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EFFORT AND EXPRESSIVENESS IN SIMULATION-BASED BUILDING PERFORMANCE EVALUATION

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ABSTRACT

This paper describes a case study to estimate the time and effort needed by novice designers to computationally evaluate the performance of building designs. A group of senior architecture students participated in the study, learning and using a software application to assess the energy performance of six project submissions for a school building design competition. The outcome of this study (time investment ranges for various components of the modeling activity) was evaluated and further extrapolated to estimate the effort needed for a more comprehensive computational assessment of the environmental performance of these designs.

INTRODUCTION AND BACKGROUND

Computational building evaluation tools have the potential to provide an effective means to support informed design decision making. Computational modeling, however, comes with a cost. Thereby, the most important cost factor is not necessarily software acquisition, but the time needed for learning and using the software. The extent of required time and effort has been quoted by a number of previous studies around the world (Mahdavi et a. 2003, Lam et al. 1999) as one of the main hindrances toward the pervasive use of computational building performance assessment tools by designers: Currently, modeling applications are mostly used, if at all, in the later stages of design and by specialists, rather than architects. Few studies, however, have explicitly dealt with the ascertainment and quantification of the actual effort needed to understand, master, and apply computational building evaluation tools. Thus, little factual information is available as to the cost and burden of computational building evaluation and its effectiveness in building design support. In this context, the present paper describes a case study, whose motivation was to estimate the time and effort needed from novice designers to computationally evaluate the performance of building designs.

The importance of the energy performance of buildings as well as the quality of the indoor thermal environment as essential design evaluation criteria is well-established (Mahdavi and Kumar 1996). Scientific foundations for the description of the thermal performance of buildings are well-understood and respective algorithmic formulations for its prediction have been developed (see, for example, Clarke 2001). More recently, efforts have been made to expand the environmental evaluation beyond operational energy into a more comprehensive set of indicators, thereby addressing the environmental impact of buildings (Mahdavi and Ries 1998, Fava et al. 1992). As applied to buildings, life-cycle assessment (LCA 2001) refers to the major activities in the course of a building's life-span from its construction, operation, maintenance, and decommissioning. The LCA process is a systematic approach and consists of 4 steps: *i)* goal definition and scoping; *ii)* inventory analysis; *iii)* impact assessment; *iv)* interpretation. Many applications have been developed to support the energy and environmental performance of buildings. Examples of energy simulation applications are ESP-r [Esru 2004], EnergyPlus [2004], and ECOTECT [2004]. A comprehensive list of such tools may be found in DOE 2004. Likewise, in the LCA area, a variety of computational tools are available that are generally built on a database of environmental information and can be used to evaluate the environmental impact of products and processes. Examples of such tools are BEAT2002 (Holleris Petersen 2002]), ELP (Forsberg and Burström 2001), Simapro (2004), Envest (2004), Athena (2004), BEE (Berge 1995), and Eco-Quantum (Kortman et al. 1998).

Few studies could be identified that explicitly deal with the quantitative assessment of the time and effort needed to prepare and conduct performance simulation studies. In a study of HVAC (heating, ventilation, air-conditioning) simulation process, Madjidi and Bauer (1995) show that the bulk of the time needed for detailed HVAC simulations is spent to collect HVAC systems data. The time required for the generation of the building model is comparatively less time-consuming. Bazjanac (2001) argues that the majority of time in the preparation of input data for energy performance simulation is spent on describing the building geometry. De Wilde (2004) reports that the energy simulation for a simple building required a full-time effort of two working days from an experienced doctoral student.

APPROACH

Overview

The time expenditure of 25 architecture students was documented as they evaluated the energy performance of six project submissions for a school building design competition. Moreover, the time needed by a doctoral student to analyze the life-cycle performance of these designs was documented.

Energy simulation study

The objective of this study was to estimate the time and effort needed to apply an energy simulation tool to assess and improve the energy performance of building designs. 25 senior architecture students participated in the study, which constituted the primary content of a semester-long elective course on building performance modeling. All students had previously attended a course on the fundamentals of thermal performance of buildings (involving a time investment of approximately 60 hours). The students' background was fairly uniform in terms of age and educational background. The students were organized in terms of 10 groups (G_1 to G_10). Each group was required to analyze and report on the energy performance of a given design using an energy performance simulation tool. Moreover, a thermally improved version of the initial design was required as part of the students' final analysis report. Thereby, changes were to be suggested only to component properties; the basic geometry and massing of the initially given designs was to be preserved.

