1. Introduction

1.1. Research background

With the continuous rising of the global population, the increase in energy demand of human society and the great dependence on traditional fossil fuel, energy issues appear gradually obvious and intractable. Under this circumstance, buildings consume more than 30% of total final energy consumption globally and account for nearly half of the electricity need on this planet. What’s worse, recent annual energy demand in the buildings sector has increased about 20% compared to that in 2000, making it occupies over 30% of total carbon dioxide emission in all sectors of the economy (IEA and IPEEC 2015).

As the energy problem has been considered as a worldwide issue, the architecture, engineering and construction (AEC) community spares no effort to reduce the energy consumption in buildings. Needless to say, architectural design – the first step towards an energy-efficient building – is one of the most important parts in reducing building energy demand, while the early stage of architectural design plays the key role in it. This paper will concentrate on integrating energy simulation into the early design stage and come up with an integrative design method.

1.2. Literature review

The early design stage discussed in this paper mainly exists in the conceptual design phase in architectural
design, which can also be referred to as the schematic design phase. It lies way ahead of the design development phase, let alone construction documents and other following stages. There are a series of different characteristics buried in the early design stage, including phasing feature, iterative nature, decisive impact, and uncertainties.

The divergent phase in early design stage was first discovered by Moore and Gay (1967) while Jones (1970) first realized the importance of cognitive style of thinking in convergent phase in the design process. Liu, Chakrabarti, and Bligh (2003) synthesized, summarized and developed the theory and put forward that the early design stage is made up of a series of divergent and convergent phases, which constitutes part of the phasing feature of the early design stage. Divergent phase is the process of generating design ideas and concepts, while the convergent phase is associated with evaluation, ranking, weighting and selection of the best design among those alternatives (Rezaee 2016). These two phases are born dependent upon each other and both of them share the equal level of importance. In addition, a deepening phase follows in order to further the development of the design (Figure 1).

Furthermore, the iterative nature of architectural design in the early stage means that the divergent and convergent phases are repeated as the design goes on (Liu, Chakrabarti, and Bligh 2003). The iterative nature differs from simple repetition of one act, instead, it means the design keeps evolving and developing when architects either select different groups of design elements in a wide picture (Cross and Roy 1994) (Figure 2) or a divergent-convergent process in a narrower view (Liu, Chakrabarti, and Bligh 2003) (Figure 3).

The decisive impact of early design stage, as the old proverb by Aristotle (Thilly 1951) "Well begun is half done", makes it powerful to influence design with little cost for big changes or movements in the early stage. So the preferred design process lays much more emphasis on the early stage than the traditional design process does (MacLeamy 2004) (Figure 4).
Uncertainties are used to describe a state where current or future circumstances or results cannot be presented due to the knowledge constraints and other reasons (Tannert, Elvers, and Jandrig 2007). A complete design process is composed of many stages that are not clearly separated from one another and one of the connecting bonds among them is the uncertainty. In other words, uncertainties, to some extent, divide the design process into phases because the process is all about reducing uncertainties and increasing certainties (Figure 5). As architectural design is a current commitment of the future goals made by architects, which is neither certain nor precise, the prediction can only be carried out with a range of possible outcomes (Rezaee 2016). The built results after construction is simply made up of design elements and parameters that sit in their ranges set-up in the early design stage (Augenbroe 2011).

Taking energy flows and energy consumption in early architectural design stages has a long history which can be traced back to Banham (1969) who emphasized energy along with the physical equipment in terms of environmental control. Stepping past the millennium, Abalos and Snetkiewicz (2015) divide the topic into four parts, namely somatistics, verticalism, thermodynamic materialism and the assemblage of monsters in the discussion of thermodynamic architecture theory and Moe (2013) explains in a similar way with the notion of materials, energy systems and amortization. However, these researches focus much on philosophical and theoretical aspects and fail to offer a clear route map or design method for architects.
There are also scholars concentrating on the integration of energy simulation into the early design stage. The linear inverse modelling (LIM) was put forward in order to forge a systematic method for generation and evaluation of design alternatives, which leads to a higher probability of better energy performance (Rezaee et al. 2015). This method is a groundbreaking innovation, but it lays much emphasis on the engineering part with a great amount of mathematic calculation, which is unfriendly to most architects. Besides, design methods helping architects to optimize building massing, material and technology are introduced with a reduced-order energy simulation toolkit (Ahuja, Chopson, Haymaker and Augenbroe, 2015), but some important characteristics of the early design stage, such as uncertainties, are not considered in the method.

