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BIM-based assessment metrics for the functional flexibility of building designs

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Abstract

The standards development, technological advancement, and lifestyle evolution lead to different scenario in the construction sector, such as the users adapting to the buildings, the buildings adapting to the users, the demolition of the buildings or parts of them, which increase the waste production and resources depletion. On this background, there is a need to conceptualize the buildings flexibility aspects into sustainability-led design. This paper proposes a novel approach to evaluate the flexibility level of buildings by introducing six selective criteria, which are implemented in a BIM environment by coupling Building Information Modelling (BIM) and Visual Programming Language (VPL) tools. The results show that it is possible to automatically calculate the flexibility of buildings during the design process phases. Therefore, the real-time iteration potential of the method provides information for the decision-making process as a means of guiding designers towards more flexible and sustainable design choices.

Keywords: Buildings flexibility; Sustainability; Metrics; Decision making, Building Information Modelling (BIM); Visual Programming Language (VPL).

1. Introduction

Although the concept of environmental sustainability has been around in the construction industry for many years, the building sector is recognized as the main natural resources and energy consumer [1]. Globally, the building sector consumes 32% of resources and 40% of energy [2]. Moreover, it is the main waste producer by generating one third of European waste [3]. Alongside these issues, the need to assess the sustainability of buildings has risen. A number of tools to evaluate the environmental sustainability have been developed and are widely applied, such as the Green Building Rating Systems (GBRSs) and the Environmental Systems Analysis Tools (ESATs). On the one hand, GBRSs consist of performance thresholds that buildings must meet in order to be certified, as well as guidelines assisting designers to meet or exceed those thresholds [4]. Certification systems, such as LEED and BREEAM, are tailored to serve the specific needs of the country where they have been developed, and they are successfully adopted to meet their purpose. However they do not address all of sustainability's requirements. On the other hand, ESATs aim at assessing the environmental impacts of a system using accepted scientific approaches. For instance, Life Cycle Assessment is so far the most popular and comprehensive method to assess the environmental impacts of buildings as it considers the entire lifecycle [5].

A direct link can be established between the resiliency of a building and its level of sustainability. The more a building is resilient and able to adapt to changes instead of producing wastes, the more sustainable it is. The buildings resilience could be defined as the building's attitude to recover from or adjust easily to an unlucky condition, event, or change, such as a change in the building use [6]. As such, the concept of resilience goes along with the concept of flexibility. Flexibility is a fundamental prerequisite for buildings in order to extend the life cycle design by encouraging the reversibility and the long-term easy maintenance of the technological choices that have been implemented [7]. Today's market developments show increased demands for flexibility and sustainability of buildings as well as a growing understanding of the importance of circular economy [8]. As per the awareness that the Earth's resources are limited, the current practices, market conditions, and driving forces indicated that the logical advancement in building construction technology is towards manufactured, modular, prefabricated, and offsite construction [6]. Building Information Modelling (BIM) can assist the building community in accomplishing these objectives as it is both a methodology and a tool able to manage building's data during its life cycle [9]. BIM is a relatively new process focused on the development, use and transfer of digital information model of a building to improve the design, construction and operations of a project [10]. BIM has the great potential to manage project alternatives bringing forward the design choices through the early performance design analysis [11]. BIM enhances collaboration in the delivery of better outcomes and green buildings [12]. For example, existing studies show the possibility of conducting a BIM-based LCA and by that designing a more sustainable building [1,13–18].

Several tools exist to assess the building's level of sustainability. Nevertheless, there is a need to conceptualize the integration of resiliency and flexibility into sustainability [6]. This paper proposes novel flexibility metrics of buildings. Next to the new metrics, a BIM-based approach is presented to automatically assess the flexibility level of buildings. The goal of the paper is to put into practice the flexibility issues of buildings by proposing a method to allow designers focusing on the effects of their design choices in real time.

1.1. The concept of flexibility

Flexibility gained attention during the Modernist movement, which aimed at renewing the principles of design and architecture in the 20th century. Building flexibility can be defined as the capability of buildings to face the cultural, technological, and economic transformation of the present-day society [7,19,20]. Montellano [21] highlights the relevance of indeterminate spaces, which create opportunities to adapt to changes. Sinclair et al. [22] explored a threefold notion of flexibility, namely spatial, functional, and aesthetic flexibility, which refer to the capacity to change respectively the space, the function, and the identity over the time. Hence, flexibility allows buildings to meet sustainability requirements for a long period by extending construction lifespan and reducing waste. Dhar et al. [23] assessed the variations made to the original layout of Khulna housing in Bangladesh. The authors found that people changes the layouts of their buildings over time for different reasons, such as for accommodating new technology, new business, and more people. Also, the layout modification is due to the changing use of the building, family structure, and ownership pattern. De Paris et al. [24] provided an overall overview of housing flexibility. They reviewed and categorized 14 peer-reviewed papers and discussed several aspects of flexibility, including economic, technical, and practical elements. The review shows that most publications refer to the last three years. According to the authors, this condition reflects the recent interest in flexibility aspects. A great awareness about flexibility exists because of several issues, such as the obsolescence of buildings that no longer fits the current changes, the economy of resources, the sustainability issues, and the scarcity of new land [24].

Several studies identify principles, trends and strategies of building flexibility. They are summarized in Table 1. For example, Slaughter [25] shows a number of design strategies to ensure the building flexibility from an economic and budget perspective. These strategies can provide cost savings during the renovation cycle through reducing the time needed to implement the changes. Till and Schneider [26] evaluated the flexibility and described generic principles as regards typical terraced houses and speculative commercial offices. On the basis of these principles, the authors developed a more comprehensive classification by proposing two broad categories, namely soft and hard use, and soft and hard technologies. Israelsson and Hansson [20] identified flexibility factors and investigated how the factors are influencing the adaptability. The authors classify the factors in accordance with soft and hard aspects. The hard aspects - material standards, production and installations, are directly connected to the building. The soft aspects - awareness aspects, finance and future planning, are not directly linked to the building but they are more important than the hard ones. Živković and Jovanović [19] presented a number of aspects that influence the internal flexibility of multi-family housing. According to the authors, the factors that mostly influence the level of flexibility are the building orientation, plan geometry, structure and size of the apartment, disposition and number of entrances, the position of technical installations, and applied structural system. Cellucci and Di Sivo [7] emphasized the strategies that allow the building flexibility to be achieved. Next to the strategies, Cellucci and Di Sivo [7] also classified the flexibility design into four domains that must be considered, namely the user's domain, functional domain, physical domain, and procedural domain.

Table 1 – Factors and strategies of building flexibility

Reference	**Principles/Factors**	**Definition/Strategies**
Slaughter [25]	Inter-system interactions	Reduce the interdependency with other system to facilitate the maintenance

	Intra-system interactions	Reducing the connections/interactions between the components
	Interchangeable components	Provide economies in ordering materials and facilitate their replacement
	Layout predictability	The regularity of the physical layout can provide critical signals to reduce the duration and extent of demolition to find the required components
	Improve physical access	Provide easy access for maintenance activities
	Specific system zone	Keeping specific areas or volumes free from other components and systems
	System access proximity	Increasing the physical proximity of the access points of specific systems to reduce the need for significant renovations
	Improve flow	Improving the flow of people or things throughout a space can accommodate change through the strategic location of specific system components
	Phase system installation	Using components that are designed to accommodate either growth in a specific system the removal of all or a portion of a system
	Simplify partial demolition	
Till and Schneider [26]	Space	Less specified use of the space
	Construction	Structures allowing easy future intervention
	Design for adaptation	Predicting future scenarios and adaptations onto the plan
	Layers	Clear identification of layers of construction from structure, skin, services, internal partitions to finishes
	Typical plan	Generic and indeterminate space
	Services	Locating services to allow future change and upgrading
Israelsson and Hansson [20]	Material standards	Materials with a life suitable for both existing and future activities
	Production	Prefabrication leads to more flexible techniques of manufacturing
	Installations	A very high degree of planning is required because of difficulty in changing installations
	Planning for future changes and service life	Future planning determines the possible future functions to which a building can be adapted
	Financial aspects	Flexible solutions increase the initial cost by an average of about 2 per cent, which can be saved directly during the first renovation
	Awareness	Property-owners and builders have to be aware that the building is subject to change
Živković and Jovanović [19]	Orientation of housing unit	One-sided, two-sided or three-sided orientation
	Geometry of plan	Dispersed or compact form of housing units
	Structure and size of the flat	Relationship between structure and size of the flat and family structure
	Number and disposition of the entrance	Central or peripheral
	Position of technical services	Grouped or individually placed, with the central or peripheral position
	Building structure	Massive or skeleton structure
	Achieved degree of freedom of interior space	The organization of interior space is conditioned by the position of fixed elements
	Potential for multifunctional	Ability of changing the function of rooms without changing their spatial dimensions

	use of space	
	Changes in number and size of the rooms	The space division is changeable by using flexible partitions
Cellucci and Di Sivo [7]	Spatial flexibility in a fixed surface area	Redundancy access; customizing privacy and social needs; undefined units; using mobile equipment
	Evolutionary spatial flexibility	Increase the surface area within the existing support; increasing the dwelling's surface area in a new structure and the increasing of the initial volume; increasing the internal surface area by the addition of living units
	Technological flexibility related to construction techniques	Adjustment and adaptability of the building envelope; using closures dried stratified; structural regularity and adaptable floors
	Technological flexibility related to the easy maintenance of installations	Integrating home automation systems; redundancy and inspection of the equipment