Six submissions to a school design competition were selected as sample designs (P_1 to P_6). As such, they represented typical instances of preliminary designs. Given 6 projects and 10 groups, some projects were analyzed by more than one group. The energy performance of the designs was to be expressed primarily in terms of heating load. Given the local climatic conditions at the designated building site (in Austria) and its pattern of use as a school, it was expected that the buildings would perform satisfactorily without cooling requirement. Simulations were performed using Ecotect. This tool is appropriate for performance assessment in the early stages of design and thus suitable for the present case study, which addresses the potential of tool usage by architects, rather than energy specialists.

At the beginning of the study, the participating students were given an introductory tool tutorial, requiring approximately 10 hours. Throughout the study, the students were required to maintain a log reflecting their time expenditures for:

i) creating a simple building geometry model in a conventional CAD environment;
ii) transferring the CAD model into the energy simulation tool and preparing it for simulation;
iii) performing the simulations for the initial design and possible iterations;
iv) documentation of the results in terms of an analysis report (including numeric and graphic representation of the results and comments).

The initially given designs were first modelled in a commercial CAD environment, as, in the professional context of typical architectural offices, building designs are first documented in CAD programms. The majority of the participating students already possessed proficiency in the use of the CAD tool prior to the commencement of the case study. The knowledge of such tools represents the standard part of a typical educational program in architecture. Upon submission of the students' final reports, the groups' time budgets were compared. For benchmarking and comparison purposes, the energy performance of all six schools was also obtained independently by a more experienced doctoral student based on the same building information and using the same energy simulation tool.

LCA study

The objective of this study was to estimate the time and effort needed to apply a computational LCA tool to assess the ecological performance of the six previously mentioned school projects. A doctoral student in Architecture applied the tool BEAT2002 to conduct the computations. For architectural LCA of preliminary designs, BEAT may be said to represent the proper level of complexity. The student had acquired the fundamentals of LCA as well as the know-how to run BEAT via self-learning (time investment approximately 160 hours and 40 hours respectively): Knowledge of LCA and respective computational tools is typically not covered in the curricula of architectural schools. The student's effort for the LCA study of the six schools was captured in terms of time investment for: *i)* project data base generation; *ii)* modeling in BEAT 2002; and *iii)* documentation of the results.

Specifically, out of the spectrum of indicators that can be computed using this application, nine environmental performance indicators were selected and the corresponding values were computed for the six previously mentioned school design project submissions. These indicators are listed in Table 1. The scope of the LCA analysis included in the present study the production of the building materials and components and their transportation to the construction site.

RESULTS

Energy Analysis

Figure 1 illustrates the energy performance of the six original projects (annual heating load), as simulated by students. For comparison purposes, the figure also includes the results of the doctoral student. The deviations may be attributed to four broad error categories corresponding to component, geometry, zone, and material description (see Table 2).

TABLE 1 – SELECTED ENVIRONMENTAL PERFORMANCE CATEGORIES FOR LCA

Indicator	Symbol	Unit
Global warming potential	GWP	kg (CO_2)
Ozone depletion potential	ODP	kg (CCl_3F)
Acidification potential	AP	kg (SO_2)
Nutrient enrichment pot.	NP	kg (PO_4^{3-})
Human toxicity	HT	kg
Photochem. Ozone form.	POCP	kg (C_2H_4)
Hazardous waste	HW	kg
Bulk waste	BW	kg
Embodied energy	EE	MJ

TABLE 2 – TYPES AND INSTANCES OF MODELING ERRORS

Error type	Instance
Component description	Error in the layer sequence of a multi-layered building component
Geometry description	Erroneous room dimensions
Zone settings	Error in internal load assumptions (magnitude and schedule)
Material description	Error in the value of thermal transmittance of an external wall

As mentioned earlier, the students groups were required to use simulation to come up with a thermally improved version of the initial design (via changing component properties). Figure 2 shows the simulated heating loads of the initial designs together with those of the improved version. Two types of design changes were mainly responsible for the energy performance improvements: *i)* Improvement of the thermal insulation properties of building enclosure components (beyond the standard assumptions in the design competition submissions); *ii)* Changes in the dimensions of the transparent building enclosure components.