2. Purpose and objective of the study

First of all, the author tries to seek a way of carrying out energy simulation at the early architectural design stage after emphasizing the significance of it. Taking energy simulation into account at the early design stage can add energy consumption to architectural scheme evaluation system as a new judging aspect, apart from design concept, plan programing, elevation composition, building massing, spatial experience and so on. On the other hand, energy simulation at the early design stage can help architects build up consciousness on energy consumption of the building with a direct mapping relation between architectural schemes and energy numbers. Otherwise, the energy consumption goals, usually numbers alone, can hardly impress architects or make a real difference to final design outcomes.

Secondly, this study is also a call for integrative design method. Building is becoming an increasingly complicated system with the help of endurable materials, lighting technology, air condition technique, prefabricated building components and so on (Bachman 2004). The building itself, as a total system, is made up of different layers and hierarchies of subsystems which can finally come to all the components (Figure 6). In order to effectively design this building system, the systematic thought of architectural design is badly

Figure 5. Uncertainties define architectural design stages.

Figure 6. The systematic attributes of buildings.
needed in the design process. Barriers among different fields and disciplines, one of the evil consequences in the age of specialization, are supposed to be torn down and architects are obliged to embrace both artistic design and technologies like simulation.

Finally, the move of integrating energy simulation into early architectural design stage leads to the integrative design method in which architectural design, acting as the total system, and energy simulation, one of the subsystems, should be bound together. In other words, with the development of the design, energy simulation also steps further with more complex calculation and more accurate results (Figure 7). This means energy simulation ought to take into consideration the characteristics of the early design stage and offer architects informative and constructive feedbacks that can be directly utilized in design optimization.

3. Methodology and difficulties of the integration

3.1. Methodology and design workflow

The integrative architectural design method based on energy simulation at the early stage enjoys the framework of an integrative design, follows the characteristics of early design stage and tries to guide the architects at the beginning of the design. In order to explicitly express the fundamental core of the design method, the phasing feature of early design stage is used to define the design steps and the method is mainly made up of two procedures: a forward design process with consideration of uncertainties in divergent and convergent phase and then an opposite design process in the deepening phase. The former estimates, examines and compares the possibility distribution of each design scheme with an uncertain value range of each design parameter before the latter optimizes the energy consumption of the design with the final outcome of certain value of the parameters.

The design workflow, as a result, can be mapped out in accordance with the phasing feature of early design stage. Before everything begins, the parameters that have a great impact on the energy consumption of the design should be selected with their value range. The value range and possibility of parameters are supposed to be set according to design codes and standards, research findings or design experience while the selection process can be carried out with sensitivity analysis.

In the divergent phase, architects are free to generate different design concepts by introducing thermodynamics or energy flows to the design in terms of building site layout, massing, envelope, HVAC system and usage schedules. In the convergent phase, the design scheme that meets most of the requirements is selected by comparing the energy consumption results of each of the schemes. As most of the design parameters, especially the ones nailed down in the first step, are uncertain in the early design stage, they can be described by different forms of possibility distribution in their value ranges (Figure 8). This leads to uncertain energy consumption results after simulation (Figure 9). There can exist various scenarios when comparing different design schemes, which can provide the architect with comprehensive feedbacks that is more valuable than certain energy consumption numbers alone (Figure 10).

In the deepening phase, a goal on energy consumption of the project is made, which can be referred to requirements of the stakeholders, local or regional building codes, or even a simple attempt to decrease the energy consumption of the building. Since the act of reducing energy consumption may need some building technologies that can possibly exceed the original budget, the upper limit of the cost can be set to avoid this circumstance. In addition, there is a great chance that several feedbacks may arise with a different selections of all the parameters, the one meeting the most requirements is obviously the best choice in the optimization (Figure 11).
3.2. Difficulties of the integration

As architects apply the integrative method in practice, there are a number of difficulties in the integration of energy simulation into architectural design. Five main obstacles are listed as follows.

