An early-design stage assessment method based on constructibility for building performance evaluation

F Contrada1,*, A Kindinis1, J-F Caron2 and C Gobin1

1 Université Paris-Est, Institut de Recherche en Constructibilité, ESTP, 28, Avenue du Président Wilson, 94230 Cachan, France
2 Université Paris-Est, Laboratoire Navier (UMR 8205), Ecole des Ponts ParisTech, IFSTTAR, CNRS, 6-8 av. Blaise Pascal, Cité Descartes, Champs-sur-Marne, 77455 Marne-la-Valle, France
* fcontrada@estp-paris.eu

Abstract. The goal of Zero Energy Buildings represents a challenge for designers: in order to meet required performance, a wide range of technologies and solutions is needed, and interactions with other stakeholders can limit productivity of building process. In this context, early-design stage plays a key role in building lifecycle: at this point, choices define design strategies, which strongly influence the following phases (developed design, construction and operational stages). In order to support decision making in early-design stage, we propose a new assessment method based on the French concept of constructibility, enabling designers to verify the relevancy and robustness of proposed solutions and process. Constructibility comes from buildability and constructability concepts, it sets some principles based on the anticipation of risks and considers both stakeholders’ satisfactions and building performance issues. The evaluation is based on seven criteria: the simplicity of the solution, the verifiability, project skills availability, the simplicity to manage, the compliance with user-centric requirements, sustainability, and cost efficiency. Multi-criteria assessment employs Analytic Hierarchy Process technique to consider professional feedbacks about risks of performance changing. In the case study, a modular office south-oriented in Paris, the multi-criteria assessment is used to enable a decision-making support between various envelope solutions. The method enables to report project weakness and it represents a new practical tool enhancing constructibility.

1. Introduction
Building sector represents one of the most important economic drivers in the world. According to McKinsey Global Institute [1], there is about $10 trillion in construction-related spending globally for goods and services every year. However, building industry is often characterised by productivity problems linked to construction delays. Consequently, the process suffers from cost overrun or quality degradation. Buildings are complex systems, and several factors related to information transfer and to stakeholders’ interaction, expertise, and responsibilities, can affect the successful progress of the process [2]. Complexity increases because new buildings are required to respect and maintain high levels of performance for several aspects (energy efficiency, comfort of users, environmental impact and, economic issues). In the ‘80s, in order to improve productivity in building process, the Construction Industry Research and Information Association (CIRIA) defined buildability as the practice to adopt by designer to facilitate building construction [3]. Later, the Construction Industry Institutes of USA, CII, and of Australia, CIIA defined the concept of constructability. This new concept enhance buildability extending the practice of sharing knowledge to the whole construction lifecycle [4]. In order to facilitate building process, both these approaches set general principles and technical concepts apt to introduce in design phase issues related to building construction and operational stages. An extensive analysis of buildability and constructability is developed in [5].
In early-design stage, uncertainty about technical solutions is very high. However, rescheduling decisions involves ineffectiveness in design, risks of performance degradation and, more generally, limitations for innovation, additional costs and the failure to meet the established deadline. Best practices improving the process already exist [6], e.g. Integrated Design Process [7] or the implementation of constructability concepts [8], but they are still not successfully used in conventional project management models. Decision-making support represents a right direction towards solving building process problems. However, even if performance-based approaches are largely used in design phase associated to decision-making techniques, they often overlook process management methods. In order to integrate performance-based approaches and process management methods, the French Constructibility Research Institute (IRC), proposed in 2010 the new concept of constructibility [9]. Constructibility enhances buildability and constructability definitions because it does not focus only on labour productivity, but it also aims to reach and guarantee building performance levels. It states that building performance is guaranteed engaging attention on the good development of the whole process. In this context, constructibility provides a framework for the anticipation of stakeholders’ efforts and sets performance requirements based on a functional analysis of the building and end-user needs. This kind of approach is useful to consider, such as in Integrated Design Process, several issues at the very beginning of the process. For decisions concerning both ZEB and innovation, this approach is useful to assess their impacts in terms of performance indices and additional efforts required in whole lifecycle. This paper presents a new assessment method involving constructibility principles. Even if the method can be used for whole-building design evaluation, in the paper a simple case study is used to explain its application in supporting early-design stage decision between two façade components.  

