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Computational LEED: computational thinking strategies and Visual Programming Languages to support environmental design and LEED credits achievement

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A B S T R A C T

Since environmental and energy issues and challenges continues to emerge as key global concerns, Green Building Certification Systems are becoming increasingly relevant in the construction industry.

In this regard, LEED (Leadership in Energy and Environmental Design) is considered one of the most widely recognized environmental assessment methods used globally in the construction industry today.

However, due to the high level of complexity of the LEED system, the tools usually used to verify the achievement of the credits lack of "design friendliness" and hardly communicate effectively with the conventional tools used by architects and engineers (e.g. CAD, BIM). This makes difficult to fully take into account, especially at the early design stage, the many interconnected aspects that contribute to the green certification, with consequent issues often arising in the design validation and/or construction phases, resulting in time delays and cost increments.

The application of innovative problem-solving methods, such as computational thinking, together with coding techniques, represents an effective way to deal with this issue. This kind of methodology, in fact, allows the requirements of a specific LEED credit to be digitally parametrised and flexibly incorporated into a "designer friendly" working environment.

In particular, Visual Programming Languages (VPLs), due to their high simplicity of usage, allow architects and engineers to develop algorithms and thus implement their technical knowledge in the field of environmental design with computer programming skills, useful to improve their tools and keep them constantly updated.

The aim of this paper is to illustrate a methodology through which, by merging computational thinking strategies with VPL tools, is possible to keep under control, in the same working environment, all the parameters required to verify in real time the achievement of LEED credits. To demonstrate the flexibility of the approach, dedicated tools developed for the verification of some specific credits at different scales – neighbourhood and building – are illustrated as operational examples of the proposed methodology.

1. Introduction: The role of environmental rating systems and computer programming in contemporary design processes

The work presented in this paper is set in the broader context of computational design, and, in particular, aims to investigate the application of "user friendly" computer programming techniques focused on performance-based design and decision support for green building technologies and environmental design solutions.

Among the various factors influencing contemporary design, the definition of green building solutions and the improvement of energy efficiency is nowadays an increasingly decisive issue, which affects typo-morphological and technological features of buildings and open spaces. According to a 2019 report by the Global Alliance for Buildings and Construction (Global ABC) [31], 40 % of global climate-changing gas emissions comes from the construction industry. To face this scenario, numerous plans and strategies are being implemented globally in the direction of environmental

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sustainability. In Europe, for example, one of the main objectives of the European Green Deal[1] [1] is to reduce energy consumption in the construction industry through a series of specific actions aimed at optimising resources and promoting experimentation of systems and tools that can improve buildings performances. This objective is closely linked to the need of integrating in the design innovative construction materials and processes that meet adequate environmental standards, in a life-cycle and circular perspective.

In this context, green rating systems are becoming increasingly important. According to specific standards, these systems provide a set assessment tools that certify the level of environmental sustainability of a design project both at the building and neighbourhood scale.

There are several rating systems diffused around the world: LEED, BREEAM, Green Star, CASBEE, Living Building Challenge, just to cite some of them. Among these, LEED (Leadership in Energy and Environmental Design) and BREEAM (Building Research Establishment Environmental Assessment Method) are considered the most representative and widely used environmental assessment methods in the construction industry today [2].

BREEAM is considered as the first green building rating assessment in the world. Launched and operated by BRE (Building Research Establishment) in the UK in 1990, BREEAM certifications accounts for 80 % of the European market share for sustainable building certifications [3].

On the other side, LEED is a voluntary and market-driven tool that serves as a guideline and assessment mechanism. Specific LEED rating systems address commercial, institutional, and residential buildings and neighbourhood developments [4] Released by the U.S. Green Building Council in 1998, LEED is considered as the most widely adopted rating scheme based on the number of countries, with over 100.000 projects across 160 countries in 2021 [5].

Both the methods predominantly evaluate environmental factors including water management, energy efficiency, materials, indoor environment quality, land uses, etc., but they differ significantly in their flexibility and the number of certified buildings. 561,600 buildings in total were certified by BREEAM, which is more than five times higher than those for LEED. Regarding geographic adoption, up to 160 countries and territories have adopted LEED for green project assessment in comparison with 80 countries for BREEAM [3].

The principal reason why there are more BREEAM certifications than those of LEED is that in Europe, which is the main target of the BREEAM method, most of the countries are well aware of sustainability issues. On the other hand, the LEED method is widespread in many more countries than BREEAM. This is because LEED is considered as a more transparent rating approach for calculating the final results, while BREEAM adopts the preweighted categories method which is more complex and stricter: BREEAM sets absolute parameters while LEED sets relative targets for percentage improvement or reduction [3]. Furthermore, the possibility of selecting specific credits across the various categories to achieve the targeted certification level, allows LEED to address in a more flexible way the technical and financial constraints linked to a given project

Although the LEED method appears less complex than the BREEAM approach, it operates over the entire process, from design to actual construction. For this reason, the parameters involved in the certification system are numerous, and the interactions between all the variants can be very difficult to manage. Consequently, LEED requires a holistic approach to successfully achieve the identified objectives. Only with an extensive integrated design and coordination effort it is possible to implement a project that harmoniously complies with all the requirements necessary to achieve the targeted certification. For this reason, there is a clear need to provide professionals working in the design and construction industry with innovative and advanced tools, capable of managing the huge amount of data required in the most flexible way possible.

The instrumental and methodological capabilities linked to the digital innovations and the information revolution make it possible, in this sense, to achieve results that were precluded a few years ago. In recent years, in fact, architecture has become increasingly dependent on computation, intended not only as a medium for the representation of complex images. In its simplest form, computation is a system that processes information through a discrete sequence of steps by taking the results of its preceding stage and transforming it to the next stage in accordance with a recursive function [6]. The latest tools derived from the development of ICT technologies are now capable of processing a huge amount of "Big Data" and managing their relationships, thus allowing designers greater control over all aspects of the project.

Within the paradigm shift generated by the "digital turn" in architecture, the implementation of computer programming principles in design processes is becoming increasingly important. Regarding this, Mark Burry predicts a future in which designers will increasingly resemble skilled digital toolmakers [7]. Computer programming can be seen as one of the main operational models for a novel approach in architecture, in which all dynamic interconnections among shape, functions, materials and technologies are being transferred from digital models to the reality of a responsive, sensitive and interactive architecture [8].

Methods of dealing with architectural design through computer programming actions define the coding and scripting actions. According to Robert Aish, computer programming tools also have a pedagogical function for the designer [9]. Through their use and the elaboration of computer constructs, the digital designer acquires a certain methodological awareness that is specific to design. Scripting, therefore, assumes a value comparable to drawing for architecture, in other words a value of investigation and in-depth study of form, function and communication capable of increasing the levels of introspection of the project itself.

Among the various programming languages currently available in the IT sector, Visual Programming Languages[2] [10] (VPL) stand out for their flexibility and user-friendliness. Being integrated into many of the tools used by architects and engineers (e.g. Rhinoceros, Revit, etc.), they offer nowadays an opportunity for these professionals to support the development of simulation and evaluation tools that implement their workflows and enable them to include numerous design issues, such as those related to environmental sustainability and energy efficiency.

This paper illustrates a holistic methodology through which, by merging computational thinking strategies with VPL tools, is possible to keep under control, in the same working environment, all the parameters required to verify in real time the achievement of LEED credits.

This paper addresses specifically the LEED due to its simpler nature if compared to other similar methods like BREEAM. Nevertheless, the logical and technical workflow presented can also be replicated on other rating systems.

[1] The European Green Deal is a set of policy initiatives proposed by the European Commission with the goal of achieving climate neutrality in Europe by 2050. It was presented on 11 December 2019 as the first act of the new Commission and as an integral part of a European strategy to implement the United Nations 2030 Agenda. The Green Deal includes an action plan to restore biodiversity, reduce pollution and promote resource efficiency by moving to a clean and circular economy.

