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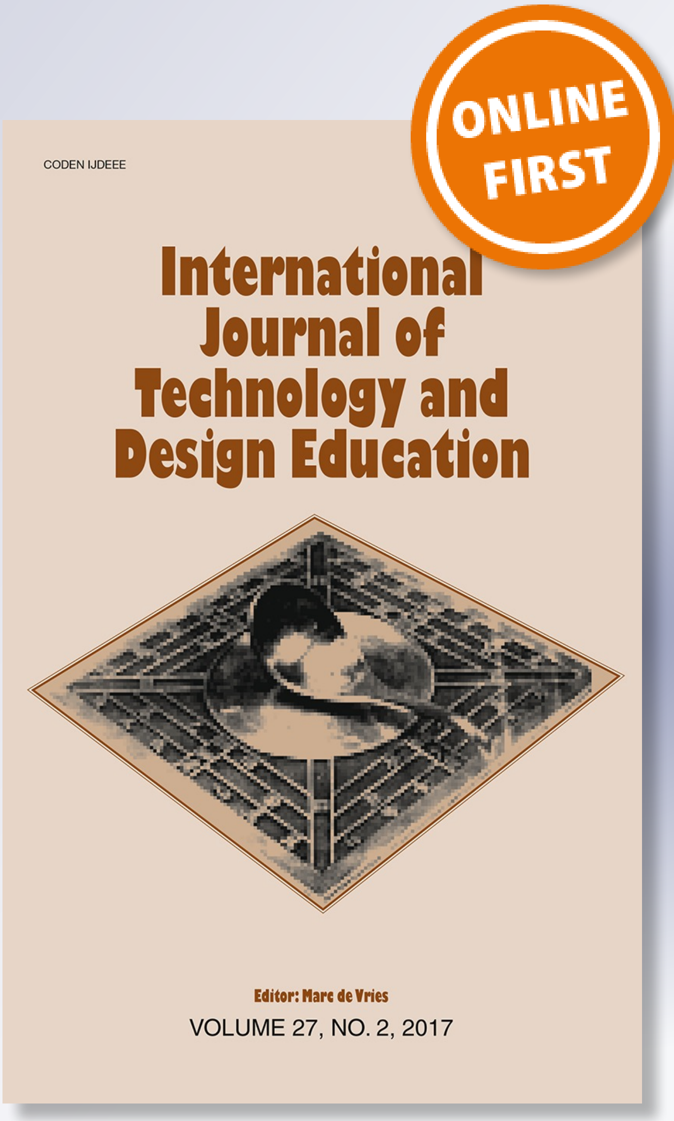

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Are their designs iterative or fixated? Investigating design patterns from student digital footprints in computer-aided design software

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Abstract This paper investigates iteration and fixation in design by mining digital footprints left by designers. High school students used computer-aided design software to create buildings in an urban area, with the goal of applying passive solar design techniques to ensure optimal solar gains of the buildings throughout a year. Students were required to complete three different designs. Fine-grained data including design actions, intermediate artifacts, and reflection notes were logged. Computational analytics programs were developed to mine the logs through three indicators: (a) frequency of the action of using energy analysis tools; (b) solar performance of the final designs; and (c) difference in solar performance between the prototype and final designs. Triangulating results from the indicators suggests three types of iteration—efficacious, inadequate and ineffective. Over half of the participants were detected as being efficacious iterative during the first design and becoming more and more fixated toward the end of the project, which resonates with previous findings on fixation effect among college students and professional designers. Overall the results demonstrate the power of applying computational analytics to investigate complex design processes. Findings from this work shed light on how to quantitatively assess and research student performance and processes during design projects.

Keywords Design fixation · Iterative design · Computer-aided design · Computational analytics · Design patterns

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Introduction

Design projects have been increasingly implemented in secondary schools because they are motivating and effective in promoting student learning of the underlying science and mathematics concepts (e.g., Ferreira and Trudel 2012; Fortus et al. 2004; Kolodner et al. 2003; Sadler et al. 2000). Little research, however, has been conducted to study how design and learning take place during these projects (Brophy et al. 2008). This paper aims to fill in this gap by investigating two common processes students undergo during design: iteration and fixation. Iteration refers to the cognitive processes designers are engaged in when revising elements of existing designs to achieve design goals. Fixation refers to the cognitive processes when designers do not make changes that would alter the designs to meet design requirements. Iteration has been proven to promote innovation and success in design (Atman et al. 2005), whereas fixation limits designers' creativity and leads to repetition in design (Purcell and Gero 1996; Smith and Tjandra 1998).