In general, as can be seen from the reviewed studies (Table 1), the most common principles of flexibility are the plan of generic and indeterminate space, regularity of layouts, the use of mobile equipment and partitions, redundancy access, identification of specific zones for service and technical areas, and redundancy and inspection of the equipment. However, although housing flexibility has been discussed in the past, it remains continuously explored on the basis of different variables [24]. Furthermore, recent studies address the need to propose a methodology that evaluates flexibility beyond mere costs issues [24]. So far, the most practical instrument to assess the adaptive capacity of buildings has been developed by Geraedts [8]. The assessment method, called FLEX 4.0, is based on the support and infill theory of Habraken [27]. Geraedts [8] identify several flexibility key performance indicators, the different default weighting factors, and their assessment values to determine the flexibility class of buildings.

1.2. Building Information Modelling

Building Information Modelling leads to the re-shaping of the construction industry as it stands for the necessary evolution of the design approach linked to the increasing complexity of the building process. BIM lays down the transition from unidirectional and asynchronous workflows to integrated and shared models [28]. Most research has agreed that BIM is a process of expanding 3D models to computable nD models to simulate the planning, design, construction, and operation of a facility. In particular, 3D BIM makes it possible to perform specific analysis based on the geometrical information of the model, such as 3D visualization, clash detection and code checking [29–31]. For example, Getuli et al. (2017) applied the BIM-based code checking to semi-automatically verify a construction site safety plan against the Italian Construction Health and Safety standard. Zhang et al. [32] presents a framework for a rule-based checking system for safety planning and simulation for fall related hazards by integrating BIM and safety. The possibility to import/export BIM properties allows performing a number of analyses with the aid of Building Performance Simulations (BPSs) tools. Opportunities now exist to extend building performance simulations through the use of scripting environments. Visual Programming Language (VPL) software tools are considered of high potential since they have geometric modelling functionalities together with the ability to create algorithms. Most design tools support one or more scripting environments and are able to use a VPL as middleware, which could be bi-directionally linked to BPS tools, resulting in an integrated dynamic model [33]. Actually, VPL could also be used as a BPS tool since it provides the capacity of scripting. Hollberg and Ruth [34], for example, used an LCA model in Grasshopper to produce the real-time optimization of buildings environmental parameters. Röck et al. [35] established an automated link between the LCA database and the BIM model using Autodesk Dynamo as a visual scripting software. The authors calculated the environmental impacts of the case-study building directly in Dynamo.

2. Method

The goal of this study is to define practical metrics for evaluating the buildings' level of flexibility. Furthermore, this study intends to implement the proposed metrics into the BIM environment in order to automatically check the buildings flexibility during the modelling activities. This approach has not been considered by any study described in the reviewed literature, and it allows engineers and architects to be aware of flexibility issues related to design choices. The methodology aims at computing the flexibility of buildings and it is applicable to any proposed criteria. The method consists of three main steps, as shown in Fig. 1. The first step is discussed in the section 2.1.. It aims to define the relevant design criteria for assessing the flexibility of buildings. Mathematical formulations are provided for each criterion and they are based on the common best practices and accepted technical standards. Examples are provided for most of criterion to show the way they work. Therefore, the study does not consider applying the method to any case study since it does not affect the validity of the criterion to be tested. In fact, the application to case studies would lead to comparative assessments aimed at verifying which buildings' typology/technology is the most flexible, which is not the focus of the paper. The second step seeks to outline the score-based performance scale to evaluate the buildings' level of flexibility according to the proposed criteria (section 2.2.). The last step is discussed in section 2.3. where a BIM-based approach is described. Here, the BIM and VPL software are linked to automatically perform the calculation. Autodesk Dynamo is employed as a visual scripting tool to customize the mathematical formulations of each criterion. The scripting tool automatically performs the calculation by reading the design properties and geometry from the BIM.

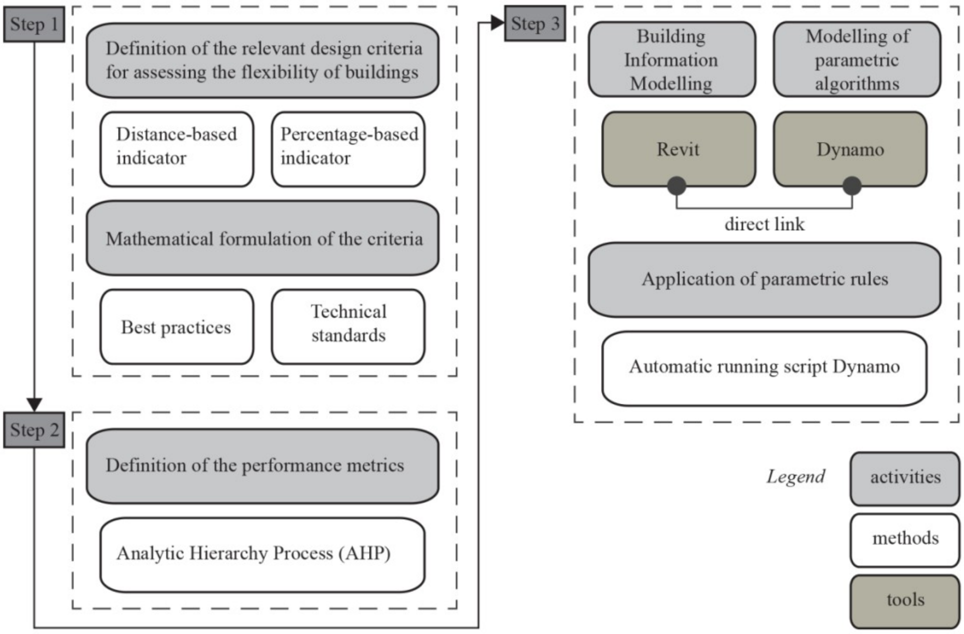

Fig. 1. Research approach

2.1. Flexibility design criteria

The present study is the first step of a broader research carried out by the authors. As such, the first criteria that largely influence the flexibility are presented here. First, six selective design criteria influencing the flexibility of a building are identified. Second, each criterion has been converted into a mathematical formulation to establish to what extent the building meets that specific flexibility aspect. According to each criterion, the mathematical formulation provides a partial indicator of the flexibility level on a percentage basis. Then, these values are compared to a global performance scale to define the total flexibility level of the building (step 2). The flexibility criteria are mainly based on geometrical rules, and they can be divided into two macro-categories listed below:

- Distance-based indicators (DIST.n): the calculation is based on the distance between points;
- Percentage-based indicators (PERC.n): the calculation is based on percentage ratio between areas.

The flexibility criteria are presented as follows.