[2] VPL is a language that facilitates computer programming replacing the formal syntax with the manipulation of graphical objects. In most VPLs, the syntactic scheme consists of "boxes" and "connectors", the former being code carriers (instructions), while the latter weave the classic flowchart structure.

2. Environmental design and digital tools

Environmental rating systems have undoubtedly increased designers' awareness of environmental sustainability and energy efficiency issues, and consequently increased the demand for advanced tools for simulating building performances. Both at the building and neighbourhood scale, the number of digital tools available for architects and engineers is constantly increasing, and there are many ways in which the interaction between site and inhabitants can be studied.

In the case of LEED, it is possible to find a large number of different software capable of managing the data required for the credits' achievement verification [11]. In addition, the official USGBC website makes available, for a limited number of credits, some calculators which, once filled in with the required parameters, check whether the project meets the standards [12].

However, the main issues linked to the digital tools mentioned above consist in their mono-focused nature and in the fact that they are basically "black box" engines, closed, and with hardly comprehensible operating procedures. This generates two main consequences: the first is purely instrumental, while the second is more "pedagogical".

The instrumental aspect of the issue mainly concerns the compatibility and interoperability between different software tools. Many simulation and assessment tools, in fact, are developed to be used as standalone applications or as external plug-ins for other software, such as BIM authoring applications. However, it can happen that, in the case of an update of the software or of the data exchange standards, the above-mentioned plug-ins or standalone tools may stop working properly.

To address this critical aspect, research in the field of IT technologies applied to design has been developing new methods to exchange information and achieve software interoperability, either through open formats such as GBXML and IFC, or using more direct communication processes that exploit the capabilities of Visual Programming Language platforms. VPLs are in fact becoming increasingly popular in BIM workflows, and an increasing number of software houses is integrating their products with visual programming interfaces: in some cases, with proprietary tools, in others through the development of specific plug-ins that allow live connections with external tools.

In the field of performance-based design supported by simulation tools, the VPL-BIM link aims to streamline the interoperability between different tools. The VPLs, in fact, make it possible to develop specific middleware tools, capable of connecting the master model managed in a BIM authoring software directly with external applications and thus integrate the calculation models into the common workflows carried out by designers in order to guide their choices towards performance-based solutions, overcoming the limits imposed by the standard ifc interchange format and reducing information loss [13].

As mentioned above, the other critical aspect of the "closed" nature of the majority of IT tools in the field of environmental design is strictly "pedagogical", itlimits the actual uptake by the users of the underlying building physics and environmental design knowledge, thus limiting the consolidation of sustainable design principles and technical solutions by architects and engineers (and especially by young professionals, often more skilled in the use of software and IT solutions). On this regard, Chris Mackey writes: «monolithic, isolated tools often hinder the learning process of the modeller and can prevent him or her from reaching a deeper understanding of the underlying components and assumptions of a computer simulation» [14]. A lack of awareness of input data generates an incorrect use of tools and can cause the so-called "Garbage In, Garbage Out"[3]: when modelers do not adequately understand the premises of a model they have built, they can end up making the wrong decision in a design process, ultimately detracting value rather than adding it.

Conversely, parametric visual programming tools enable different performance assessment methods to be customised and connected with an ever-evolving building geometry. The designer can tailor new sets of broad, holistic regenerative design targets by programming and linking new sets of relationships to simulation engines or an entirely new set of equations [15]. The action of programming allows the user to have constantly updated tools and pushes for more awareness and control over data and calculation processes.

Among the various visual programming tools, the most widely used in the architecture sector is certainly Grasshopper 3D, included in its stable version in the modelling software Rhinoceros (McNeel). Grasshopper is an open-source, customisable Python code system that allows even people without advanced coding skills to write algorithms and program their own tools as they wish. Unlike the digital tools typically used for architecture and design, Grasshopper allows construction industry professionals, to develop their computational literacy: either they understand how inputs, processing, and output works, or they will not be able to use the tool. Regarding environmental issues, plugins such as Ladybug Tools are an excellent example of such evolutionary dimension. Due to their logical and well visualised structure, they provide a comprehensive understanding of the issue of environmental and energy modelling [16].

According to these observations, it is possible to state that user-friendliness and flexibility are the main Grasshopper strengths; furthermore, the large number of educational resources freely available on the web, such as the *Grasshopper Primer* [17] and the Grasshopper official website [18], simplifies the learning process of these tools and enables a constant knowledge exchange with experts through dedicated online forums..

It is mainly for this reason that the tools described in the following paragraphs have been developed in the Rhino – Grasshopper working environment, which guarantees both "designer-friendlin ess" and the possibility to modify and implement tools and workflows according to users' requirements.

3. LEED and computational thinking: the Computational LEED workflow

The term "computational thinking", first mentioned in the 1980s s by the mathematician Syemour Papert [30,32], introduces a problem-solving methodology based on the principles of computer science. As Jeannette Wing says: «Computational thinking is reformulating a seemingly difficult problem into one we know how to solve, perhaps by reduction, embedding, transformation, or simulation» (...) [19]. In other words, this extremely flexible approach makes it possible to reshape a problem and to set up its resolution process through a sequence or different phases: starting from an initial phase of breaking down the problem into smaller parts, then it follows a process of collection, selection, and analysis of all the essential data that are useful to solve the problem (or one of its parts), discarding those that are not necessary. Based on this operation, it will then be possible to decide which are the individual steps that will lead

[3] "Garbage in, garbage out" is a phrase that spread among computer scientists with the birth of the first computers. According to this principle, it is not possible for a computer to generate correct results if the input data are inaccurately selected and inserted.

to the final solution. This last phase is known as "Algorithm design"[4] [20].

Although "computational thinking" essentially describes a methodology and mainly concerns a set of mental tools, its relationship with programming and with the tools of computer science is quite evident. In the field of architecture, in fact, because of their nature, the processes and tools typical of algorithm aided design fit perfectly with the logical "problem-solving" workflow described above, allowing to systemise various parameters, strategies and techniques in one or more design algorithms, so to efficiently achieve the targeted design goals.

For this reason, the application of such mental and instrumental strategies in the management of the various parameters linked to the achievement of one or more LEED credits can be successful especially to accelerate and control in detail the entire certification process, and facilitate the evaluation of different technical alternatives by the project team.

To shape the LEED certification as a problem to be solved by using computational design methods, a systemic thinking approach is needed. By considering the entire project as a set of interconnected parts, it is possible to break down and analyse each individual part according to the LEED categories that each of them may imply. Then, a further decomposition phase must be carried out, in which, for each of the selected categories, the credit(s) to be achieved have to be connected. Then, all the data related to the achievement of the criteria can be analysed and e processed together with the other interconnected project parameters, depending on technical and design choices. In this way, the performances required by the certification system will no longer be considered as simple verification tools downstream of the design process and will become real inputs to be considered ex ante.

The methodology described above has been applied by using Visual Programming Languages to produce a series of digital tools which, by implementing a three-dimensional model, verify the adherence of the project to one or more LEED credits, providing feedback in the case of achievement failure. The feedback itself becomes then is a guideline to modify and improve the design choices according to the targeted benchmarks.

The digital tools used for this experimentation are Rhinoceros (ver. 7, SR 10) and Grasshopper 3D as VPL. In addition to the reasons outlined above related to their "designer-friendliness", this specific software choice was given also by the fact that Grasshopper has several plug-ins that can be used for data management and energy simulations, which due to the "open" nature of the tool, can be easily implemented and updated by the large community on the web.