2. Methodology
As building performance strictly depends on the whole process choices, we set a new assessment method enabling a decision-making support taking into account best practices and performance issues. The goal is to establish a new multi-criteria assessment method that refers to the French constructibility approach. This method allows stakeholders: to verify design matching with project requirements; to inform designer about best practices in design stage and following ones; to evaluate proposed solutions in order to compare them.

Starting from a state of the art about performance-based approaches and best practices (in particular constructibility principles), the methodology relies on following steps: 1) criteria definition for decision-making; 2) criteria development through sub-criteria and quantification method and; 3) choice of sub-criteria aggregation method based on decision-making techniques.

2.1. Background and criteria definition
Behind best practices, constructability represents a solid and well-known approach. Nima et al. provide 23 constructability concepts (CCs) aimed to improve productivity in building process and representing a list of recommendations for stakeholders [8]. Referring to project lifecycle, Kifokeris and Xenidis suggest a discretisation of these CCs for initiation, execution, and delivery phases [5]. The same authors and Jiang [10] analyse several tools implementing CCs. On the other hand, according to Gowri [11], performance-based approaches can be classified as knowledge-based tools (such as guidelines), performance evaluation tools (such as energy simulation tools) and rating systems (such as BREEAM, LEED or HQE methods). Guidelines are useful in early-design stage because they give recommendations depending on location issues, kind of project and design strategies. Since recommendations refer to some bioclimatic design strategies, generally no direct link exist with a quantitative performance evaluation [12]. Simulation tools [13] support choice in early-design stage but they often need high level of information about building components and they are often characterised by models interoperability limitations, in terms of physical phenomena interferences and of models interoperability (geometrical and analytical ones) [14]. Rating tools allow the designer to realise a multi-criteria assessment of the whole building and to consider the lifecycle process. This kind of tools provides an economic value to the building through a certification. However, since the result consists in a global score, their framework allow stakeholder to arrange selected targets at the cost of other ones.
Consistently with the literature review, we provide seven main criteria for a new assessment method. Criteria are intentionally limited in number and each criterion enables to take into account the whole lifecycle process and several interactions between stakeholders.

**C1 - The simplicity of the solution**: related to the analysis of the process, this criterion takes into account the ease of control of technical components. Several CCs consider simplicity as fundamental aspect for building process productivity [8]. It relates to technical aspects of design phase, such as standardisation, modularity and regularity, and of construction phase issues, such as prefabrication level, number and kind of technical connections, and component production and assembly. According to the best practices, the widest possible simplifications and rationalisations should be implemented in designs, but not to an extent of qualitatively worsening the project outcome [6].

**C2 - The verifiability**: related to the analysis of the process, this criterion takes into account the capability to verify, examine, and control the project progress and technical components in design, construction and operational phase. Best practices in design stage shall consist in the use of design support tools (e.g. BIM and simulations) and of established commissioning protocols for project. The evaluation of verifiability enables to establish, depending on building components, the kinds of tests to be realised in construction phase. Early-design improvements are also provided by using the method considering components accessibility in operational stage.

**C3 - Skills availability**: related to the analysis of the process this criterion allows designers to evaluate the need of additional skills for a given technology. A lack of specific skills may lead to weak analysis in design stage. Actually, process has to be improved analysing as soon as possible the availability of professional skills through the whole lifecycle. The method allows user to consider availability of skills and tools for technical details specification and modelling in design stage; workforce and special machines in installation phase; and for end-users education in operational phase. Since ZEB design has to consider consumptions and carbon emissions amount, information and educational tools for end-users provide a good functioning of established components and systems.

**C4 - The simplicity to manage**: related to product analysis, this criterion aims to evaluate the ease in maintaining performance levels and managing technical solution throughout building lifecycle. Through this criterion, evaluation integrates components issues, such as durability, transport, installation, maintenance and end of life, systems regulation, and interaction between users and building components and control strategies. This criterion enables to consider maintenance for building components and user interventions on hi-tech solutions, such as adaptive facades or HVAC control system [15].