2.1.1. Criterion DIST.1: Structure modularity

Flexibility is achieved through interchangeable units based on modular construction system [19,36]. In particular, this criteria looks at the structure modularity, which means that the distances between two next load-bearing elements refer to a single repeatable module. According to this criterion, the more a building' structure is modular, the more it is flexible. A modular structure implies benefits in the future reconfiguration of the interior spaces of a building, since the compliance with a certain module allows to easily modify the functions of that space. The framed system with beams and pillars best foster the reconfiguration of the rooms compared with the massive structure. The frame-based structure has several advantages, such as the minimum dimensions of the load-bearing elements and the opportunity to make openings independent from the structural elements. As such, for the purpose of this paper, the criterion DIST.1 - as well as the relative algorithm, is developed with reference to framed structures. DIST.1 is defined as:

$$DIST.1=\frac{N_{mod,X}}{N_X}\cdot\gamma_X+\frac{N_{mod,Y}}{N_Y}\cdot\gamma_Y+\frac{N_{mod,Z}}{N_Z}\cdot\gamma_Z \qquad \text{with} \qquad \gamma_i=\frac{N_i\cdot cd_i}{N_X\cdot cd_X+N_Y\cdot cd_Y\cdot N_Z\cdot cd_Z} \tag{1}$$

Where,

$N_{mod,i}$ it is the number of the spans that meets a common module in the i-th direction;

N_i is the total number of spans in in the i-th direction;

γ_i is a weighting factor related to each directions (x, y, z), which depends on cd_i

cd_i is a direction factor, with cd_x = 0.4, cd_y = 0.4, cd_z = 0.2.

The weighting factors γ_i are introduced to reward the correspondence to a common module along the direction in which there are more spans. The direction factors cd_i aim at giving priority to the flexibility in plan rather than in elevation. The method considers a tolerance of 5% when calculating the distance between points to verify the correspondence to the common module. This is meant to offset small errors occurring during the design, or the need to use distances that are not perfectly identical, for example, due to architectural constraints.

2.1.2. Criterion DIST.2: Geometrical regularity of plan

The form of housing units affects the flexibility level of buildings. Geometrical regularity means a compact form of the plan rather than a dispersed one. A compact form increases the possibilities of future reallocation, multi-functionality, redistribution or downsizing of the units [19]. In fact, geometric regularity implies the absence of architectural constraints that could reduce the flexibility of spaces. The mathematical formulation of this criterion refers to the specification introduced by the Italian Technical Standards for Constructions (hereafter NTC/2018) [37]. According to the Italian standard, a building plan can be defined regular as long as it meets the following requirements:

a. The ratio between the sides of the circumscribed rectangle is less than 4.
b. The form of the plan is compact. In the event recesses in the plan, the difference between the areas obtained from the convex line circumscribed to the housing units and the area of the housing units does not exceed 5%.

In addition to the previous requirements, symmetry is an additional parameter that can affect building flexibility as it can allow easier internal redistribution of spaces. Hence, we can set a third requirement:

c. Symmetry.

Fig. 2 shows an example of the three requirements considered by the criterion. Hence, the criterion DIST.2 can be mathematically expressed by:

$$DIST.2 = \frac{\sum_F \left\{ \left(1 - \frac{X}{Y} \cdot \frac{1}{4}\right) \cdot \gamma_1 + \left[1 - \left(\frac{A_{Rmax}}{X \cdot Y} \cdot \frac{1}{0{,}05}\right)\right] \cdot \gamma_2 + \left[1 - \left(\frac{x_A}{X/2} + \frac{y_A}{Y/2}\right) \cdot \frac{1}{2}\right] \cdot \gamma_3 \right\}}{F} \tag{2}$$

That is applicable when: $1 < \frac{X}{Y} \leq 4$ and $\forall \ A_{R,i}, \frac{A_{R,i}}{X \cdot Y} \leq 5\%$

Where,

F is the number of floors of the building under investigation;

X is the major side of the rectangle that circumscribes the plan;

Y is the minor side of the rectangle that circumscribes the plan;

A_{Rmax} is the area of the major recess;

x_A is the distance between the barycentre of the plan and the barycentre of the circumscribed rectangle, in x-direction;

y_A is the distance between the barycentre of the plan and the barycentre of the circumscribed rectangle, in y-direction;

γ_i is a weighting factor related to each requirements previously discussed, with $\gamma_1 = 0.375$, $\gamma_2 = 0.375$, $\gamma_3 = 0.25$.

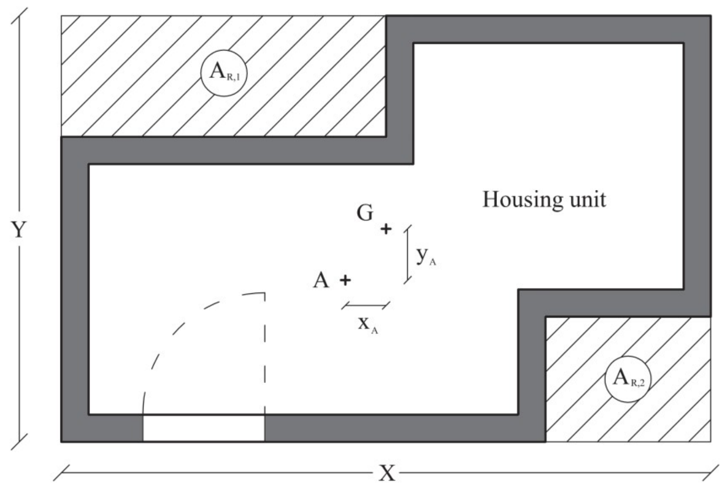

Fig. 2. Example of the requirements considered by the criterion DIST.2

As can be seen in (2), the equation consists of three main polynomials, which are related with the three different requirements. The polynomials are presented in the order that the related requirements are previously discussed (from a to c). Each polynomial is multiplied by different weighting factors to reflect the different levels of importance of the flexibility requirements. It is considered more appropriate to assign a greater value to the weighting factors related to the requirements of the NTC/2008 as they meet both the Italian technical standards for constructions and the flexibility criteria.

2.1.3. Criterion DIST.3: Location of technical services

Technological services (bathrooms, kitchens, technical rooms, etc.) are considered almost invariant elements during the building lifecycle due to the difficulty of modifying the positions of the grids [19]. Therefore, it is of high concern to choose their location within the housing plan. As a general rule, in order to pursue the flexibility objectives, it would be preferable to group technological services in a centrally-positioned single block. This greatly assists the possible rotation of the rooms around the block, and it provides the building with a higher level of flexibility. For this reason, the proposed mathematical formulation aims at determining the position of the technological services by calculating the distance - in both directions, between the vertical shaft for hosting all the facilities and the barycentre of the housing unit. Such considerations are mathematically expressed by:

$$DIST.3=\frac{\left\{1-\left[\left(\frac{x_C}{X/2}+\frac{y_C}{Y/2}\right)\cdot\frac{1}{2}\right]\right\}}{N_C}\% \quad (3)$$

Where,

x_C	is the distance between the barycentre of the shaft and the barycentre of the housing plan in x-direction;
y_C	is the distance between the barycentre of the shaft and the barycentre of the housing plan in y-direction;
X and Y	are the sides of the rectangle circumscribing the housing plan;
N_C	is the number of shaft for hosting all the facilities.

2.1.4. Criterion PERC.1: Removable building elements

The removable building elements facilitate the dismantling of sub-systems and the re-configurability of the space [38]. These technologies meet the requirements of flexibility, compliance to the standards evolution, technical and user requirements. Also, the use of dry-assembled technologies leads to the reduction of maintenance issues, as well as the cutback of unsorted wastes at the end-of-life of the building elements. The criterion PERC.1 considers four removable building elements categories, namely partition walls, external walls, floors, and load-bearing elements (beams and pillars). In particular, PERC.1 evaluates the percentage of removable construction elements compared to the total amount for each category. The criterion is defined as:

$$PERC.1 = \frac{A_{rp}}{A_p} \cdot \gamma_p + \frac{A_{rew}}{A_{ew}} \cdot \gamma_{ew} + \frac{A_{rf}}{A_f} \cdot \gamma_f + \frac{L_{rlb}}{L_{lb}} \cdot \gamma_{lb} \tag{4}$$

Where,

A_{rp} is the total area of the removable partition walls;

A_p is the total area of the partition walls;

A_{rew} is the total area of the removable external walls;

A_{ew} is the total area of the external walls;

A_{rf} is the total area of the removable floors;

A_f is the total area of the floors;

L_{rlb} is the total length of the removable load-bearing elements;

L_{lb} is the total length of the load-bearing elements;

γ_i is the weighting factor related to each categories of removable elements, with $\gamma_p = 0.4$, $\gamma_{ew} = 0.3$, $\gamma_f = 0.2$, $\gamma_{lb} = 0.1$.