The outcome of this investigation is therefore a set of computational tools, particularly useful for architects and engineers, that integrate environmental sustainability indicators and benchmarks into a software environment that is widely used in the design and construction industry. The use of programming tools to implement LEED protocols in a 3D modelling software can ensure a better integration of environmental issues in design processes.

Each category of LEED credits has been implemented through ad-hoc VPL scripts, which process the related input data depending on the design solutions adopted and calculate the achieved performance. In case the solution does not meet the required benchmark, the tools give the user suggestions about the improvements needed to achieve the credit.

[4] According to the definition given by Ipek Gursel Dino «An algorithm is a finite set of instructions that aim to fulfill a clearly defined purpose in a finite number of steps. An algorithm takes one value or a set of values as input, executes a series of computational steps that transform the input, and finally produces one value or a set of values as output».[20].

Since LEED BD + C protocol includes credits linked to the site, other than to the specific buildings, inputs on both built and open spaces are required. At the building scale, the main input required include materials' specifications (including vegetated surfaces), geometrical features of buildings and building components (e.g. shading panels), renewable energy production and HVAC system typology. At the neighbourhood scale, surface materials, vegetative cover (including trees) and building geometries are required.

Launching the Grasshopper definitions, the user gets the information whether the corresponding credits are achieved. In case minimum benchmark is not achieved, the tools give specific recommendation about the needed improvements to get the credit Fig. 1.

To simplify the input from the user side, in some cases, dedicated xls templates linked to the Grasshopper components have been designed to collect the needed information, e.g. about materials, from the manufacturers' technical sheets. In this way, a database of recurring products and technical solutions used is progressively stored in the system, thus simplifying the design and verification process the more the tools are used, ideally requiring only 3d massing, with land use attribution and technical specifications added through drop-down menus.

The following sections illustrate in detail the methods and workflows developed for two credit categories of the LEED BD&C protocol: Materials and Resources – Building Product Disclosure and Optimization and Sustainable Sites – Open space. The aim is to demonstrate the flexibility and replicability of the workflow both at the building scale and at the neighbourhood scale.

3.1. Computational LEED workflow at the building scale: LEED BD&C materials and resources – Building product disclosure and optimization

The tool allows to verify the achievement of the three credits included in the Building Product Disclosure and Optimization (BPDO) category: *Environmental Product Declarations, Sourcing of Raw Materials and Material Ingredients.* From a methodological perspective, the workflows for all the three credits achievement have many similarities, so it was possible to develop a single tool that could check them all simultaneously.

Fig. 2 shows how the previously explained logical workflow is specified for this specific tool.

According to the LEED Reference Guide [4], the main intent of the BPPDO credits is to encourage the use of products and materials that have low environmental, economic, and social life-cycle impacts. In particular, the *Environmental Product Declaration* credit rewards projects that use materials and products that have a Life Cycle Assessment (LCA) in accordance with ISO 14,044 or an Environmental Product Declaration (EPD)[5] [21,22]. As regards the *Sourcing of raw materials* credit, it rewards projects that use products verified to have been extracted or sourced in a responsible manner, for example: products containing a certain percentage of recycled material, biomaterials, recovered or reconditioned materials, etc. Lastly, the *Material Ingredients* credit relates to the chemical composition of the materials used. To achieve this credit, project teams have to choose products whose chemical components are catalogued according to a standard accepted by the LEED system and for which both a minimum use and generation of harmful components have been ascertained.

Starting from a study of the three credits listed in the "LEED Reference Guide for Building, Design and Construction v4", it was pos-

[5] EPDs (Environmental Product Declaration) are type III environmental labels (ISO 14025) and provide quantitative data on the environmental profile of a product calculated according to LCA procedures and in accordance with specific PCRs (Product Category Rules), that are internationally defined rules for each product category.

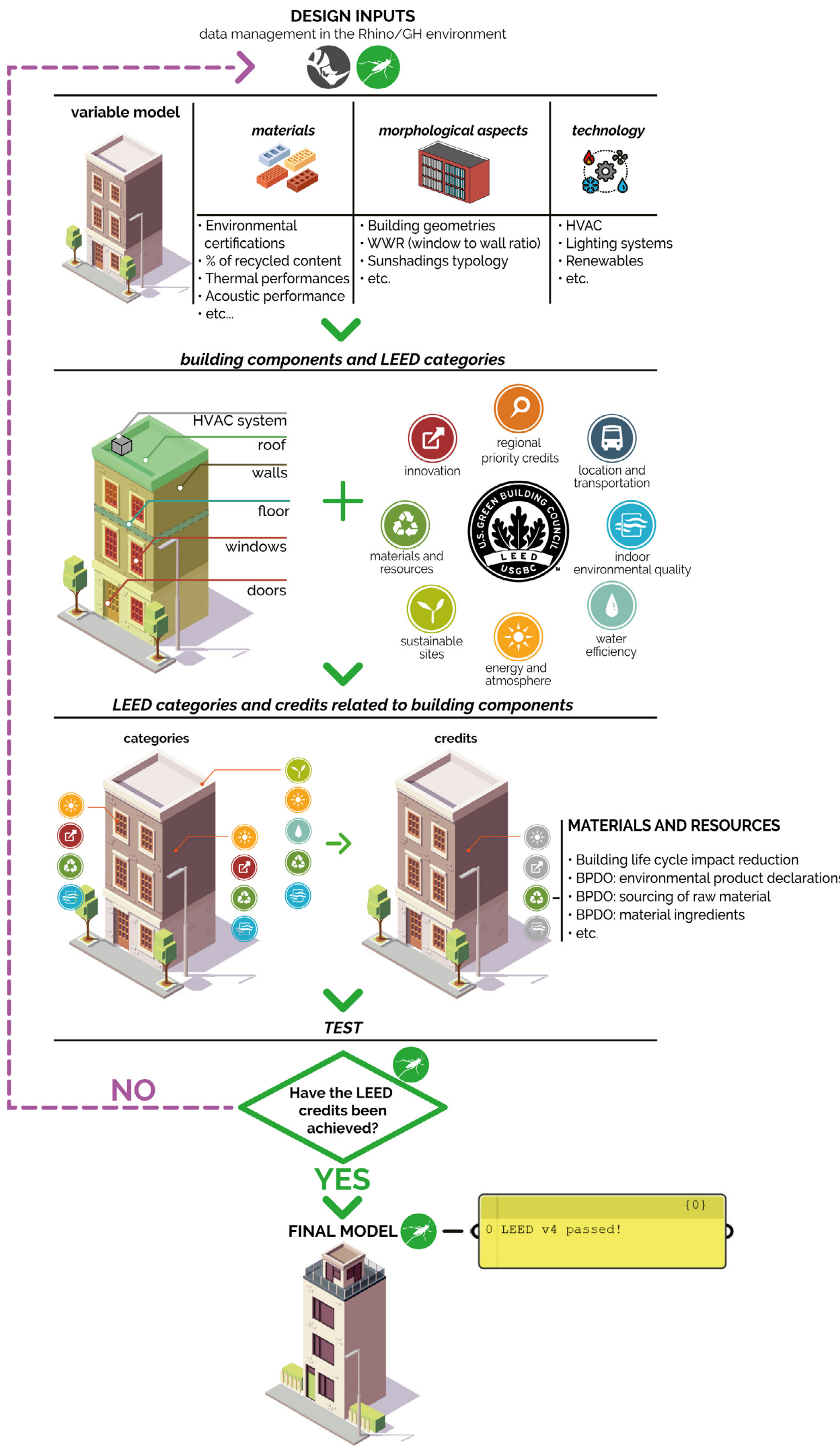


Fig. 1. Computational LEED logic workflow: systemic thinking approach applied to the LEED credits achievement.