The participating students documented their time expenditures in terms of four main modeling activities (see Table 3). These involve time spent on: *i)* generating a simple geometric model of the design in a CAD tool; *ii)* transferring the geometry model to the energy simulation tool and adding the necessary semantic information; *iii)* performing the simulation runs; *iv)* documenting the simulation results. Note that the times given in Table 3 include also the time needed for the simulation of design changes (about five iterations per group) involving modifications of the thermal properties of enclosure components and the size of openings in the enclosure. Moreover, Table 3 includes reference times as needed for the same modeling tasks by an experienced doctoral student. The latter are, with the exception of CAD modeling activity, shorter than those of the student groups: The doctoral student, while more experienced in energy simulation, had not been using CAD tools as frequently as the participating students.

The overall results of the environmental assessment of the six schools (projects P_1 to P_6) are summarized in Figure 3 in terms of relative indices. For each category, the worst performing design was given the index value of zero. The performance of other schools was derived by proportionally relating their actual indicator value to the indicator value of the worst performing school in that category. The time expenditures of the doctoral student for *i)* modeling the six buildings in the LCA tool and *ii)* documenting the results were also monitored and are shown in Table 4. Note that the information in this table does not include the time needed for the generation of the project database, which amounts to approximately 24 hours for a new project with the size and complexity comparable to the design submissions considered in the present study. Once a project database is generated, the time needed for the generation of databases for similar projects (sharing a number of building materials and components) can be reduced down to about 50%.

DISCUSSION

Time matters

Consider the following scenario. A novice designer with an educational background in architecture (involving at least a semester-long course on the fundamentals of thermal performance of buildings) needs to estimate the energy performance (heating load) of a roughly 2200 m^2 building based on a preliminary design (with the resolution level of a typical design competition submission). The designer has recently completed an intensive 10-hour tutorial on using a simulation tool for the assessment of the thermal performance of preliminary designs. The assessment should explore possible energy performance improvements (around 20% heating load reduction) via design changes (involving roughly five iterations on component properties and dimensions). For this scenario, our study implies a required time expenditure of about 30 to 40 person-hours (see Table 3). Figure 4 illustrates the portions of this time spent toward generating the building model for simulation, running the simulations, and documenting the results.

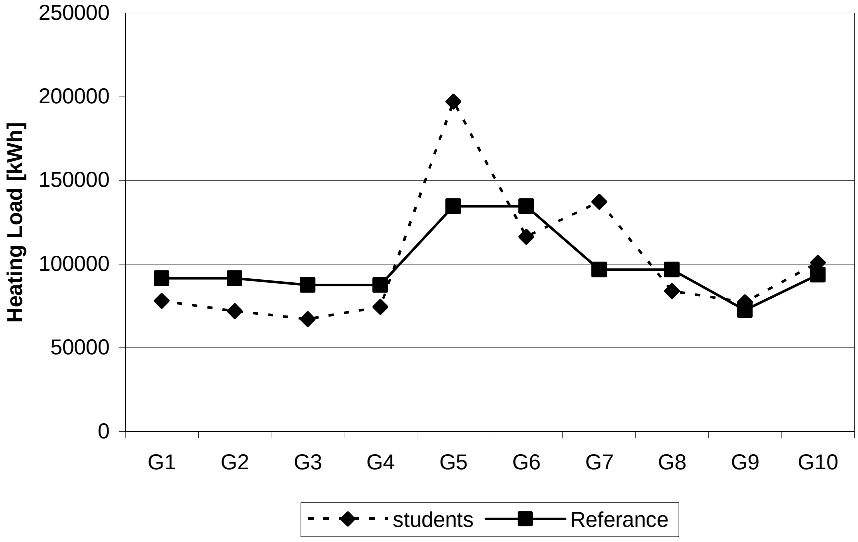

Figure 1 – Simulated energy performance of the six design projects (annual heating load)