As can be seen in (4), the equation consists of four main polynomials, which are related with the four removable building elements categories previously discussed. Each polynomial is multiplied by a weighting coefficient, which is related to the needs of the elements belonging to a specific category to be modified during the buildings' lifecycle. In this case, the different values of the weighting coefficients reflect the possibility and the feasibility of removing the different removable building elements categories during the entire building's lifecycle.

This criterion requires a model preparation activity when implemented in a BIM eviroment. In fact, it is crucial to categorize each BIM object as removable or non-removable building elements. To do this we employed the assembly code already available in Revit. By assigning this kind of parameter it is possible to specify an alphanumeric code that uniquely identifies every system, sub-system, and technological element, according to the Uniformat II classification (Fig. 3).

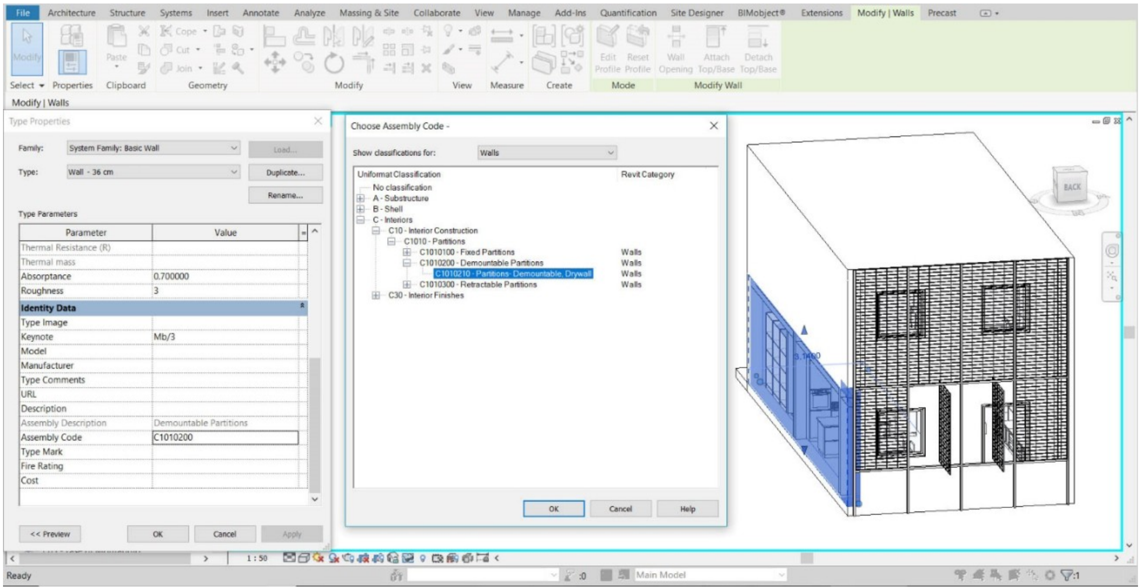

Fig. 3. Building model preparation: assigning assembly code parameter

2.1.5. Criterion PERC.2: Percentage and orientation of windows

The number of outer walls strongly conditions the layout of the internal spaces as they require natural lighting and ventilation [19]. Few outer walls can restrict the redistribution of the rooms. To simplify the concept and the mathematical formulation of the criterion, we consider the rectangle that circumscribes the housing plan of the dwelling. Hence, depending on the views, it can be identified different housing units: one-sided orientation – when openings are placed only on one façade, two-sided, three-sided, and four-sided orientation. Furthermore, the horizontal distribution of the windows on the walls can affect the flexibility of the housing units as shown in Fig. 4. The case (a) in Fig. 4 is strongly dependent on the kind of windows, which results in difficulty of changing the spatial dimensions of rooms. The windows of the case (b) have the same total area, but they are organized differently. The distribution of windows in the case (b) improves the flexibility of the internal space, which could result, for example, in the configuration of the case (b.1). To deal with these aspects, the criterion considers the number of orientations and the presence of windows. Here, two types of openings are distinguished: windows and curtain walls. The aim of the criterion is to establish whether the number and extent of the openings is sufficient to help the re-distribution of internal spaces. Such considerations are expressed by:

$$PERC.3=\frac{\sum_{F}\left[\sum_{j}\left(\frac{L_w+L_{cw}}{L_W}\right)\cdot\frac{1}{4}\right]}{N_F} \quad (5)$$

Where,

F	is the floor of the building under consideration;
j	is the j-th orientation of the building;
L_w	is the total length of the windows;
L_{cw}	is the total length of the curtain walls;
L_W	is the total length of the walls.

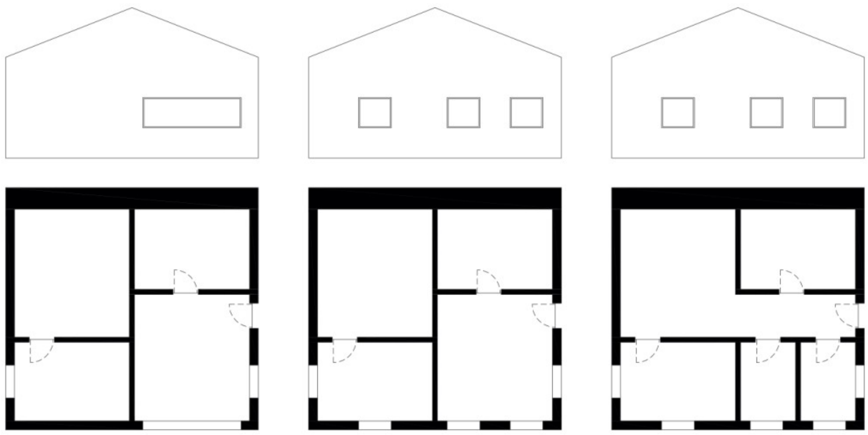

Fig. 4. Possibility of configuring internal spaces in relation to the windows distribution. Left, case (a); middle, case (b), right, case (b.1)

2.1.6. Criterion PERC.3: Internal mobile partitions

The use of mobile partition walls is useful for varying the configuration of housing spaces that need to accommodate different functions in the short term. The mathematical formulation of this criterion is similar to the criterion PERC.1. Hence, PERC.3 considers the percentage of mobile partitions compared to the total area of internal partition walls, and it is defined as follows:

$$PERC.3 = \frac{A_{mp}}{A_p}\% \quad (6)$$

Where,

A_{mp} is the total area of the mobile partition walls;

A_p is the total area of the partition walls.

2.2. Definition of the flexibility metrics

The method proposes a score-based metrics, which is quite similar to the credit-based environmental impact assessment tools, for example BREEAM and LEED. The application to the project of each criterion previously described provides a partial flexibility indicator in percentage terms. However, the criteria could differently affect the buildings flexibility. As such, the achieved partial flexibility indicators are scaled to a global metrics scoring them by a weighting factor that reflects the flexibility priority of each criterion.

2.2.1. AHP based metrics

The heterogeneity of the proposed criteria leads to difficulties in identifying common properties based on which the criteria could be compared. Hence, to define the priority of each criterion, the Analytic Hierarchy Process (AHP) is employed.

The AHP methodology is used to make decisions in an organised way to generate priorities [39]. The AHP is a Multi-Criteria Decision Aid (MCDA) and it is based on the well-known Saaty 3-steps method: i) hierarchical structuring the problem, ii) weight evaluation, iii) summary of priority [40]. The decision problem needs to be broken down into basic components, which are independent criteria. To this end, the goal of the AHP is identified and the related criteria, sub-criteria, and alternatives to reach the goal are determined [40]. This allows the transformation of a multidimensional scaling problem into a one-dimensional scaling problem [41]. Next, in order to identify the related priority vectors (i.e., the weights assigned to each criterion), each criterion is analysed individually. The AHP uses the principal eigenvalue method for deriving the ratio scale priority vectors from positive reciprocal matrices [41]. Such matrices are established through pairwise comparisons among the criteria by assigning them a score of relative importance through the Saaty's Fundamental Scale of absolute numbers [39]. To verify the reliability of the pairwise comparisons, a consistency test is performed trough the Consistency Ratio (CR). As shown by [40], CR is obtained by considering the ratio between Consistency Index (CI), which is used to check the coherence of the assigned judgement, and its expected value denoted Random Index (RI). The last step is the summary of priority, which is performed to define the global weights.