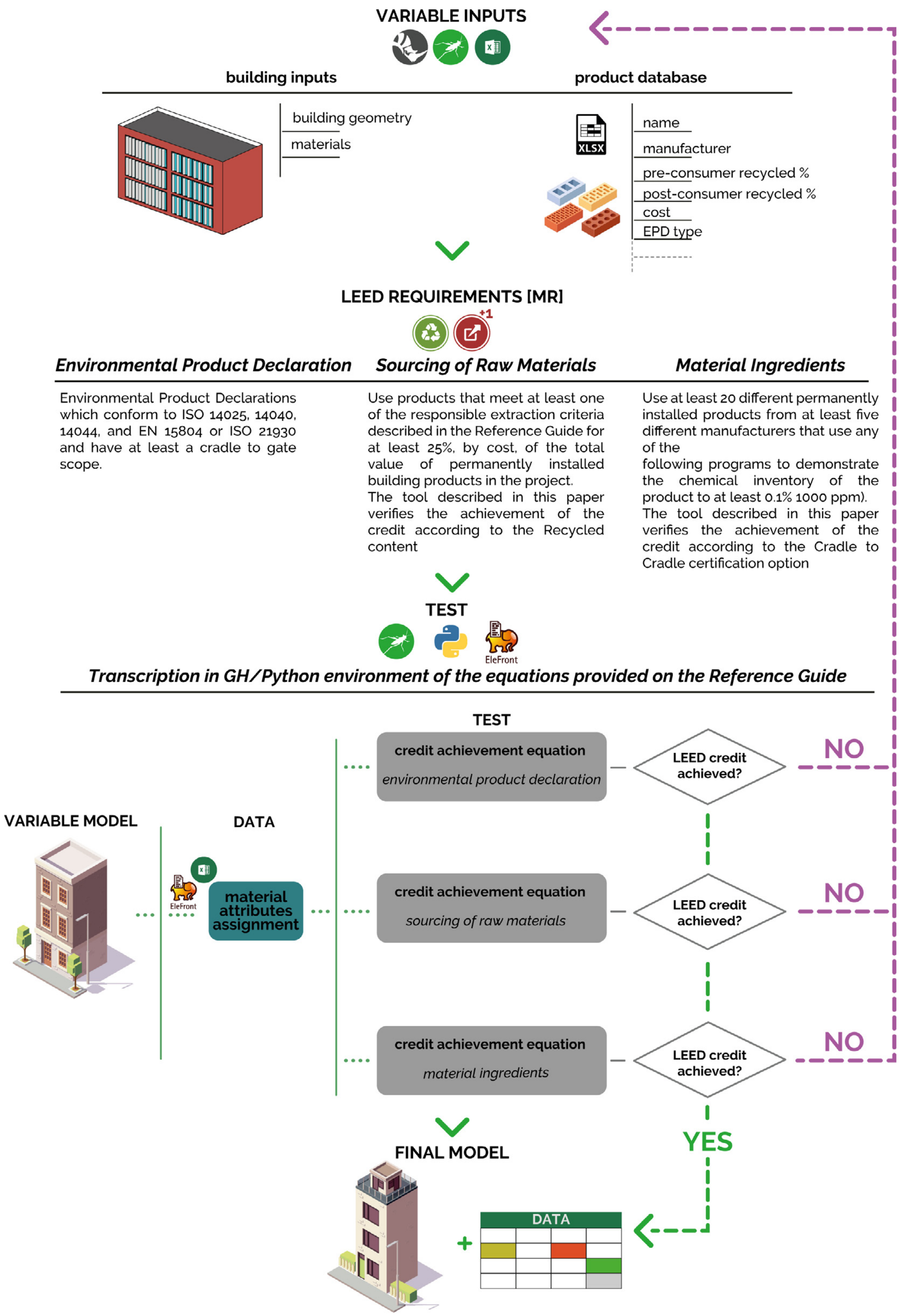
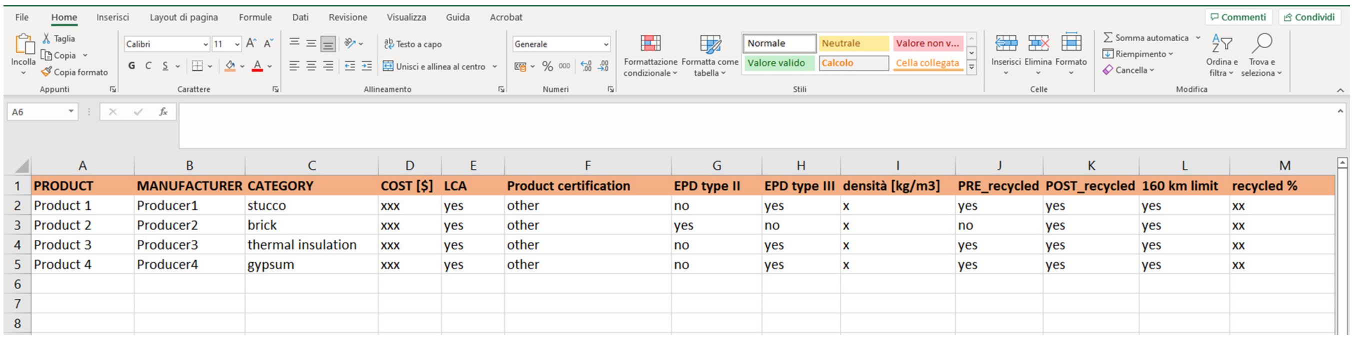


Fig. 2. Logical workflow for the "Building Product Disclosure and Optimization" tool.

sible to extrapolate all the information needed to develop the tool. As frequently happens, the guide indicates more than one way of obtaining each credit. To establish an effective relationship between VPL and 3D modelling software, methods that favoured a designer-oriented workflow were selected, i.e. with a direct connection between data and modelled geometries, and in which the retrieval of materials-related information was particularly simple for the project team.

For the *Environmental Product Declarations* credit, option 1 was chosen: i.e. to use at least 20 different construction products, provided by at least 5 different manufacturers, that have a Life Cycle Assessment (LCA) or an Environmental Product Declaration (EPD).



	A	B	C	D	E	F	G	H	I	J	K	L	M
1	PRODUCT	MANUFACTURER	CATEGORY	COST [$]	LCA	Product certification	EPD type II	EPD type III	densità [kg/m3]	PRE_recycled	POST_recycled	160 km limit	recycled %
2	Product 1	Producer1	stucco	xxx	yes	other	no	yes	x	yes	yes	yes	xx
3	Product 2	Producer2	brick	xxx	yes	other	yes	no	x	no	yes	yes	xx
4	Product 3	Producer3	thermal insulation	xxx	yes	other	no	yes	x	yes	yes	yes	xx
5	Product 4	Producer4	gypsum	xxx	yes	other	no	yes	x	yes	yes	yes	xx
6													
7													
8													

Fig. 3. Product database created in Microsoft Excel.