(1) Ambiguity in selection of the design parameters. Choosing the appropriate parameters in each specific design task can lay a solid foundation for the subsequent energy simulation work. So high-level requirements are requested in the sensitivity analysis.
(2) Variability of the design parameter value. A good understanding of the uncertainties is strongly needed, both in the range of each parameter and in the possibility distribution. The range and distribution may vary among different schemes.

(3) Determine the value of the design parameters through optimization. This is the only opposite design that pins down the parameter values with energy consumption goals.

(4) Decision making based on optimized parameter values. As optimization is done, a large amount of design feedback may turn up, according to which architects are supposed to evolve the design in order to lower the energy consumption with a limited budget.

(5) Guide the architectural design practice with proper decisions after the optimization, which will finally be implemented in actual design and embodied with building components in the early design stage.

4. Case study with the example of Student Recreation Center of Tongji University based on energy simulation tool EPC

The case study of Student Recreation Center of Tongji University is presented to show how this integrative design framework works in practice.

4.1. Introduction of EPC

EPC, abbreviation for Energy Performance Calculator, is a simplified-resolution energy simulation tool based on Microsoft Office Excel. There are totally eight tab pages in EPC (Figure 12) in which architects only need to load the right weather file in “Climate” tab and fill in the boxes in “Input” tab. There are several main categories of parameters in the Input tab, including “Building General”, “Heat Capacity”, “Building System”, “Building Integrated Energy Generation System”, “Energy Source”, “Zone”, “Building Temperature Set-point Schedule”, “Envelope” and “Material” (Figure 13). After real-time simulating calculation in “Calculation” tab with the related formulas inserted inside (Figure 14), the simulation results are presented with tables and charts in the “Result” tab page (Figure 15).

EPC has many derivative tools and one of them is EPC TechOpt, which can optimize the value combination of design parameters and lead architects to a global optimal solution with the Monte Carlo method. Since no 3D models are needed to be built inside the software, the simulation process is accelerated, the Excel boxes are easy to manipulate and great possibilities are provided for uncertainties, EPC is a very suitable tool for energy simulation at the early design stage.

4.2. Sensitivity analysis of design parameters with their value ranges

Value ranges of all considered parameters are set according to design codes and standards, research findings or design experience. For example, the range of window-wall ratios are set with the reference of “Design Standard for Energy Efficiency in Public Buildings” (DGJ 08-17-2015, Shanghai Housing and Urban-Rural Development Management Committee 2015). Sensitivity analysis is made with the parameter value ranges and climate data of Shanghai to clarify the importance hierarchy of the parameters in terms of their influence on energy consumption, which can be reflected by the total change of building energy consumption and its changing rate. In other words, the higher importance hierarchy a parameter stands, the
Figure 12. Eight Excel Tab Pages of EPC.

Figure 13. Main categories of parameters in input tab.

Figure 14. Calculation tab of EPC.
larger and faster change of building energy consumption can be influenced. A tornado graph can be drawn and some parameters lacking significance can be ruled out in the integrative design so that architects can focus more on the parameters with the highest priority (Figure 16).

4.3. Integrative design in the divergent phase

With the help of environmental analysis together with preliminary design of building site, massing, envelope, equipment and schedule, two main design concepts with four sub-concepts are provided by architect, which are “Conglomeration”, “Honey comb”, “Thermodynamic chimney” and “Vertical courtyards”, respectively (Figure 17).

4.4. Integrative design in convergent phase

With the possibility distribution of each parameter in their ranges, as Figure 18 shows the example of A-1 scheme “Conglomeration”, the energy simulation results of the four schemes can be calculated by EPC with @Risk (Figure 19). The selection of possibility distribution of the parameters relies on the reference of similar architectural design, architect’s experience and the design features of different schemes, which means that the distributions differs in various design schemes. In addition, other design inputs, such as building occupancy, building temperature set-point schedule in different time and seasons are also considered in the simulation. The Monte Carlo method is used here where the values of each parameter are randomly picked in accordance with their possibility distribution 5,000 times to complete the simulation result graph. This is a forward design process meaning that the parameters are given, though they are uncertain with possibility distribution, and the energy simulation result is the final outcome (Equation 1).

\[
x : (x_1, x_2, x_3, \ldots, x_n) \rightarrow y \tag{1}
\]

In which:
- \(x\): design parameters
- \(y\): building energy simulation

We can see that B-1 scheme is most likely to enjoy the lowest energy consumption. Taking into consideration the requirements of stakeholders, total budget, complexity of construction, land conservation, campus overall scene and many other factors along with energy consumption, the B-1 scheme is finally chosen in convergent phase as the best design solution.