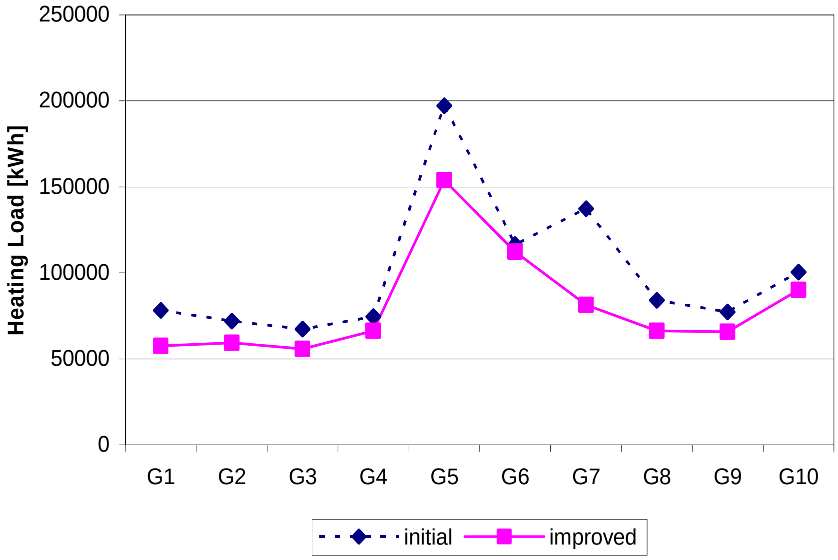

Figure 2 – Simulated energy performance of the original and improved versions of the six design projects

TABLE 3 – OVERVIEW OF THE TIME EXPENDITURES (MEANS AND STANDARD DEVIATIONS IN HOURS) BY THE PARTICIPATING STUDENTS GROUPS (TOGETHER WITH REFERENCE TIMES OF AN EXPERIENCED DOCTORAL STUDENT) FOR PERFORMING VARIOUS MODELING-RELATED TASKS

	CAD model	Energy model	Simulation	Documentation	Total time/project
Mean (students)	4.6	15.0	9.9	6.0	35.4
STD (Students)	1.6	3.1	4.2	2.9	6.5
Mean (Ref.)	5.7	11.7	4.7	7.4	29.5
STD (Ref.)	1.5	2.9	1.2	1.0	4.8

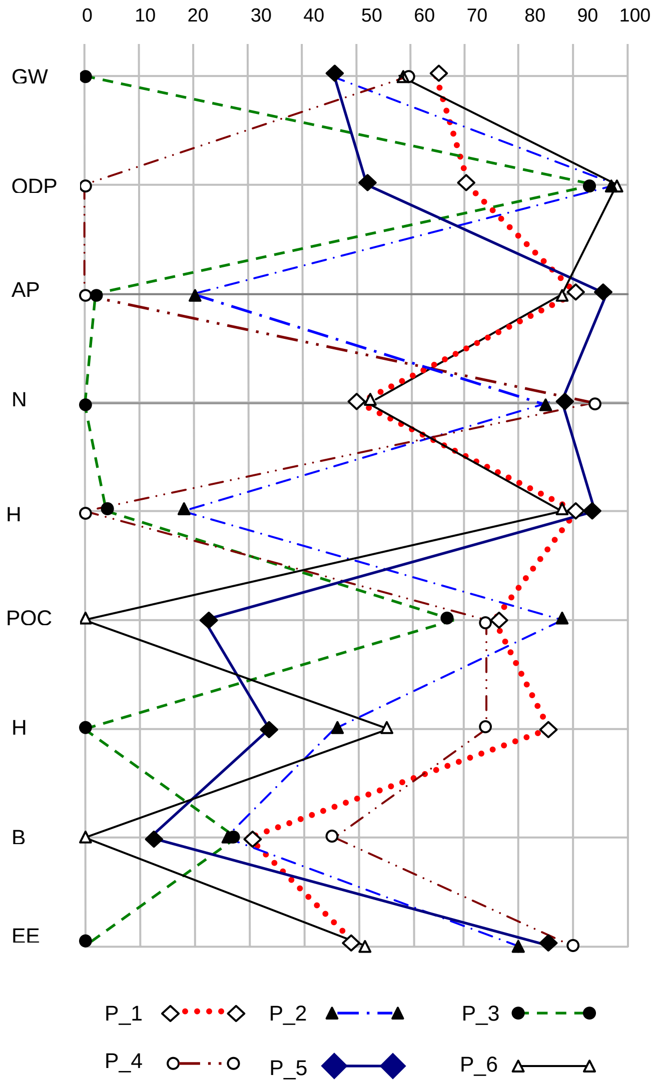

Figure 3 – Calculated relative performance of six design projects (P_1 to P_6) in terms of nine environmental impact indicators (zero denotes the worst performance, 100 the best possible performance in a given category)