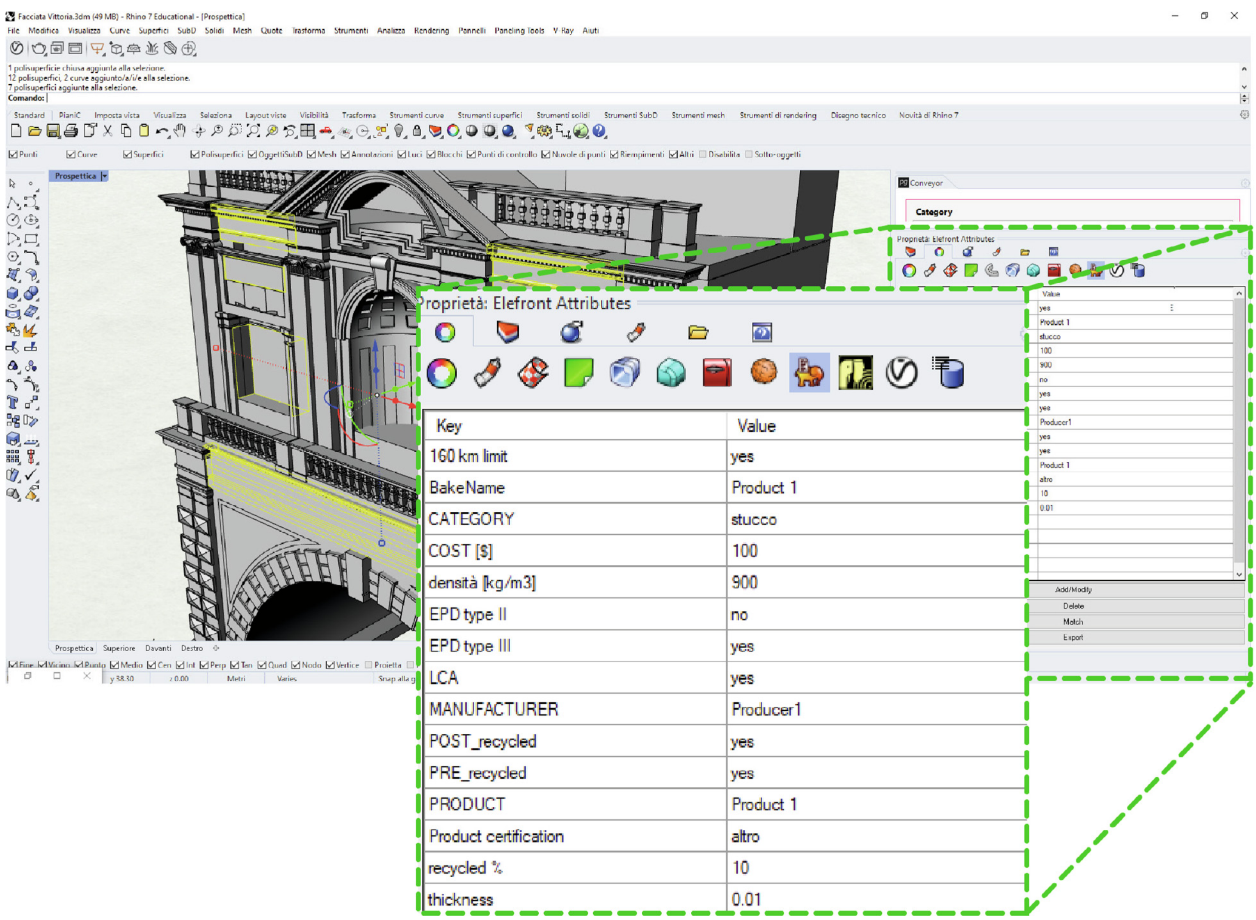


Fig. 4. Product information imported in the Rhinoceros model and linked to the geometries (the information shown in the image is for illustrative purposes only).

Option 2 was selected for the *Sourcing of Raw Materials* credit: i.e. to use products that meet at least one of the six sustainable extraction criteria identified in the guide, for at least 25 %, in cost, of the total value of the products used. Among the six criteria, the one chosen for the development of the tool was the presence of recycled content, information which is generally readily available in the technical documentation accompanying the products.

Lastly, for the *Materials ingredients* credit, option 1 was chosen: i.e. to use at least 20 different products, from at least 5 different manufacturers using one of the seven methods proposed by the guide to demonstrate their chemical composition to the extent of at least 0.1 % (1000 ppm). Among the seven methods, the *Cradle to Cradle*[6] certification [23] method was preferred. The reasons for this choice are related to the availability of this information and to the fact that, depending on the level of certification achieved by a product, it is possible to obtain an additional point by using option 2. The requirements of this option, in fact, can be fulfilled together with option 1 and reward projects using products whose component

[6] Cradle to Cradle Certified® is the global standard for products that are safe, circular and responsibly made. It assesses the safety, circularity and responsibility of materials and products across five categories of sustainability performance: Material Health, Product Circularity, Clean Air & Climate Protection, Water & Soil Stewardship, and Social Fairness. [23].

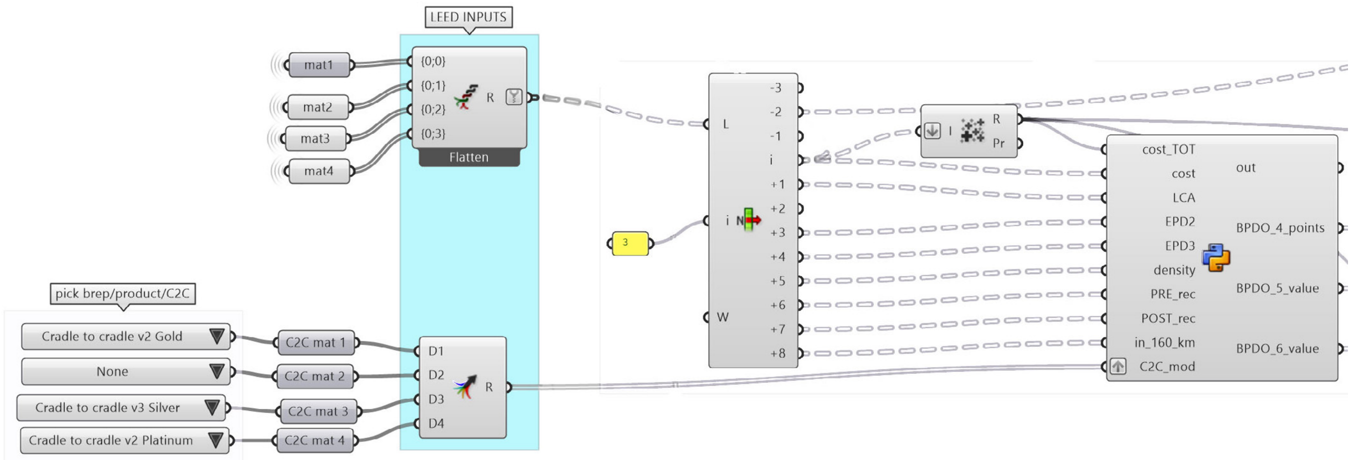


Fig. 5. Custom Python component that processes data coming from the material database to verify the achievement of the BPDO credits.

EQUATION 1. Total number of products with environmental product declarations

$$\text{Total \# of products} = \left\{ \begin{array}{c}\text{\# of products}\\ \text{with product}\\ \text{specific}\\ \text{declarations}\end{array} \times 0.25 \right\} + \left\{ \begin{array}{c}\text{\# of products}\\ \text{with industry}\\ \text{specific}\\ \text{declarations}\end{array} \times 0.5 \right\} + \left\{ \begin{array}{c}\text{\# of products}\\ \text{with type}\\ \text{III EPD}\end{array} \times 1 \right\}$$

Fig. 6. Equation that calculates the product value according to BPDO: Environmental Product Declarations credit [4].

EQUATION 2. Percentage of responsibly sourced products

$$\text{\% of materials cost} = \frac{\left\{\left(\begin{array}{c}\text{applicable}\\ \text{product}\\ \text{cost}_1\end{array}\right)\left(\begin{array}{c}\text{criterion}_1\\ \text{valuation}\\ \text{factor}\end{array}\right)\left(\begin{array}{c}\text{location}\\ \text{valuation}\\ \text{factor}\end{array}\right)\right\} + \left\{\left(\begin{array}{c}\text{applicable}\\ \text{product}\\ \text{cost}_2\end{array}\right)\left(\begin{array}{c}\text{criterion}_2\\ \text{valuation}\\ \text{factor}\end{array}\right)\left(\begin{array}{c}\text{location}\\ \text{valuation}\\ \text{factor}\end{array}\right)\right\} + \ldots}{\text{Cost of all permanently installed prodcuts}} \times 100$$

Fig. 7. Equation for the adjustment of the cost value of the installed products according to the BPDO: Sourcing of Raw Material credit [4].