This study investigated iteration and fixation student experienced during a computer-aided design (CAD) project. Ninth graders used Energy3D, a CAD software, to design a cluster of buildings in a metropolitan area. They were required to complete three different designs to meet the same design goals—constructing at least two high-rise and two low-rise buildings; and the high buildings should have optimal solar gains throughout a year by achieving similar solar performance on December 31st and June 30th. Figure 1 shows the screenshots of the design template and a sample design. Energy3D automatically logs designers' actions and intermediate artifacts once every 2 s. We focused on the following research questions in this paper:

- Did students become more iterative or fixated as they proceeded in the solar urban planning project?
- Did students' iteration/fixation design patterns change from Design 1 to 3 during the solar urban planning project?

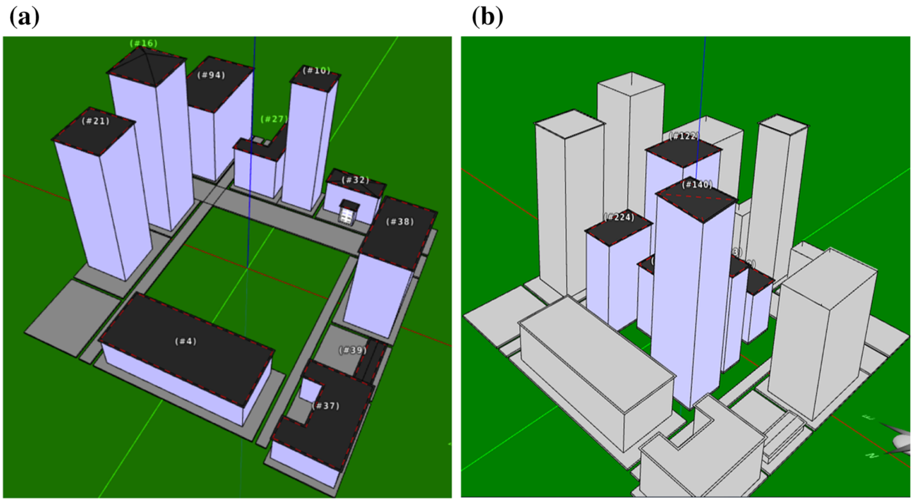

Fig. 1 **a** The solar urban planning project template. Students need to build at least two high-rise buildings and two low-rise buildings for commercial and residential uses. **b** A design completed by a student that includes six buildings (two high-rise, two mid-rise, and two-low-rise buildings)

We analyzed the computer logs of design behaviors and artifacts to answer these questions. Informed by constructionism (Kafai and Resnick 1996; Papert 1980, 1993), we view learning during design as a result of the dynamic interplay among learners, computer software, and intermediate artifacts created by the learner (Xie et al. 2014a, b). By analyzing the actions students performed in Energy3D and comparing the properties of the intermediate and final designs students completed, we can infer students' internal processes. Based on the design requirements and classroom observations of students working on the project, three iteration/fixation indicators were developed: (a) frequency of the action of performing energy analysis, a key action that is associated with subsequent changes in the solar performance of the design, (b) solar performance of their final designs, and (c) difference in the solar performance between prototype and final designs. Median split was performed for the first and second indicators to distinguish between iterative or fixated designers. With regard to the third indicator, different values suggested different internal processes: zero indicated fixation whereas a negative or positive value indicated iteration with varying degree of success. Results from the three indicators were triangulated to reveal more accurate information about the complex design processes.

Rationale and literature review

Iteration in design

Linear problem solving strategy typically is insufficient for solving design problems due to their open-endedness and ill-defined structure (Jonassen 1997; Sinnott 1989). Iterative design, which involves designers in constantly evaluating and revising the design artifacts to better meet the design requirement, is integral to successful design (Crismond and Adams 2012; Kline 1985; Pahl and Beitz 1988; Smith and Tjandra 1998). During iteration, designers are intuitively engaged in cycles of "gathering information, processing that information, identifying possible design revisions, and executing those revisions in pursuit of a goal" (Adams 2001, p. 2). New constraints and contradictions are uncovered during the cycles, leading to an improved problem scoping and new and often better design solutions (Braha and Maimon 1997; Dym et al. 2005; Hybs and Gero 1992; Vincenti 1990). Such a process promotes innovation in design. In analyzing the cognitive process of a practicing architect in a design session, Suwa et al. (2000) found almost half of the architect's design process consisted of bi-directional relations between unexpected discoveries and invention of issues or requirements. Compared to novices, expert designers were observed to more frequently revisit and revise their designs, consider more alternative solutions, and produce more innovative design solutions (Adams et al. 2003; Atman et al. 1999, 2005; Dorst and Cross 2001; Suwa et al. 2000).