**C5 - The compliance with the user-centric requirements**: related to the analysis of the product, this criterion allows the designer (or the client) to verify that the proposed solution is able to meet performance requirements. According to the Performance Based Building (PeBBu) approach proposed by Szigeti and Devis [16], it is necessary to verify the achievement of performance targets required by the project programme. This kind of control avoids bad choice in technical solutions as early as conceptual design. Moreover, performance requirements express goals to be satisfied settled by end-user needs (e.g. comfort and protection). In this context, we focus the evaluation on indoor environmental quality, in particular on thermal and visual comfort and on ergonomic issues. Depending on performance requirements, the new method can be adapted to different objectives.

**C6 - Sustainability**: related to the analysis of both the product and process, this criterion provides high performance and sustainable new constructions. Sustainability represents one of the most important contemporary challenges. Sustainability assessment refers both process and product, focusing on resources consumption and environmental impacts through a lifecycle analysis.

**C7 - The cost efficiency**: related to the analysis of the product the economic criterion is often the most important decision driver in building design and process. The new method integrates an economic assessment based on global cost approach [17]. It is thus possible to compare several technical solutions taking into account the whole process.

2.2. Criteria development: definition of a rating system and evaluation metrics

In order to facilitate the introduction of support tools and knowledge sharing process in early-design stage, the assessment method provides a quantification of qualitative criteria (the ones related to best
practices) though a rating from “one” to “six” depending on the degree of best practices utilisation. A complete introduction of the best practice in early-design is rated “six”, while the lack of constructibility concept is rated “one”. For each criterion, middle values are also defined. The assessment via the established rating system enables a quantification for criteria C1, C2, C3, and C4.

Criteria C5, C6, and C7 express product performance via numerical indices commonly used in building performance evaluations. According to standards and client strategies (e.g. achievement of a specific label), the user can select the proper numerical index. The assessment for C5 is based on the comparison between performance requirements and results of space design and building simulation models in terms of thermal (e.g., PMV, operative temperature and number of discomfort hours [18]) and visual comfort (e.g. daylight factor or spatial daylight autonomy [19]). In the same way, users can choose the environmental indicators for the sustainability evaluation. Carbon emission of proposed solutions can be assessed using Life Cycle Assessment tools or simplified methods via the existing environmental data defined by manufacturers for construction components. Cost efficiency criterion allows the designer to compare several solutions thought a ratio between investment cost and global cost (including investment and operative cost). For further details about criteria assessment, see [13].

2.3. Sub-criteria aggregation

The seven criteria summarise several aspects expressed by several sub-criteria. In this way, the analysis and the consequent improvement may interest a specific aspect of a criterion. We choose to use a decision-making technique to aggregate sub-criteria and have a global normalised value describing each criterion. Decision-making techniques represent a branch of operational research. After a review of decision-making techniques [13], we decided to integrate the Analytic Hierarchy Process (AHP) [20] in the assessment method: AHP allows the user to convert qualitative evaluations in numerical ones via a hierarchical established scale. It is thus possible to compare several elements with different measurement units. AHP method also incorporates a technique for checking the consistency of established weights. Via several pairwise comparisons, we established an intensity matrix for each criterion according to professional feedbacks about risks of performance changing [13]. Matrix enable to evaluate the weight of each sub-criterion (\(C_{n,i}\)) in the criterion aggregation. For C1, C2, C3 and, C4 the rating is normalised to the maximum (six). For criteria C5, C6, and C7, the normalisation is given by the ratio between calculated value and requirement of each index.

3. Case study

A modular office (2.7x5.0x2.7m) south-oriented located in Paris with a WWR of 98% represents the case study. We use the new method for a multi-criteria evaluation of two envelope solutions: a traditional double pane window coupled to a fixed shading system (SS) and a switchable window (SW). SS is modelled though six tilted fixed horizontal louvres, each measuring 270x45cm, with a solar transmission coefficient of 0.2 and distanced 40cm from the façade. For SW we study an electrochromic glass considering different control strategies defining four technical solution:

- **SWS**: the glass changes its color if beam and diffuse solar radiation incident on the window exceeds 189W/m² [21]. A glare control is also active. The reference point is the middle of the workspace at 0.8m above the floor.
- **SWT26**: the glass changes its color if indoor air temperature exceeds 26°C. Glare control is also active.
- **SWD&G**: based on daylighting and glare controls. Thermo-optical characteristics are adjusted to meet the daylight illuminance set point (300lux) in the reference point.
- **SWD**: based only on daylighting control.