EQUATION 1. Percentage of compliant materials' cost

$$\text{\% of materials cost} = \frac{\left\{\begin{array}{c}\text{product}\\ \text{cost}\end{array}_1 \left(\begin{array}{c}\text{criterion}\\ \text{valuation}\\ \text{factor}\end{array}\right)\left(\begin{array}{c}\text{location}\\ \text{valuation}\\ \text{factor}\end{array}\right)\right\} + \left\{\begin{array}{c}\text{product}\\ \text{cost}\end{array}_2 \left(\begin{array}{c}\text{criterion}\\ \text{valuation}\\ \text{factor}\end{array}\right)\left(\begin{array}{c}\text{location}\\ \text{valuation}\\ \text{factor}\end{array}\right)\right\} + \ldots}{\text{Cost of all permanently installed products}} \times 100$$

Fig. 8. Equation for the adjustment of the cost value of the installed products according to the BPDO: Material Ingredients credit [4].

optimisation can be documented through one of the four criteria described inf the guide. According to one of these criteria, the value attributed to a given product depends on the type of Cradle to Cradle certification it has (e.g. Gold products are assessed at 100 % of their value, Platinum products at 150 %).

Following the selection of the required options, the developed algorithm interacts with an external database to be filled in with all the information related to the materials used in the project. This database is structured as a Microsoft Excel sheet in which each row indicates a specific material, while each columns indicates the

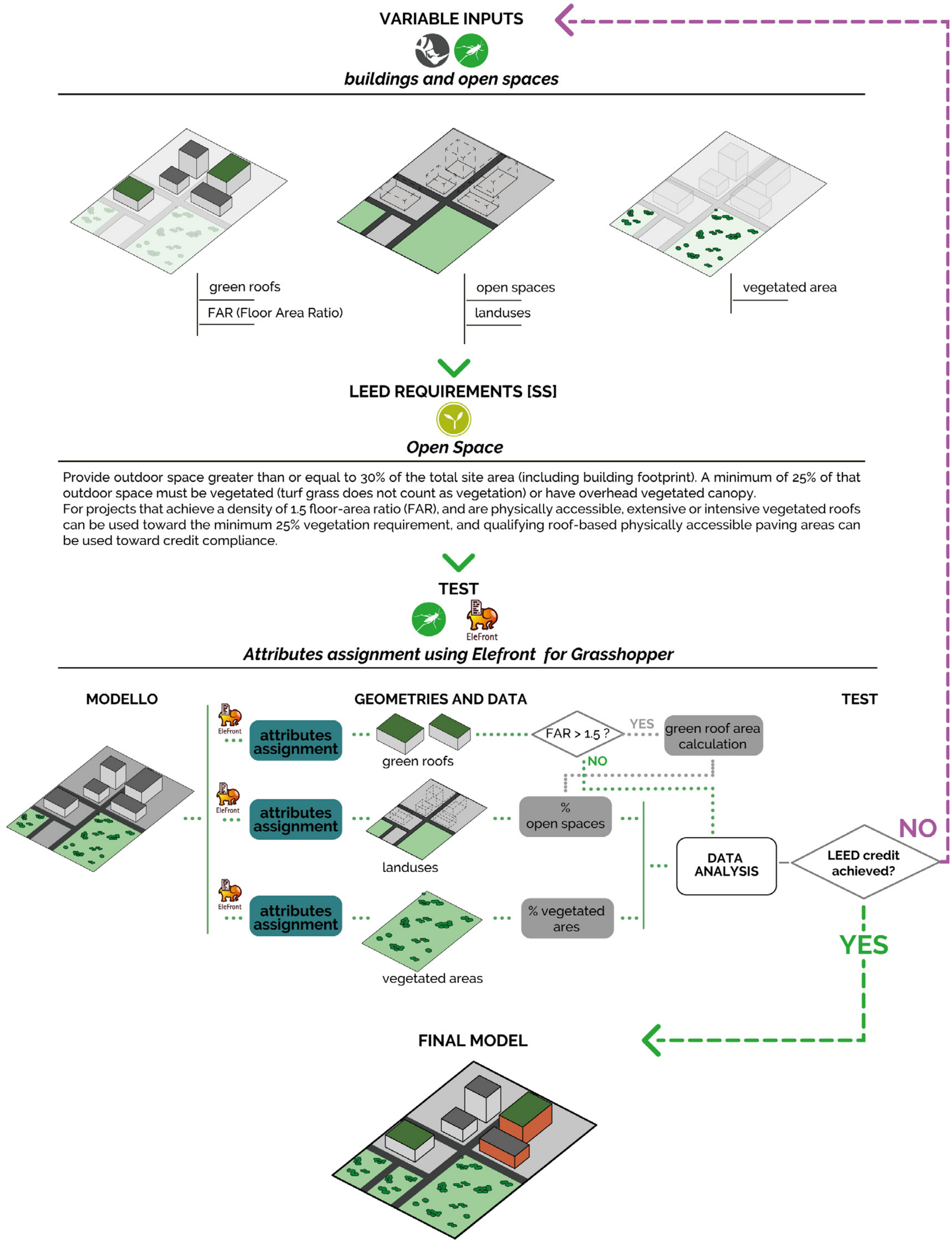


Fig. 9. Logical workflow for the "Open Space" tool.

information needed to verify the criteria (Fig. 3): name of the manufacturer, presence of an LCA or EPD, price, amount of pre-consumer and/or post-consumer recycled content.

This Excel database is imported into the Grasshopper algorithm using a component of the Lunch Box plug-in (Proving Ground). Once imported, all the information is organised in a data tree: each path of the data tree corresponds to a material in the database and the lists within the paths contain information on that material. The data organised in this way will then be applied to the geometries modelled in Rhino / Grasshopper using a dedicated plug-in, *Elefront*, which is able to manage and modify the geometries' attributes[7] and thus to inform the model. After this, all material

[7] In computation, an "attribute" is a specification that defines a property of an object (geometries in the case of Rhino models). An attribute of an object usually consists of a key (name) and a value. In the tool presented in this contribution, each key corresponds to a specific material category (producer name, price, recycled content, etc.) and each value corresponds to the information related to that category.

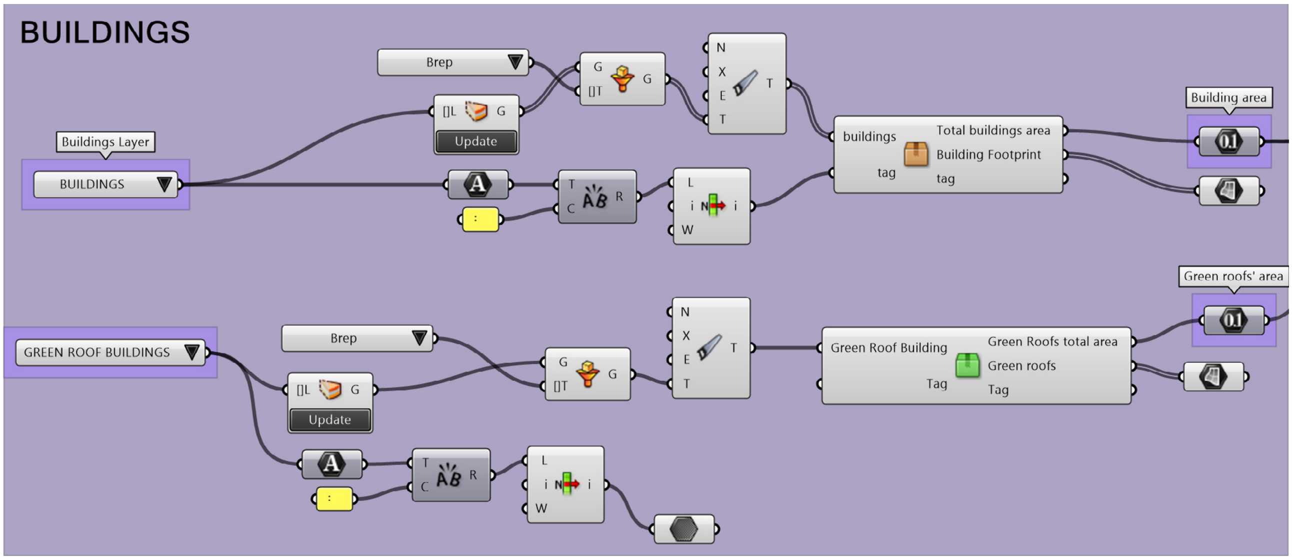


Fig. 10. Elefront workflow to import Rhinoceros geometries in Grasshopper automatically.

information related to the design choices, such as quantity used and price, will automatically update as the model changes (Fig. 4).