Various factors can trigger iteration, including self-monitoring activities, the aim of seeking better solutions, and a greater awareness of iteration strategies and processes (Adams 2001). In this study students were prompted to iterate their designs through two tools built in Energy3D:

(1) The heliodon simulator (Fig. 2a), which shows the solar path at different times or in different seasons at different locations on the Earth. Students can use the simulator to observe how sunlight shines into a building as the Sun moves across the sky.
(2) The solar radiation simulator (Fig. 2b), which shows the distribution of solar radiation received by a building over its surface. Blue in the heat map represents a low solar radiation and red represents a high solar radiation. It also shows the number of solar energy (in kWh) received by a building on any day.

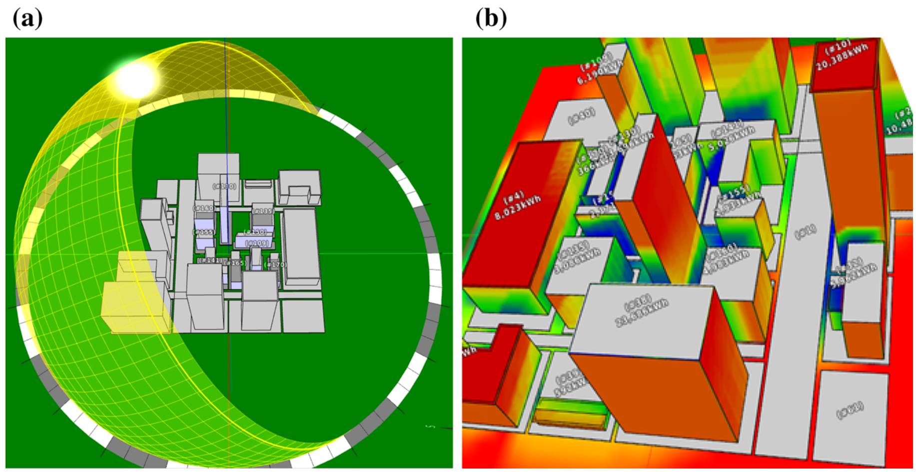

Fig. 2 **a** The heliodon simulator shows the sun path at the given location and at a given time, **b** the solar radiation simulator shows the heat map of daily solar radiation on the surfaces of buildings

These simulators are the only tools offered by Energy3D to provide real-time data about the solar performance of a building. Students are expected to use these tools frequently to examine their designs and evaluate whether the designs meet the design requirement of achieving similar solar performance on December 31st and June 30th. Considering the complexity involved in the design task (e.g., shapes, locations of the buildings, shadowing of the existing construction), it is almost impossible for a student to complete a successful design without using these simulators at least once. Previous implementations of the solar urban planning project show that all students used these tools multiple times (Xie et al. 2014b). Running energy analysis can inform students the solar performance of their current design and encourage them to make further design and revision decisions. It is highly possible that students who perform more times of energy analysis tend to revise the existing design more frequently.

Fixation in design

Fixation in design also has been frequently documented in researchers' notes and anecdotal accounts (Chrysikou and Weisberg 2005; Marsh et al. 1999; Perttula and Sipilä 2007). In a study that involved showing pictures of potential design solutions to designers before they started designing, Jansson and Smith (1991) noted that these designers were less likely to invent novel solutions than those who were not shown the pictures. Similar phenomena were observed even when the participants were explicitly instructed to not use features from the pictures. Other research confirms the occurrence of fixation among designers of other disciplines, especially when they were presented with information from similar design solutions before their own design work started (Tseng et al. 2008).

Fixation has been commonly associated with negative impact on design as it limits creativity and results in repetition in design (Chrysikou and Weisberg 2005; Marsh et al. 1999; Perttula and Sipilä 2007). When fixataion occurs, designers are subconsciously attached to certain aspects of the design and could not "think out of the box," which results in failure in innovation. One reason is that the design solutions presented to the designers blocked their access to the conceptual space, where innovative ideas germinate. As a result designers became fixated and were not able to come up with novel solutions (Jansson and Smith 1991).

It is difficult to mitigate design fixation as there exist at least three types of fixation: unconscious adherence to the influence of prior designs, conscious blocks to change, and intentional resistance to new ideas (Youmans and Arciszewski 2014). A designer may experience more than one types of fixation simultaneously during design. Years of professional experience cannot diminish fixation. Even professors who research fixation effects in engineering design were found to become fixated during design, without even realizing that fixation was happening (Linsey et al. 2010).

In this article the term "fixation" refers to instances when students carry out design activities at a low creativity level (Zahner et al. 2010). We consider a designer being fixated if he is not engaged in activities that would change properties of the design artifacts relevant to the design requirements. For instance, upon the completion of a house, a student spent a substantial amount of time on viewing the house from different angles. His actions did not change the solar energy received by the house. He is considered being fixated even though he still performed activities.