TABLE 4 – TIME REQUIRED (IN HOURS) BY A DOCTORAL STUDENT FOR LCA

Project	LCA Modeling	Documentation	Total time/project
1	15	12	27
2	12	12	24
3	11	11	22
4	11	11	22
5	10	10	20
6	10	10	20
Mean	11.5	11	22.5
STD	1.9	0.9	2.7

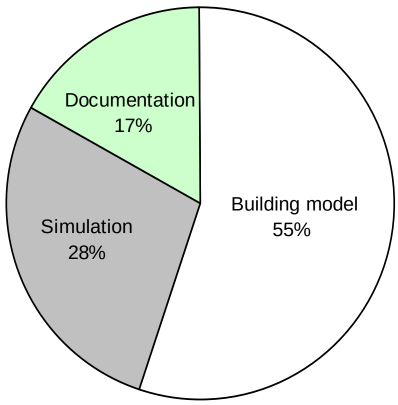

Figure 4 – Relative time allotment for various energy simulation-related tasks

Given the overall time budget for the design of a building, we conclude that time expenditure requirement alone does not explain the paucity of energy simulation tool usage by architects in the preliminary stages of design. The required domain knowledge is an integral part of the educational curricular of most architecture schools; it may be updated via a reasonable investment in continued education, as expected from professionals in general. As to the tools and their usability, more performance simulation tools have become available recently that are suited for use in early stages of design. Such tools are not more difficult to use than typical CAD tools used by almost all architects. Thus, reasons for the paucity of tool usage amongst architects may have to be used elsewhere: A considerable fraction of architects do not seem to consider performance assessment as integral to their professional role. As with the structural analysis, they seem to believe that such tasks should be "out-sourced" (i.e., performed by building physics "experts"), even though the majority of the architects do believe they should know more about building performance and its evaluation methods [Mahdavi et al. 2003]. Moreover, many design professionals complain about being overloaded and underpaid. Perhaps additional dedicated social investments in measures and tools toward better performing buildings should be considered.

We must note, however, that time expenditure requirements for simulation-based thermal performance analysis can of course quickly go beyond the specifics of the above scenario. It might be the case that more design iteration would be desirable (involving also changes in building geometry). Likewise, further performance indicators (e.g. those addressing thermal comfort issues in the summer period, daylight availability) may have to be considered. One could argue that some additional simulation efforts beyond those considered in the above scenario would be still within the architects' realm of possibilities both in term of time investment and required expertise. However, in order to judge this question in a reasoned manner, a versatile time estimation instrument would be required. Such an instrument could consider various dimensions of a simulation study in terms of the factors that affect the required effort for simulation. Table 5 includes the primary dimensions of such a "simulation effort space".

TABLE 5 – SOME BASIC DIMENSIONS OF THE "SIMULATION EFFORT SPACE"

Dimension	Remark
Size	The physical dimensions of the project
Complexity	The complexity of the form and assembly of the design
Resolution	Preliminary versus detailed design
Semantic iterations	Number of modifications to material, component, and system properties
Geometric iterations	Number of modifications to the building form, massing, and topology
Performance indicators	Types and number of performance indicators (energy, light, acoustics, …)
Simulator's experience	Novice versus expert tool user

Our specific case study provides basic clues with regard to some of the dimensions of Table 5. We combined such data together with additional assumptions regarding the remaining dimensions of the simulation effort space, to construct a demonstrative prototype simulation time estimation tool (see Appendix A for the mathematical formulations of these assumptions). Figure 5 provides a few illustrative examples of predictions using this tool for three distinctive scenarios (see Table 6). Thereby, the relationship between project size and the total required simulation study time are estimated for three different scenarios as described in Table 5. It was assumed that: *i)* all projects had low levels of resolution and complexity; *ii)* all performance indicators could be computed using the same performance simulation application. Low, intermediate, and high level of experience in usage of simulation tools was numerically denoted with 1, 2, and 3 respectively.

Note that Figure 5 is merely meant to illustrate the potential toward estimation of required simulation effort based on various pieces of information on the dimensions of the simulation effort space. The tool's underlying knowledge-base is quite rudimentary at this point and needs to be substantiated and validated in the course of future studies.