The values linked to the attributes are then used as input for a dedicated Grasshopper component programmed in Python, which processes them and returns a specific output for each criterion (Fig. 5).

For the Environmental Product Declarations credit, the component assigns a different score to each material depending on the type of environmental declaration and calculates the total value of the products according to the equation in Fig. 6. If this value is greater than 20 and if the number of the manufacturers is greater than 5, then the algorithm will notify the achievement of the credit and also whether the extra credit for *exemplary performance*[8] is obtainable.

The component works in a similar way in the case of the Sourcing of raw materials credit. According to the option 2 of the credit, it applies some multiplication factors to the cost value of each product, depending on the type of evaluation criterion (in this case, pre or post-consumer recycled content) and on the distance between production and project site.[9] The tool then calculates the percentage of the sum of the values thus obtained compared to the total price of all products used (Fig. 7), If this value is higher than 25 % then the credit is achieved. Also in this case the algorithm will indicate whether the exemplary performance has been achieved.

In order to verify the achievement of the Material ingredients credit, the component performs a similar operation, applying multiplication factors to the value of the materials cost in relation to the selected evaluation criterion (in this case, the Cradle to Cradle certification) and to the distance of production of these materials from the project site (Fig. 8). If the value obtained is greater than 25 % of the total cost of the materials and if they come from at least 5 different manufacturers, then the tool will indicate that the credit has been achieved. If the value obtained is more than 50 % of the total cost, then the algorithm will notify the achievement of the extra credit for exemplary performance.

As additional support, two Python components have been programmed into the Grashopper definition. If activated through a "boolean toggle" component, they open the web pages of the Cradle to Cradle Products Innovation Institute [24] and EPD international system[25], which contain continuously updated databases of certified products.

The tool described above is, in some respects, similar to the "Building Product Calculator" proposed by USGBC [26]. However, the proposed tool aims to simplify the workflow and to bring the main intents of these credits' achievement in the early design phase. Establishing a direct link between a simplified Excel database and a 3D model, the tool facilitates the monitoring process of building products environmental impacts.

Despite this, the tool still has some limitations, mainly related to the compilation of the database. Although it requires less information than the USGBC tool, it still requires a considerable amount of time both in searching for technical information and in the transcription of those information itself, which must be entered manually by the user. Such limitation, however, exist mainly in the initial set-up phase, and can also be seen as an opportunity for the practitioner of systematizing the technical information coming from manufacturers (often mandatory to include anyway, as part of the overall project documentation). Once the database is populated, it represents by itself a fundamental resource for the project, aside of green building certification process.

3.2. Computational LEED workflow at the neighbourhood scale: LEED BD&C sustainable Sites – Open space

The tool that checks the achievement of the *Open Space* credit in the *Sustainable Sites* category is an example of the scalability of the proposed method at the neighbourhood scale, and its connection with more complex 3d models that include buildings, outdoor paved areas and vegetation.

The purpose of this credit is to encourage the design of outdoor open spaces that stimulate human-environment interaction, social relationships, recreation, and physical activity. Specifically, it is possible to get the Open Space credit if the design provides open spaces for at least 30 % of the total site area including the footprint of the buildings. At least 25 % of these spaces must be vegetated (turfgrass does not count as vegetation) or have vegetated canopy.

[8] "Exemplary performance" identifies, for some credits, the performance threshold that must be met to earn an extra point.

[9] According to the *LEED Reference guide* [4] «(...) products sourced (extracted, manufactured, purchased) within 100 miles(160 km) of the project site are valued at 200% of their base contributing cost. For credit achievement calculation, the base contributing cost of individual products compliant with multiple responsible extraction criteria is not permitted to exceed 100% its total actual cost(...)».

In this case, the Grasshopper algorithm derives all the information entirely from the modelled geometries, returning feedback on the achievement of the credit from a simple volumetric model analysis. This is particularly useful in the early concept phases of the work. The main inputs of this algorithm depend therefore on how the Rhinoceros model is organised; in particular, buildings should be modelled as closed polysurfaces and subdivided into two layers depending on the presence of a greenroof; open spaces instead should be modelled as planar surfaces and can be divided into layers according to the different land uses; finally, tree coverings should be modelled as surfaces parallel to the ground and their shape should represent the extension of the tree canopy. The last input is the FAR (Floor Area Ratio) value (Fig. 9).

Elefront is also used for the development of this second definition. The plug-in in this case will automatically import all the geometries modelled on a specific Rhino layer into Grasshopper and, conversely, export all the geometries generated in Grasshopper to a layer (Fig. 10). This will optimize the whole workflow and allow an organised management of the layers of the file and the modelled elements.

Once the geometries have been imported, the algorithm will derive the total area of the site by adding the building footprints to the open space area. It will then compare the result with the open space area only. Based on the result the tool will then generate a Boolean value: TRUE, if the open space area is more than 30 % of the total project area and FALSE if not. (Fig. 11).

In addition, the algorithm will perform a similar calculation as above for the total vegetated area, comparing tit with the total open space area. If the FAR is greater than 1.5, the algorithm will add the area of green roofs to the cumulative vegetated area.

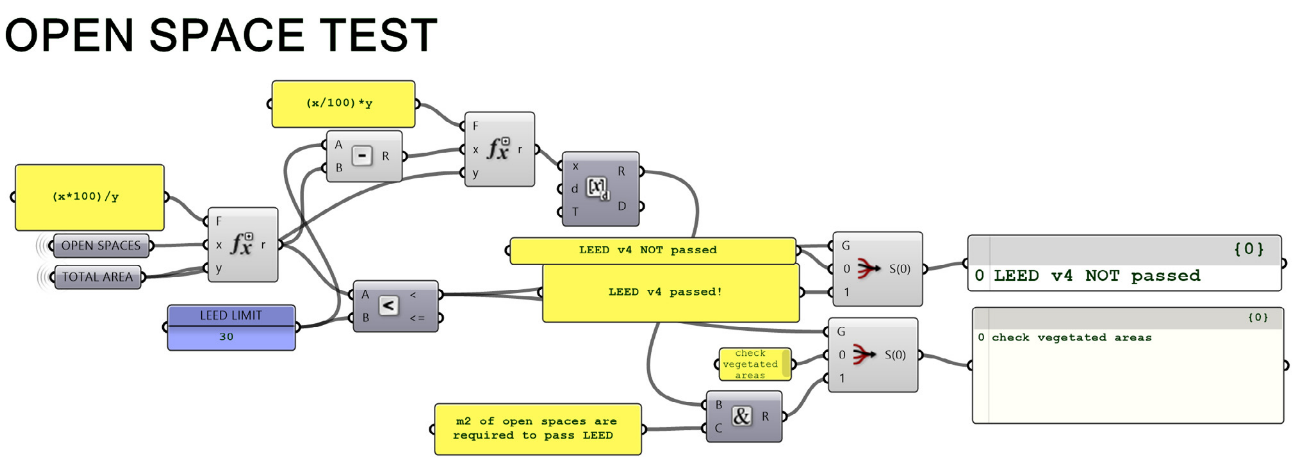


Fig. 11. Calculation in the Grasshopper workspace of the open space percentage.