According to the AHP method, expert consensus was used to arrive at flexibility criterion pairwise judgement. We used an audience of 30 experts for applying the pairwise comparisons. The audience is made up of 15 experienced engineers and 15 researchers from Polytechnic University of Bari. The weights of the criteria based on the AHP are shown in Table 2 in percentage terms, and it is used to define the global metrics. Values are rounded to the nearest integer. When applying the proposed flexibility metrics, each criterion is calculated separately scoring from 0 to 100 (%). Then, the values are weighted according to the global metrics previously defined. The summary of the scores of the global metrics provides the flexibility level of the building.

Table 2. Flexibility metrics

Criteria	Partial metrics	Global metrics (AHP-based)
DIST.1	100 %	18 %
DIST.2	100 %	14 %
DIST.3	100 %	18 %
PERC.1	100 %	20 %
PERC.2	100 %	15 %
PERC.3	100 %	15 %

2.3. BIM-based approach

The metrics proposed in the previous section are implemented into the BIM environment in order to automatically check the flexibility level of buildings. This allows designers to check the buildings' flexibility throughout the design process. Consequently, architects and engineers could use the method as a decision-making tool to improve the flexibility and sustainability of their design choice.

Designers are increasingly using VPLs for scripting since they define the parametric method of design optimization. VPL tools allow programming with visual expressions through graphical manipulation of elements rather than written syntax. For example, Dynamo is based on the logic of boxes and arrows, where boxes are the functions connected by arrows, lines or arcs. These arrows represent the relations connecting the functions. VPL tools can be linked to BIM software and the programming results are showed in real time in the view report of the BIM. For this study, the advantage coming from Dynamo consists in the broad integration with BIM Revit that does not need to export the model with IFC format. The complete integration between Revit and Dynamo results in a bi-directional workflow. In fact, Dynamo scripts directly affect Revit elements (families, parameters, and relationships), while any change made in the BIM environment is automatically implemented by Dynamo without the need to re-import the BIM model.

To establish an automated BIM-based method to perform the flexibility assessment of buildings, on the one hand, a BIM model was created using Autodesk Revit. On the other hand, six customized scripts, which are based on the mathematical formulations of each criterion, were developed using Autodesk Dynamo as visual scripting software. The BIM model provides the design-specific properties and geometry, while the scripting tool automatically performs the calculation by reading the BIM model and running the scripts. The research concept of the BIM-based approach is shown in Fig. 5. Algorithms implemented in Dynamo are shown in detail in Appendix A.

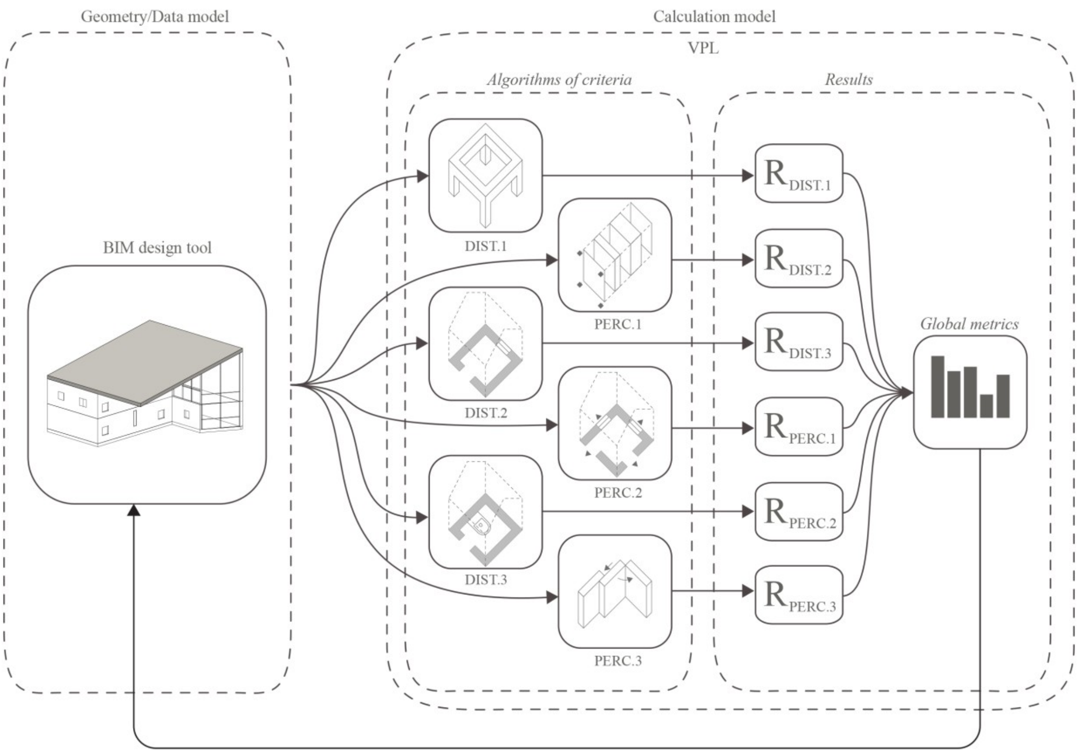

Fig. 5. BIM-based approach of the research

The proposed algorithms are based on three main steps as can be seen in Appendix A. First, the initial function (box) allows selecting the elements of the simulation (pillars, walls, floors, windows, etc.) from the BIM environment. Then, once the BIM objects have been imported into Dynamo, the next boxes perform different simulation to calculate the distance between different elements, the distance between the barycentre of the plan and the barycentre of the circumscribed rectangle, the area of the elements, etc., depending on the criterion involved. Finally, subsequent boxes are used to perform different mathematical operations, such as the sum, the average, etc. These last functions allow performing the equations of each flexibility criterion previously discussed.

3. Results and Discussion

The definition of design criteria and the related mathematical formulation makes it possible to assess the flexibility level of buildings. Such an evaluation can be automatically performed through the possibility of scripting by VPL tools, such as Dynamo. Indeed, the process automation is backed by the formulation of algorithms for each flexibility requirements within Dynamo, which is used as a calculation model (Fig. 6). To allow the automatic application of the buildings flexibility metrics, six scripts have been written with Dynamo - one for each flexibility criterion identified, which are able to collect the building elements from the BIM model by identifying the geometrical-spatial relations among them, and perform the mathematical operations required for the calculation. Finally, the scripts can be run. Once the algorithms have been run, a real-time calculation is performed, which consist in a partial flexibility indicators on a scale from 0 to 100 (partial metrics). Then they are weighted to define the global metrics. The partial flexibility indicators already provide an indication of the buildings flexibility level according to the specific criterion under investigation. To this end, this step can be used as a decision-making tool to push engineers and architects towards flexibility-oriented design. According to the flexibility level that has been reached, designers can step back to the BIM model in order to change their design choices and run again the scripts to verify the relevance of the decisions made. This way it is possible to reiterate the process until reaching the optimal design solution.