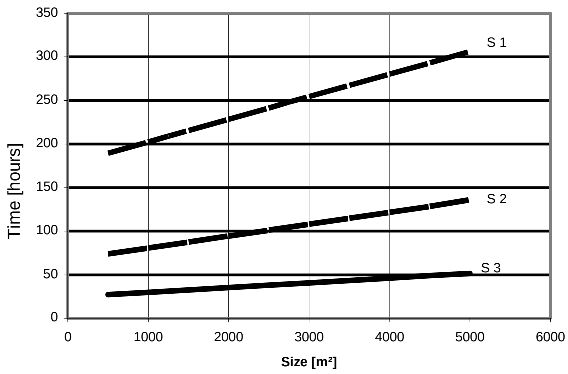

Figure 5 – Illustrative examples of time requirement estimations as a function of project size for 3 simulation scenarios (S1 to S3 as per Table 6)

TABLE 6 – ILLUSTRATIVE SIMULATION STUDY SCENARIOS DEPICTED IN FIGURE 5

	S1	S2	S3
Semantic iterations	10	5	3
Geometric iterations	4	3	2
Performance indicators	3	2	1
Level of user expertise	1	2	3

The previous discussion of the required simulation effort circled around those performance indicators, which are covered in typical architectural curricula (e.g. heating load). Yet, increasingly, energy performance is being viewed as just one of the many parameters to be factored in the evaluation of buildings. According to this view, the environmental impact associated with building construction and operation, for example, must not only consider energy use during the operation phase but many other processes (involving embodied energy, emission of green house gases, etc.). To accommodate these additional considerations, a comprehensive environmental LCA would be necessary. In view of required time and expertise, however, such a comprehensive analysis represents a different scenario from the energy simulation case.

A novice designer with an educational background in architecture who intends to perform a computational LCA study would have to spend about 200 hours to acquire the required domain knowledge and to learn to use a proper tool (this estimation is based on a self-study scenario and may be reduced if a formal LCA course and tool tutorial option is available). To our knowledge, few architectural firms could or would be prepared to consider such level of investment, unless corresponding code compliance requirements are set in place and commensurate adjustments to the professional design fee structure are made. Given the scenario of a designer with knowledge of LCA and corresponding tools, the actual time required to calculate the environmental performance of preliminary building designs is, however, not excessive: Our case study (Table 4) suggests a time requirement of about 40 to 50 person-hours for the LCA of a preliminary design for a roughly 2200 m^2 building. Figure 6 illustrates the fraction of this time spent toward generating the project database, LCA modeling, and documentation.

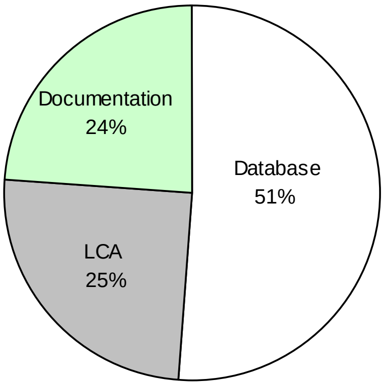

Figure 6 – Relative time allotment for various LCA-related tasks

Considerations of effectiveness

In all cases where clear building performance guidelines are available, the derivation and interpretation of corresponding indicators is straight-forward. As such, a simulation study may show if a design is meeting a specific performance requirement in terms of mandated values of a corresponding indicator. Heating load or predicted annual energy use are examples of such indicators. We do not mean to imply that providing evidence for code compliance is the sole (or even the most important) mode of using performance simulation to support design: Much more can be learned about the future performance of an actual building through simulation of its behavior in the design phase. Nonetheless, this code compliance or benchmarking functionality of performance simulation is well-understood in principle by practitioners and is becoming more of a routine component of the building design process.

Heating load, for example, may be quite a limited indicator in that it represents only one of the many indicators of a design's quality. But given a proper simulation procedure, it is possible in principle to derive and interpret its value in a conclusive manner. The same cannot be said of other indicators considered in this paper. For example, LCA tools can provide a large set of diverse environmentally relevant indicators. Not only it is rather difficult and cumbersome to assemble reliable input information for such assessments, but also it is quite a challenge to interpret their results. In this regard, Figure 3 provides a point in case. Even though the results of the analysis have been expressed here in relative terms, it is not easy to gain a clear impression as to the relative environmental performance of the six projects involved. It is of course possible to derive a weighted average of multiple indicators in terms of a single aggregate indicator of environmental performance. However, the reasoning behind such weighting approaches is often inconclusive and difficult to objectify. In this context, a conjecture may be appropriate. When we move from limited, concrete, and quantitative indicators to more comprehensive evaluation perspectives, we inadvertently lose on the conclusiveness of our evaluative tools and their results.