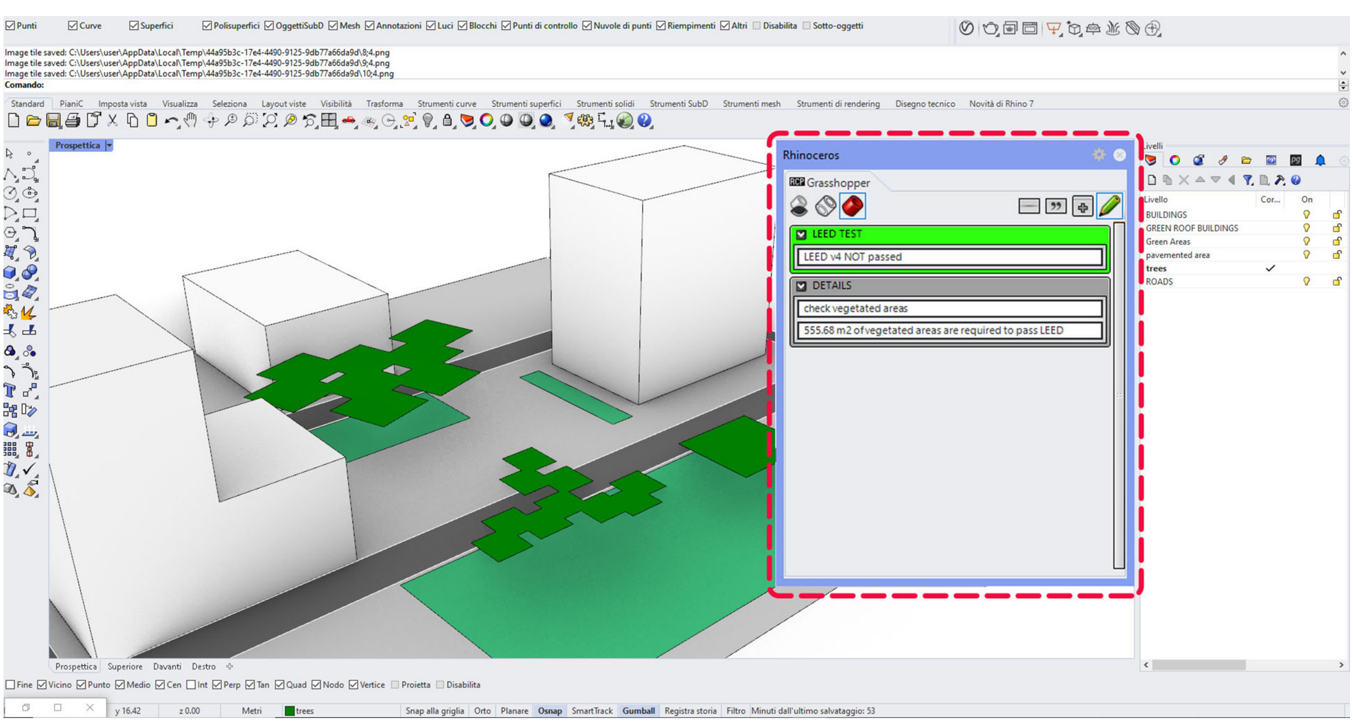


Fig. 12. Result of the test and details in the Rhino workspace.

A second Boolean value is then produced: TRUE if the vegetated areas cover at least 25 % of the open spaces, FALSE if not.

At this stage the tool will perform a logical product between the two Booleans. If the result of the operation is TRUE then the credit has been achieved, otherwise the tool will produce some messages indicating the quantity, in square metres, of the area to be implemented, both for open spaces and for vegetated areas (Fig. 12).

4. Conclusions

The proposed approach, based on the relationship between computational thinking and scripting applied to design, exploits the 3D modelling software Rhino and the VPL Grasshopper to create a uniform, designer-friendly working environment in which design strategies actions are efficiently linked to technological/environmental performance. Furthermore, the implementation of the requirements of a rating system like LEED in such a working environment, other than simplifying the processes of verification and optimisation of performances, makes it possible to increase the knowledge and sensitivity of designers towards the themes of sustainability and energy efficiency and to combine this knowledge with the "creative component" linked to the morphological aspects of the project and to the selection of materials and technical systems.

Rhinoceros is a pure three-dimensional modelling software, therefore, compared to the various BIM applications available on the market, it can also work with a limited amount of information allowing designers to quickly produce conceptual models. For this reason, the methodology described, and the tools developed are particularly effective: they can be integrated into the design workflow from the earliest stages and accompany the entire project development. Moreover, the flexible nature of VPLs allows an integration of the tools also into a BIM workflow in more advanced design phases.

Nowadays, an increasing number of software houses is pushing for Grasshopper integration. Autodesk itself, for example, while integrating a proprietary VPL platform (Dynamo) within Revit, supports since 2021 a plug-in, developed by McNeel itself, capable of establishing a live connection with Rhino and Grasshopper: *Rhino.Inside.Revit* [27]. This plug-in allows both software to be managed as additional components of Revit, thus providing a direct link for the exchange of information between them, and allowing the tools illustrated in this paper to be integrated into a BIM workflow. The integration of plug-ins such as Rhino. Inside. Revit allows a model to be exported and assessed according to the LEED system requirements, triggering a dynamic flow of verification and possible modification of the project in relation to the objectives to be fulfilled in a flexible and dynamic manner.

In addition, the open source nature of Grasshopper means that these tools can be constantly updated and improved, e.g. by implementing other parameters and credit options. This represents the real strength of the proposed methodology. An integrated framework of Computational and Design Thinking methodologies, combined with the use of computer programming techniques, represent the cultural and operational foundations towards a flexible design approach.

The nature of computer programming techniques allows the tools to be integrated in different ways that go beyond the mere modelling of LEED standards shown in this paper. In fact, the presented work aims to demonstrate that regardless of the specific subject area, regulatory aspects or chosen rating system, the underlying logical and technical workflow is, by its very nature, generally applicable. Users with advanced computational skills can indeed make changes to performance indicators, benchmarks or workflows themselves. Beyond the final output of the experimentation presented above, which relates exclusively to the LEED system, an advanced computational approach, and the direct integration of programming tools into the design workflows give to architects and engineers the possibility to make their tools more and more accurate according to their needs, to overcome the limits imposed by common "black box" software and therefore to have a more efficient control on the solutions' performances at different scales.

Digital modelling, machine skills, high-resolution data sets and algorithms are becoming an increasingly indispensable part of the contemporary construction industry. In this context, the main challenge for all professionals in the field is primarily to understand, control and coordinate the processes of how all the information is managed in order to produce an architectural object [28]; VPLs provide a valuable support in this regard. Nevertheless, although Grasshopper, and VPLs in general, are user-friendly programming languages suitable even for non-expert users, the management of information and models in such working environments requires professionals to be up to date with the methodological and operational innovations associated with the digital revolution. The programming of the tools presented in this paper in a designer-friendly working environment, which is widely used over professional practice, aims, in this regard, not only to represent a decision-support system addressed to various types of professionals in the construction industry, but also a way to reduce the existing gap between professionals and advanced digital tools and to disseminate and deepen the themes of performance-based design and 'data culture' for the digital management of design information.

Data availability

No data was used for the research described in the article.

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.

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