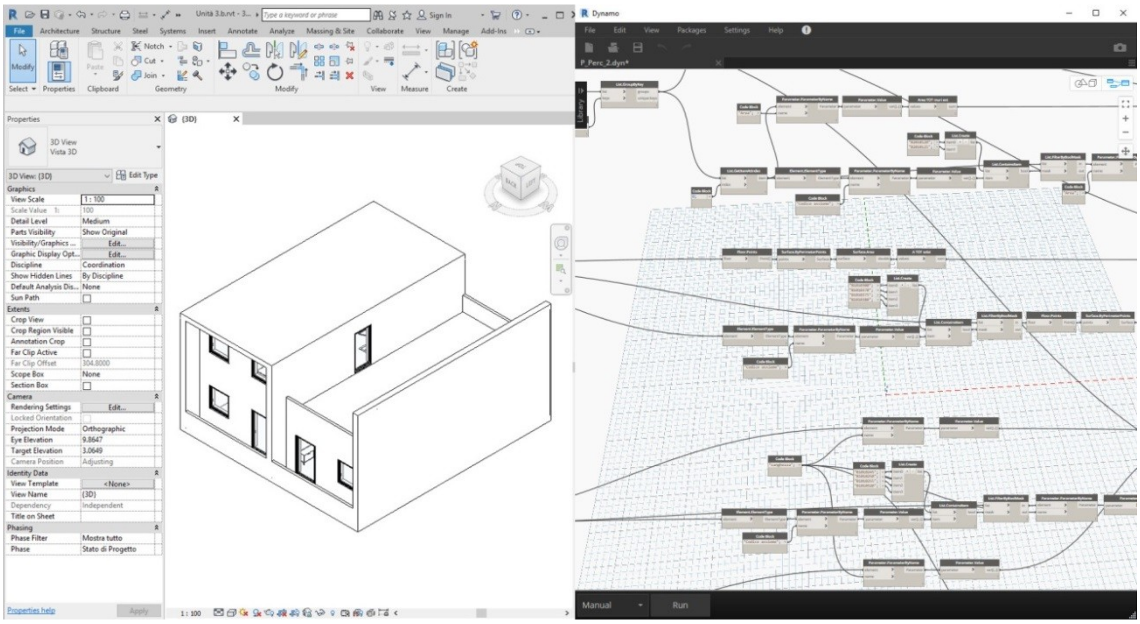

Fig. 6. Example of PERC.2 application

However, the proposed workflow cannot avoid the BIM model preparation phase. Designers defining building models that will be used for rule checking or other kind of simulations must arrange them so that the models provide the information needed in well-defined agreed upon structures [42]. Hence, the application of the algorithms in a VPL environment can be implemented only when the model itself has been adequately set. In order to ensure the scripts work properly without errors, the BIM model must have been enriched with the right semantic information. Current BIM platforms default to a minimal set of properties and provide the capability of extending the set. Nevertheless, BIM users must add parameters to each relevant object to produce a certain type of simulation [9]. Most of the proposed flexibility criteria only need geometrical associations generated by Revit. Among the proposed flexibility criteria and the related calculation, PERC.1 is the only one that requires a specific model preparation activity. In fact, to structure the algorithm of PERC.1 it is crucial defining a certain BIM parameters that allows Dynamo to classify each BIM object as removable or non-removable building elements.

The proposed framework should be evolved in the future. First, the method currently only considers applying the AHP to the criteria involved in the flexibility metrics proposed. Actually, some criteria involve the use of specific weighting factors, which have been defined in a conceptual way according to the flexibility issues. Further developments of this first approach are needed in order to define the relative importance of each weighted factors. As such, a further sub-criteria will be set in the future according to the hierarchical structuring the problem of AHP method. Second, some criteria have been streamlined in order to simplify the first scripts proposal. For example, the criterion DIST.1 only refers to the framed structures, which best meet the flexibility goals. In the future, a different algorithm should be investigated to take into consideration, for example, the load-bearing masonry. Finally, the present paper is the first approach of a broader research study. As such, only few criteria have been identified according to the most common principles of flexibility as shown in the literature review. In the future, the investigation of further flexibility criteria should be carried out to address minor flexibility issues as well.

4. Conclusion

Resilient buildings go along with the flexibility concepts, which affect in turns the sustainability principles. However there is a need to conceptualize the integration of flexibility key aspects of buildings into the sustainability-oriented design. The novelty of the present study is the definition of a method to calculate the flexibility level of buildings. The suggested approach consists of defining specific criteria that reflect the most common principles of buildings flexibility. According to each criterion, a mathematical formulation is proposed in order to measure them in a practical way. Since each criterion plays a different role in reaching the flexibility level, a multi-criteria decision approach was employed to identify their relative importance. Next to the definition of the flexibility metrics, a BIM-based approach is proposed to automatically perform the calculation. To this end, different algorithms were implemented in a VPL tool, which is bi-directionally linked to the BIM environment where the BIM elements already host the semantic information required. Thus, the flexibility level of the building can be iteratively calculated during the design process in order to guide designers towards flexible choices. The method enables designers to use the flexibility metrics as a decision-making tool to reach more sustainable solutions since the early design phases. The present study is a first approach to the definition of a global metrics. The scope of the present paper is focused on selective criteria, upon which further investigations that bring more profound knowledge to the measurement of building flexibility metrics can be carried out. To further improve the proposed framework, the weighting factors involved in the calculation of the criterion should be subjected to the multi-criteria decision method, and different flexibility criteria should be investigated to reflect others flexibility issues. Here, the selected flexibility criteria refer to different building systems to stress the concept of the single criterion. Future applications should be limited to specific building systems so that the assessment takes place on a well-defined domain. This would lead in the future to convincing results in terms of flexibility calculation of buildings.

