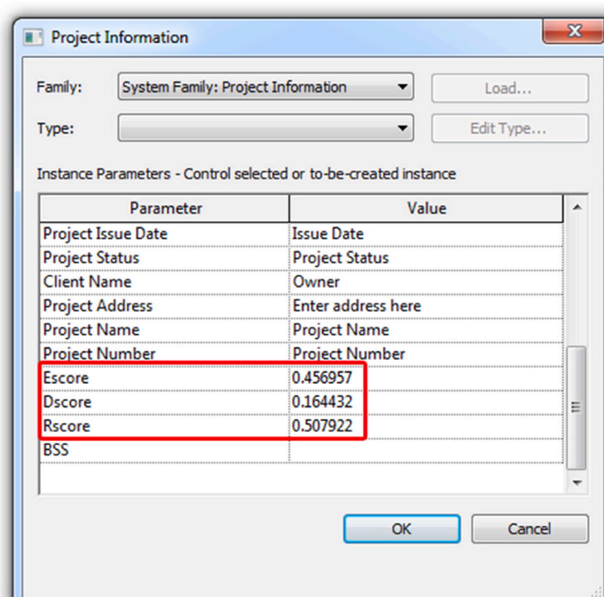

Fig. 9. Results of sustainability assessment for the base case.

sustainability assessment service providers to evaluate and tradeoff between different building alternatives in terms of sustainability. The paper contributes to filling the gap of lack of sufficient information to implement sustainability by providing indicators and data that were not included in the previous tools. The provided indicators combine between practicability (e.g., deconstructability and material recovery) and environmental performance indicators. The paper contributes to enriching research on developing technological support tools by introducing a framework for digitizing material passports through BIM technology to leverage automation, data storing and sharing features.

On the other hand, there are some challenges and limitations that should be mentioned. Despite the easiness of calculating deconstructability and recovery scores due to their reliance on statistical data from the building model, the environmental score may encounter some challenges as it necessitates a lifecycle inventory database that is not always available. Also, the economic aspect is excluded from this study due to the large amount of data required to build an effective economic indicator and link it to economic fluctuations occurring in the construction industry, which represents a limitation that should be taken into consideration in the future researches.

9. Conclusions

This paper presented a framework to develop a digital Material Passport (MP) with the aim of achieving sustainability at the building level. The information provided in this tool is divided into qualitative information and quantitative indicators. The qualitative one provided technical information of building parts. It also provided a guidance for stakeholders on safety, circularity and disassembly practices to take place in a sustainable manner. The quantitative indicators generated by the material passport included deconstructability, recovery and environmental scores. These indicators help architects/engineers to tradeoff between several building alternatives. Deconstructability score provides an indication to the designer to the separability of the building parts. Recovery score indicates to the reusability or the recyclability of the building materials. Whereas, the environmental score indicates to the lifecycle impact of the building materials. The MP is digitized using Autodesk Revit® to exploit automation, data storage and sharing features of BIM technology. A case study of a residential building is investigated to demonstrate the features of the digitized MP. The case included three design alternatives; a traditional cast-in-place one and two modular building alternatives with dry and wet connection. Results showed that both modular building alternatives achieved the highest scores of deconstructability, recovery and environmental performance. Compared to a traditional building, a significant improvement in deconstructability is achieved when using modular alternatives with a preference for buildings that use dry connections. Also, the reusability score achieved a noticeable improvement. Whereas, environmental score has made progress with the building that uses dry connection. While no worthy progression is noticed for the modular alternative that uses wet connections. These results confirm the effectiveness of the presented MP in this paper, as the indicators showed logical results for the studied cases. It also provided the stakeholders with the required instructions to achieve sustainability. The tool presented in this study contributed to revealing the adequate type of qualitative and quantitative information to support the sustainability of buildings. Despite the information provided by this tool, it can be enhanced in the future to provide more sustainability assessment indicators, including economic aspects, in order to broaden the base of beneficiaries of this tool. This can be achieved by linking BIM models with dynamic databases that synchronize the ongoing economic changes and fluctuations of the construction industry.