4.5. Integrative design in deepening phase

According to the energy efficiency code in Shanghai, the energy consumption of the reference building in this case is simulated through EPC, which turns out to stand at about 80% in the simulation result distribution range, meaning that nearly 4,000 simulation results are better than it. The architect then makes an ambitious energy consumption goal, 105.0 kWh/m²/yr, standing at about the 25% spot (Figure 20). Now the question turns into finding the parameter value combinations of the energy consumption goal, which is an opposite design process (Equation 2).

\[
y \rightarrow x : (x_1, x_2, x_3, \ldots, x_n) \tag{2}
\]

In which:
To make things easier, some most likely values are carefully assigned for each parameter so that EPC TechOpt can use the Monte Carlo method again to find the combinations to achieve the goal. There could be several different combinations available with various costs. So after taking the budget into consideration by adding constraints to the Excel Solver, the combination with lowest cost is obtained, which is the optimized goal-achieving solution (Figure 21).

The next step in integrative design is to incorporate the optimized parameter combination into the design in the deepening phase. For instance, 45-degree shading fins are suggested so the architect designs a prototype of shading system based on the optimized result – the fins can grow on every side on the façade with a sort of autonomy on its own, making itself one of the design highlights and making the building unique (Figure 22). It not only helps meet the energy consumption requirements, but also gives architects opportunities to improve the design in return (Figure 23).

### 4.6. Conclusion of case study

In the early design stage of Student Recreation Center of Tongji University in Shanghai, the integrative design method is applied and the whole design process is shown, including parameter value range setting, sensitivity analysis of the parameters, concept design in divergent phase, possibility distribution of parameters and comparison of energy simulation results in convergent phase, and finally, optimization of architectural design in the deepening phase. In this process, several key steps are discussed in the following conclusions.
Figure 17. Architect’s sketches and simplified models of the four design schemes in the divergent phase.

Figure 18. Probability distribution of each parameter in A-1 scheme.

Figure 19. Energy simulation results of the four design schemes.
(a) The process can be clearly described by two formulas in the study, with a forward one and an opposite. Both the design parameters and simulation results are uncertain in the former formula, which aims to simulate the building energy consumption range and distribution. In contrast, the design parameters become certain with the energy consumption goal set in the opposite formula, which gives architects challenges and opportunities to improve the design.

(b) The sensitivity analysis is the foundation of the whole process. Whether parameters with high relative impact can be chosen, to some extent, determines the reliability of integrative design method.

(c) A good choice of possibility distribution of the parameters is also very important since it influences the energy simulation results, comparison
among schemes and so on. Architects are highly responsible for it.

(d) The final optimization simulation result with EPC TechOpt in the case study shows a high relevance with the climate in Shanghai, which is categorized into “hot summer and cold winter region” in China. The window U values can be lower but the limited budget does not allow further improvements. As a result, the 45-degree shading fins is a trade-off with consideration of the budget. This is also another crucial aspect in the optimization of design in deepening phase.

5. Conclusion

This paper talks about integrating energy simulation into the early design stage and goes on to discuss the integrative method and the way of implementing this method in practical architectural design. The author starts the paper with characteristics of early design stage and its relation with building energy simulation. Then, the integrative method is put forward together with the difficulties in the integration. The application of this method is presented in a practical project in Shanghai with an example simulation tool, EPC.

Though there might be some shortcomings of both the integrative method and the simulation tool EPC discussed in this paper, hopefully they can be improved in the future together with performance visualization in simulation results and more human comfort in design.

Disclosure statement

No potential conflict of interest was reported by the authors.

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