Appendix A

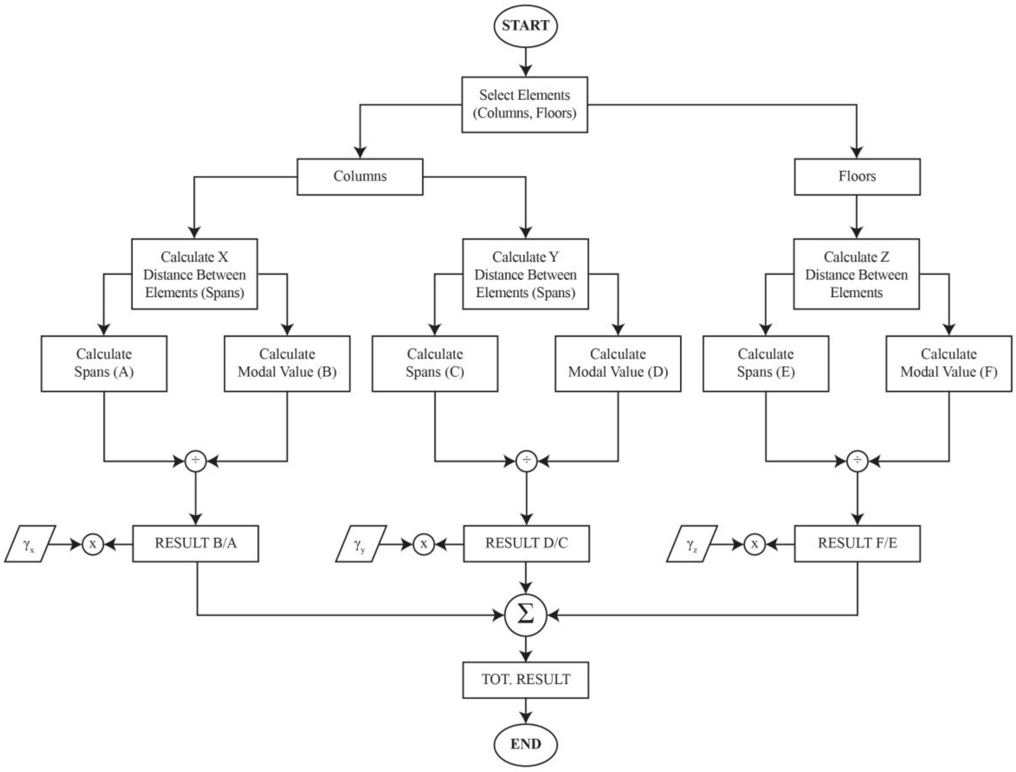

Fig. A.1. Algorithms of the criterion DIST.1: structure modularity

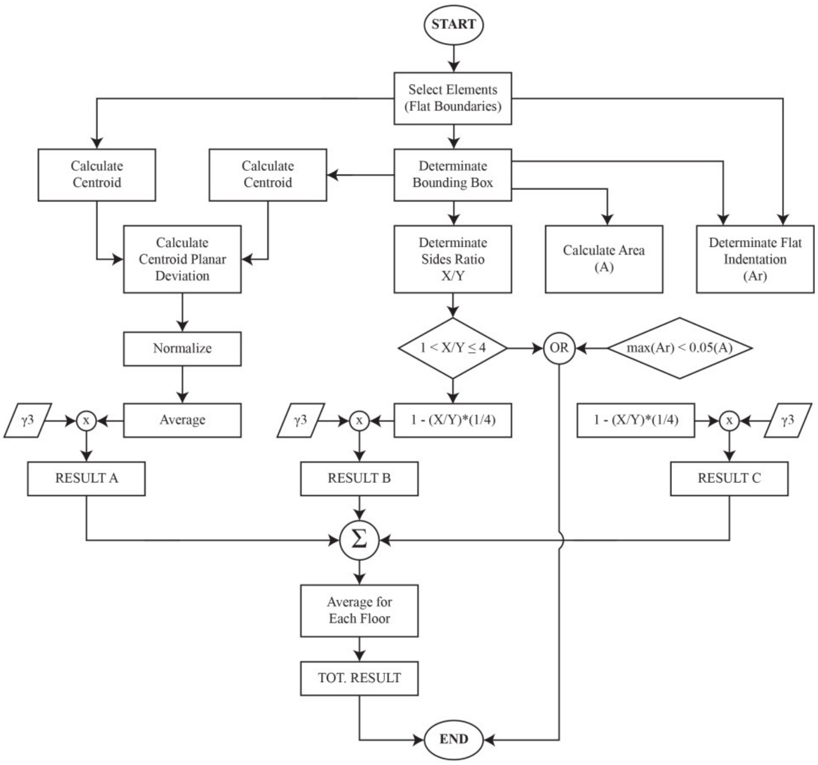

Fig. A.2. Algorithms of the criterion DIST.2: geometrical regularity of plan

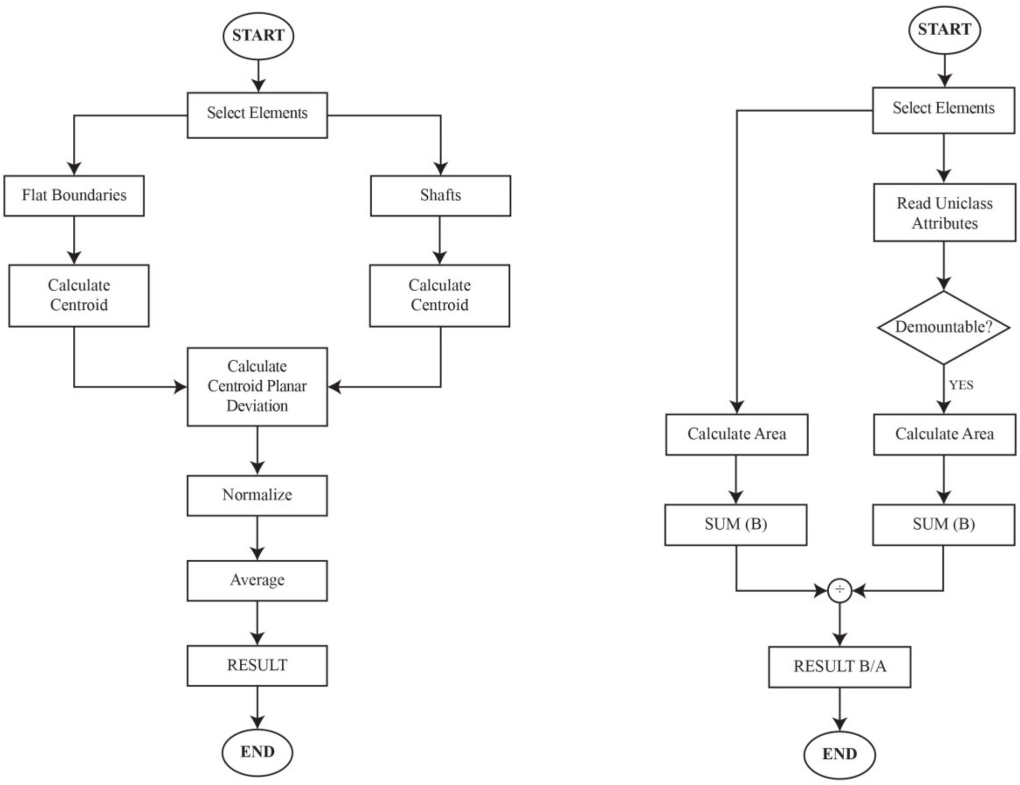

Fig. A.3. Algorithm of the criterion DIST.3: location of technical services (left) and PERC.1: removable building elements (right)

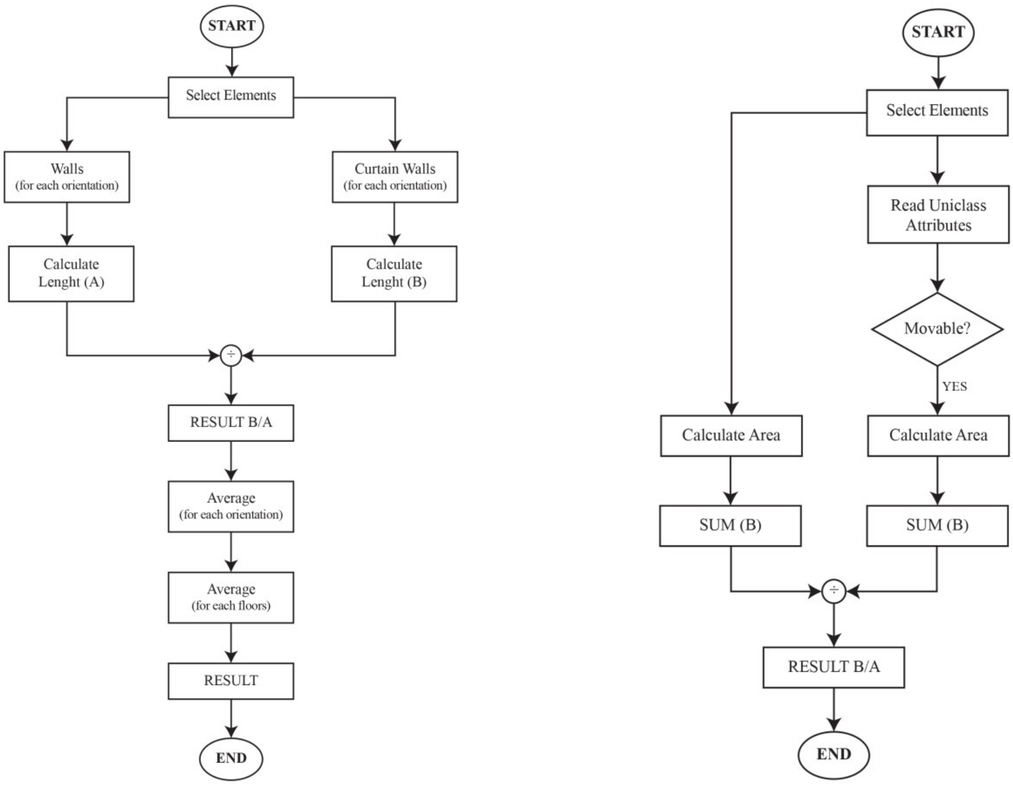

Fig. A.4. Algorithm of the criterion PERC.2: percentage and orientation of windows (left) and PERC.3: internal mobile partitions (right)

References

[1] J.K.W. Wong, J. Zhou, Enhancing environmental sustainability over building life cycles through green BIM: A review, Automation in Construction 57 (2015) 156–165. doi:10.1016/j.autcon.2015.06.003.

[2] M. Yeheyis, K. Hewage, M.S. Alam, C. Eskicioglu, R. Sadiq, An overview of construction and demolition waste management in Canada: A lifecycle analysis approach to sustainability, Clean Technologies and Environmental Policy 15 (2013) 81–91. doi:10.1007/s10098-012-0481-6.

[3] European Commission, Service Contract on management of construction anddemolition waste − SR1, (2011). https://publications.europa.eu/en/publication-detail/-/publication/0c9ecefc-d07a-492e-a7e1-6d355b16dde4 (Accessed on 18 July 2019).

[4] M. Shan, B. Hwang, Green Building Rating Systems: Global Reviews of Practices and Research Efforts, Sustainable Cities and Society 39 (2018) 172–180. doi:https://doi.org/10.1016/j.scs.2018.02.034.

[5] C. Cavalliere, G.R. Dell’Osso, A. Pierucci, F. Iannone, Life cycle assessment data structure for building information modelling, Journal of Cleaner Production 199 (2018) 193–204. doi:10.1016/j.jclepro.2018.07.149.

[6] G.E. Marjaba, S.E. Chidiac, Sustainability and resiliency metrics for buildings - Critical review, Building and Environment 101 (2016) 116–125. doi:10.1016/j.buildenv.2016.03.002.

[7] C. Cellucci, M. Di Sivo, The Flexible Housing: Criteria and Strategies for Implementation of the Flexibility, Journal of Civil Engineering and Architecture 9 (2015) 845–852. doi:10.17265/1934-7359/2015.07.011.

[8] R. Geraedts, FLEX 4.0, A Practical Instrument to Assess the Adaptive Capacity of Buildings, Energy Procedia 96 (2016) 568–579. doi:10.1016/j.egypro.2016.09.102.