CONCLUDING REMARK

The paucity of tool usage by architects to derive the preliminary indicators of building performance (such as energy indices) cannot be explained solely based on the required level of knowledge and effort. However, more comprehensive (e.g. LCA-based) computational assessment of detailed building designs is currently beyond both the capability and the capacity of most architects. In general, the efforts to simultaneously maximize comprehensiveness and objective reproducibility in architectural design evaluation have had limited success. Performance simulation tools can provide us with various views and appraisals of designs. These are very useful, as they are – if properly generated – reproducible and observer-independent. But they are also partial, in that they usually have a very specific and technical scope. There remains a significant degree of choice on the side of an evaluator as to which of those partial views and appraisals, if any, are made effective in the overall design decision making and quality evaluation processes. This is not meant to devalue the role of assessment tools that aim at objectivity, but to point to the limitations of their role in the current building delivery process: The gap between the sum total of available analytical evidence about a design's attributes and an overall evaluative judgment regarding its quality can be filled in practice with all kinds of subjective impulses and bottom-line monetary considerations.

APPENDIX A: ILLUSTRATIVE ALGORITHMS FOR THE "SIMULATION EFFORT SPACE"

The total time (Z) required for a simulation task (in hours) is derived as the sum of the time components needed for construction of the CAD and simulation models (Z_{mc}, Z_{mp}), simulation runs (Z_{sim}), and documentation (Z_{doc}):

$$Z = Z_{mc} + Z_{mp} + Z_{sim} + Z_{doc}$$

These time components are computed in terms of weighted products of parameter concerning project size (S), degree of informational resolution (R), complexity (C), performance indicators (I), semantic and geometric iterations (SI, GI), and degree of the user's expertise (E):

$$Z_{mc} = 4.6 \cdot (S_{mc} \cdot R_{mc} \cdot C_{mc} \cdot I_{mc} \cdot SI_{mc} \cdot GI_{mc} \cdot E_{mc})$$

$$Z_{mp} = 15 \cdot (S_{mp} \cdot R_{mp} \cdot C_{mp} \cdot I_{mp} \cdot SI_{mp} \cdot GI_{mp} \cdot E_{mp})$$

$$Z_{sim} = 9.9 \cdot (S_{sim} \cdot R_{sim} \cdot C_{sim} \cdot I_{sim} \cdot SI_{sim} \cdot GI_{sim} \cdot E_{sim})$$

$$Z_{doc} = 6 \cdot (S_{doc} \cdot R_{doc} \cdot C_{doc} \cdot I_{doc} \cdot SI_{doc} \cdot GI_{doc} \cdot E_{doc})$$

For some of these terms approximate functions were derived below that use, as input information, project size A (in m^2), number of performance indicators (n_{ind}), number of semantic and geometric iterations (n_{si}, n_{gi}), and the degree of user expertise (d_{exp}=1 denotes novice, d_{exp}=3 expert user). For the case study described in this paper, all terms pertaining to resolution and complexity were assigned 1, indicating low levels of project resolution and complexity. As the experiment did not include projects of significantly deviating levels of complexity and resolution, associated functions were not derived.

$$S_{mc} = S_{mp} = 2.3 \cdot 10^{-4} \cdot A + 0.5$$

$$I_{mc} = SI_{mc} = E_{mc} = 1$$

$$I_{mp} = (6 + n_{ind}) \cdot 7^{-1}$$

$$I_{sim} = (4 + n_{ind}) \cdot 5^{-1}$$

$$I_{doc} = (2 + n_{ind}) \cdot 3^{-1}$$

$$SI_{mp} = SI_{sim} = SI_{doc} = (3 + n_{si}) \cdot 8^{-1}$$

$$GI_{mc} = (0.2 + 0.8 \cdot n_{gi})$$

$$GI_{mp} = GI_{sim} = SI_{doc} = (0.3 + 0.7 \cdot n_{gi})$$

$$E_{mp} = E_{doc} = (1.1 - d_{exp} \cdot 10^{-1})$$

$$E_{sim} = (1 - \log d_{exp})$$

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