Author statement

Islam Atta: Conceptualization, Methodology, Investigation, Software, Validation, Writing- Original draft preparation. **Emad S. Bakhoum:** Supervision, Methodology, Project administration, Investigation, Validation, Writing, Reviewing and Editing, **Mohamed M. Marzouk:** Conceptualization, Methodology, Supervision, Project administration, Investigation, Validation, Writing- Reviewing and Editing,

Declaration of competing interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

Appendix B. Supplementary data

Supplementary data to this article can be found online at https://doi.org/10.1016/j.jobe.2021.103233.

Appendix A. Supplementary data

Table A.1
LCA results of considered building materials in the study

Material	HH	EQ	CC	RS	Impact
	(DALY/kg)	(PAF m^2.yr/kg)	(kg CO2/kg)	(MJ Primary/kg)	Pers/yr/kg
RC	1.574E-07	7.389E-03	2.038E-01	1.584 E+00	2.428 E+05
Precast	8.981E-08	4.837E-03	1.584E-01	1.005 E+00	1.544 E+05
Steel	3.176E-06	1.167E-01	1.846 E+00	2.422 E+01	3.701 E+06
Wood	1.471E-07	1.878E-01	7.381E-02	1.287 E+00	1.972 E+05
Clay bricks	1.041E-07	8.236E-03	2.445E-01	2.635 E+00	4.031 E+05
Concrete blocks	4.342E-08	4.177E-03	7.472E-02	5.565E-01	8.535 E+04
Ceramic tiles	1.574E-07	7.389E-03	2.038E-01	1.584 E+00	1.704 E+06
Cement tiles	1.135E-07	8.381E-03	2.528E-01	1.392 E+00	2.141 E+05
Three Laminated timber	8.356E-08	1.883E-01	6.157E-02	1.075 E+00	1.649 E+05
HDF	1.023E-07	3.791E-02	1.122E-01	1.985 E+00	3.031 E+05
Gypsum plasterboard	3.420E-07	3.388E-02	3.496E-01	4.567 E+00	6.978 E+05
Plastering putty	2.064E-07	1.142E-02	2.208E-01	5.177 E+00	7.891 E+05
Clay plaster	3.101E-08	2.523E-03	4.130E-02	6.138E-01	9.371 E+04
Adhesive mortar	1.217E-06	9.857E-02	1.226 E+00	1.991 E+01	3.038 E+06
Cement mortar	1.053E-07	1.128E-02	2.096E-01	1.457 E+00	2.235 E+05

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(*continued*)

Material	HH	EQ	CC	RS	Impact
	(DALY/kg)	(PAF m^2.yr/kg)	(kg CO2/kg)	(MJ Primary/kg)	Pers/yr/kg
Lime mortar	2.596E-07	1.956E-02	6.794E-01	3.646 E+00	5.610 E+05
Acrylic paint	3.710E-06	3.534E-01	3.630 E+00	5.606 E+01	8.559 E+06
Alkyd paint	5.643E-06	2.293 E+00	6.260 E+00	6.792 E+01	1.040 E+07
Polycarbonate	3.923E-06	1.031E-01	6.788 E+00	1.070 E+02	1.634 E+07
Glass	1.806E-06	1.665E-01	1.695 E+00	2.248 E+01	3.434 E+06
Fiber cement	9.182E-07	9.957E-02	1.274 E+00	1.181 E+01	1.809 E+06
Aluminum	1.289E-05	6.183E-01	1.164 E+01	1.425 E+02	2.178 E+07
MDF	9.305E-08	3.291E-02	8.970E-02	1.755 E+00	2.678 E+05

Table A.2
Assumptions of *Ei* for building materials

Material	*Ei* (%)	Material	*Ei* (%)
Ceramic tiles	10	Dry mix	85.85
Mosaic tiles	87.43	Clay bricks	10
HDF	82.21	Concrete blocks	87.82
RC concrete	93.43	Glass	98.97
Precast concrete (Structure)	95.82	Polycarbonates	10
Precast concrete (Walls)	39.76	Aluminum opening	10
Cement mortar	92.64	Steel opening	83
Plastic paint	17.67	Wood opening	99.09
Alkyd paint	10	MDF opening	98.77
Plastering putty	10		

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