[9] R. Sacks, C. Eastman, G. Lee, P. Teicholz, BIM Handbook: A Guide to Building Information Modeling For Owners, Designers, Engineers, Contractors, and Facility Managers. Third Edition, Jhon Wiley & Sons, Inc., Hoboken, New Jersey, 2018. (ISBN 9781119287544).

[10] Computer Integrated Construction Research Group, Building Information Modeling Execution Planning Guide, 2010. https://www.bim.psu.edu/bim_pep_guide (Accessed on 18 July 2019).

[11] J. Schade, T. Olofsson, M. Schreyer, Decision-making in a model-based design process, Construction Management and Economics 29 (2011) 371–382. doi:10.1080/01446193.2011.552510.

[12] A. Ghaffarianhoseini, J. Tookey, A. Ghaffarianhoseini, N. Naismith, S. Azhar, O. Efimova, K. Raahemifar, Building Information Modelling (BIM) uptake: Clear benefits, understanding its implementation, risks and challenges, Renewable and Sustainable Energy Reviews 75 (2017) 1046–1053. doi:10.1016/j.rser.2016.11.083.

[13] H. Chong, C. Lee, X. Wang, A mixed review of the adoption of Building Information Modelling (BIM) for sustainability, Journal of Cleaner Production 142 (2017) 4114–4126. doi:10.1016/j.jclepro.2016.09.222.

[14] S. Eleftheriadis, D. Mumovic, P. Greening, Life cycle energy efficiency in building structures: A review of current developments and future outlooks based on BIM capabilities, Renewable and Sustainable Energy Reviews 67 (2017) 811–825. doi:10.1016/j.rser.2016.09.028.

[15] A. Kylili, P.A. Fokaides, J. Vaiciunas, L. Seduikyte, Integration of Building Information Modelling

(BIM) and Life Cycle Assessment (LCA) for sustainable constructions, Journal of Sustainable Architecture and Civil Engineering 4 (2015) 28–38. doi:http://dx.doi.org/10.5755/j01.sace.13.4.12862.

[16] N. Soares, J. Bastos, L.D. Pereira, A. Soares, A.R. Amaral, E. Asadi, E. Rodrigues, F.B. Lamas, H. Monteiro, M.A.R. Lopes, A.R. Gaspar, A review on current advances in the energy and environmental performance of buildings towards a more sustainable built environment, Renewable and Sustainable Energy Reviews 77 (2017) 845–860. doi:10.1016/j.rser.2017.04.027.

[17] B. Soust-Verdaguer, C. Llatas, A. García-Martínez, Critical review of bim-based LCA method to buildings, Energy and Buildings 136 (2017) 110–120. doi:10.1016/j.enbuild.2016.12.009.

[18] E. Naboni, The Use of Facade Mockups in LCA Based Architectural Design, Procedia Engineering 180 (2017) 759–766. doi:10.1016/j.proeng.2017.04.236.

[19] M. Živković, G. Jovanović, A method for evaluating the degree of housing unit flexibility in multi-family housing, Architecture and Civil Engineering 10 (2012) 17–32. doi:10.2298/FUACE1201017Z.

[20] N. Israelsson, B. Hansson, Factors influencing flexibility in buildings, Structural Survey 27 (2009) 138–147. doi:10.1108/02630800910956461.

[21] A.S. Montellano, Housing flexibility by spatial indeterminacy: The case of the Casa de las Flores in Madrid, International Journal of Architectural Research 9 (2015) 4–19. doi:http://dx.doi.org/10.26687/archnet-ijar.v9i2.661.

[22] B.R. Sinclair, S. Mousazadeh, G. Safarzadeh, Agility, Adaptability + Appropriateness: Conceiving, Crafting & Constructing an Architecture of the 21st Century, ARCC Journal for Architectural Research 9 (2012). doi:10.17831/enq:arcc.v9i1.65.

[23] T.K. Dhar, M.S.M. Hossain, K.R. Rahaman, How does flexible design promote resource efficiency for housing? A study of Khulna, Bangladesh, Smart and Sustainable Built Environment 2 (2013) 140–157. doi:10.1108/SASBE-10-2012-0051.

[24] S.R. De Paris, C.N.L. Lopes, Housing flexibility problem: Review of recent limitations and solutions, Frontiers of Architectural Research 7 (2018) 80–91. doi:10.1016/j.foar.2017.11.004.

[25] E.S. Slaughter, Design strategies to increase building flexibility, Building Research & Information 29 (2001) 208–217. doi:10.1080/09613210010027693.

[26] J. Till, T. Schneider, Flexible housing: the means to the end, Architectural Research Quarterly 9 (2005) 287–296. doi:https://doi.org/10.1017/S1359135505000345.
[27] N.J. Habraken, Supports, An Alternative to Mass Housing., Architectural Press, London, 1972. (ISBN 9780851396255).
[28] B. Succar, Building information modelling framework: A research and delivery foundation for industry stakeholders, Automation in Construction 18 (2009) 357–375. doi:10.1016/j.autcon.2008.10.003.
[29] M.S. İlal, H.M. Günaydın, Computer representation of building codes for automated compliance checking, Automation in Construction 82 (2017) 43–58. doi:10.1016/j.autcon.2017.06.018.
[30] W. Solihin, C. Eastman, Classification of rules for automated BIM rule checking development, Automation in Construction 53 (2015) 69–82. doi:10.1016/j.autcon.2015.03.003.
[31] V. Getuli, S.M. Ventura, P. Capone, A.L.C. Ciribini, BIM-based Code Checking for Construction Health and Safety, Procedia Engineering 196 (2017) 454–461. doi:10.1016/j.proeng.2017.07.224.
[32] S. Zhang, J. Teizer, J.K. Lee, C.M. Eastman, M. Venugopal, Building Information Modeling (BIM) and Safety: Automatic Safety Checking of Construction Models and Schedules, Automation in Construction 29 (2013) 183–195. doi:10.1016/j.autcon.2012.05.006.
[33] K. Negendahl, Building performance simulation in the early design stage: An introduction to integrated dynamic models, Automation in Construction 54 (2015) 39–53. doi:10.1016/j.autcon.2015.03.002.
[34] A. Hollberg, J. Ruth, LCA in architectural design—a parametric approach, The International Journal of Life Cycle Assessment 21 (2016) 943–960. doi:10.1007/s11367-016-1065-1.
[35] M. Röck, A. Hollberg, G. Habert, A. Passer, LCA and BIM: Visualization of environmental potentials in building construction at early design stages, Building and Environment 140 (2018) 153–161. doi:10.1016/j.buildenv.2018.05.006.
[36] Y. Kim, On Flexibility in Architecture Focused on the Contradiction in Designing Flexible Space and Its Design Proposition, Architectural Research 15 (2013) 191–200. doi:10.5659/AIKAR.2013.15.4.191.
[37] Aggiornamento delle Norme Tecniche per le Costruzioni, Ministero delle Infrastrutture e dei

Trasporti (Update of the Technical Standards for Construction, Ministry of Infrastructure and Transport), 2018. https://www.gazzettaufficiale.it/eli/id/2018/2/20/18A00716/sg (Accessed on 18 July 2019).

[38] M. Živković, A. Keković, S. Kondić, The motives for application of the flexible elements in the housing interior, Architecture and Civil Engineering 12 (2014) 41–51. doi:10.2298/FUACE1401041Z.

[39] T.L. Saaty, Decision making with the analytic hierarchy process, International Journal of Services Sciences 1 (2008). doi:10.1504/IJSSCI.2008.017590.

[40] G. Uva, V. Sangiorgio, S. Ruggieri, F. Fatiguso, Structural vulnerability assessment of masonry churches supported by user-reported data and modern Internet of Things (IoT), Measurement 131 (2019) 183–192. doi:10.1016/j.measurement.2018.08.014.

[41] V. Sangiorgio, G. Uva, F. Fatiguso, Optimized AHP to Overcome Limits in Weight Calculation: Building Performance Application, Journal of Construction Engineering and Management 144 (2018). doi:10.1061/(ASCE)CO.1943-7862.0001418.

[42] C. Eastman, J. Lee, Y. Jeong, J. Lee, Automatic rule-based checking of building designs, Automation in Construction 18 (2009) 1011–1033. doi:10.1016/j.autcon.2009.07.002.