Since our application focus on the selection of a technology able to modulate solar radiation, building construction mode, systems, structural connections, and process management are considered the same for the two solutions. Numerical models were developed in EnergyPlus v.8.9. Switchable glazing characteristics of an available product (SageGlass®) were calculated in WINDOW 7.6 for clear and dark
states in order to describe components just through U-factor, Solar Heat Gain Coefficient (SHGC), and Visible Transmittance (VT) (Table 1). In early-design stage, building components are often considered through these three main characteristics. For C5, C6 and C7 evaluation, inputs for systems and occupancy schedules were the same. Radiant ceiling panels provide both heating and cooling. Mechanical ventilation follows a mixed-mode ventilation strategy with a control on indoor dry-bulb temperature and, for the free cooling, on outdoor temperature.

| Thermo-optical characteristics | SS | SW - Clear | SW - Dark |
|-------------------------------|----|------------|-----------|
| SHGC                          | 0.29 | 0.41 | 0.09 |
| U-factor [W/(m²K)]            | 1.03 | 1.03 | 1.03 |
| VT                            | 0.59 | 0.60 | 0.10 |

Assessment for criteria C1, C2, C3 and C4 involves an analysis of both project and process through the defined rating system. Criterion C5 enables a comparison between technologies in term of spatial Daylight Autonomy for visual comfort and of operative temperature for thermal comfort (lower than 26°C in summer and higher than 19°C in winter period). Normalisations for criterion C6 refer to established values of European Union energy and environmental certifications (330 kWhEP/m².y and 35 kGeqCO2/m².y for building use during 30 years). These values represent the upper limit for the class including all calculated values. Environmental assessment refers to the online available INIES database. For C7, investment cost refers to a market analysis for the two solutions (on average 450€ for SS and 600€ for SW). Moreover, for global cost assessment we consider a discount rate of 4% and, referring to French statistical data, gas and electricity cost of 0.027€/kWh and 0.044€/kWh respectively.

3.1. Results and discussion

Since construction features and project management are the same for all technical solutions, C1 and C2 have the same values. As showed in Figure 1, differences arise in C3 because SW needs further skills in modelling and sensor management (C3.2), if designer does not consider additional efforts. Solutions assessment for C4 differs on the interaction with end-user (C4.5) because SS prevent user regulations. SW is better than SS for visual comfort (C5.2) and SWD control strategy is the best solution. For C6, results are very close but SS is the best solution for all sub-criteria.

Figure 1. Graphical results of C3, C4, C5, and C6 and differences for C3.2, C4.5 and C5.2 sub-criteria.

Table 2 reports the results of aggregated criteria: despite the close results, SW represents the best solution for C4, C5, and C7 even with a higher investment cost. Designer will choice a solution depending on the additional required efforts i.e. more developed skills or financial commitment.

Table 2. Summary of the global evaluation (best results in gray)
4. Conclusions and perspectives

With this paper, we presented a new evaluation method based on constructibility principles. The method can be used for both multi-criteria evaluation and decision-making support in early-design stage. Assessment is based on seven criteria developed in further sub-criteria. AHP was selected as decision-making technique enabling to consider the risk of performance change via professional feedbacks. The case study shows an application of the method in supporting the choice between building envelope components. The method was also tested for post-project evaluation of two buildings [13]. Its robustness depends on further applications on more complex projects. The method enables to report project weakness referring to established best practices and additional analysis for innovative technical solutions. It represents a new promising tool enhancing the French constructibility. Further developments focus both on multi-objective optimisation based on the seven criteria, and on tailoring intensity matrices and sub-criteria structure to local policies, products, and practices. A cost assessment has to be developed in order to consider additional studies needed for the application of the method.

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