Solar urban planning project

The solar urban planning project required students to construct four to eight buildings on a blank square city block (100×100 m^2) surrounded by existing buildings of different heights. Figure 1a shows a snapshot of the design template. Students needed to generate three different design solutions to meet the same design goals:

(a) New construction needs to include at least two high-rise (over 60 m tall) buildings (e.g., an apartment building and an office building) and at least two low-rise (<20 m tall) buildings (e.g., a convenient store or gym).
(b) The high-rise buildings should be designed to receive similar amount of solar energy on December 31st (to lower the heating costs in the winter) and June 30th (to lower the cooling costs in the summer).

Considering that buildings receive much more solar energy in the summer than in the winter, students were instructed to create buildings so that they receive as much solar energy on December 31st as possible and as less solar energy on June 30th as possible.

At least three factors need to be considered to complete a successful design: (a) the shadowing among the new construction and the existing buildings, (b) the shadowing of one new building on other new construction, and (c) seasonal differences in the solar energy on the surface of the new construction between summer and winter. Students must take these factors into account and make trade-off decisions among multiple competing variables.

Students can use the energy analysis tools to analyze the solar performance of the design and identify gaps between their designs and design goals. Small changes in students' designs can lead to dramatic changes in the solar performance, which prompts students to revise their designs accordingly. The project forced students to consider alternative solutions by requiring them to complete three different designs. These efforts endeavor to reduce the occurrences of fixation that are commonly found in using CAD tools in classrooms (Brown 2009; Ibrahim and Pour Rahimian 2010; Robertson and Radcliffe 2009).

Method

Participants

Seventy-seven high school students (9th graders) from five physics classes (class C, D, E, F, and G) in a public school in the northeastern area of the United States participated in this study. The school has an enrollment of around 1300 students, 19% of which are minority students and 12% of which are eligible for free or reduced-price lunch program. None of the participants had any architecture design or city planning experience. Students learned solar energy and energy transfer in the physics class. The teacher (Mr. B) was an experienced high school physics teacher who had been teaching in the same school for over 20 years. Mr. B had worked as an engineer for 12 years before becoming a physics teacher.

Students used laptop computers to run Energy3D and worked individually on the solar urban planning project for seven instructional periods (50 min per period). All students completed three different designs of the city block (231 completed designs in total). On the first day of this implementation, one of the authors held a 10-min demonstration of Energy3D to all participants, which introduced how to use energy analysis tools to analyze the solar performance of the buildings. He also elaborated the second design goal by instructing students to design high-rise buildings so that they receive as much solar energy on December 31st as possible and as less solar energy on June 30th as possible. For the rest of the implementation, the authors were in the classroom to provide technical support to students, e.g., helping students save and retrieve designs, and troubleshooting when their computer screens froze.

Data collection

Student process data were collected through unobtrusive computer logging, that is, students' entire learning processes were captured without being noticed by them (Baker and Clarke-Midura 2013; Feng et al. 2009; Shute and Ventura 2013). Energy3D automatically logs students' actions once every 2 s (if an action has occurred) and their intermediate artifacts and reflective notes once every 20 s if there is any change to the previous artifact. Table 1 summarizes the actions students could perform using Energy3D. An artifact log folder typically contains 300–500 intermediate files and the action log file typically contains 3000–5000 lines of data. The intermediate files include snapshots of the design artifacts, students' reflective notes, the seasons, time, dates set in the design, and other parameters such as solar energy received by the new construction. The logged action data include the timestamps, types, targets, and parameters of the actions (see Fig. 3 for an example of the logged action data).

Data analysis

Java programs were written to automatically analyze computer log files, including calculating the frequency of different design behaviors and the properties of intermediate design artifacts. As a first step, the programs calculated the time students spent on each design to capture a general idea of how students proceeded during the project.

Next, two phases of analysis were carried out to answer the research question: (1) analyzing whether a student performed iterative design or experienced fixation during each

Table 1 Actions logged in Energy3D

Action classes	Examples
Add/remove an element (wall, foundation, roof, door, window)	"Add Foundation": {"Type": "Foundation","Building": 113, "ID": 113, "Coordinates": [{"x": 45, "y": −35, "z": 0}, {"x": 45, "y": 0, "z": 0}, {"x": 0, "y": -35, "z": 0}, {"x": 0, "y": 0, "z": 0}, {"x": 45, "y": -35, "z": 1}, {"x": 45, "y": 0, "z": 1}, {"x": 0, "y": −35, "z": 1}, {"x": 0, "y": 0, "z": 1}]}}
Revise an element (edit, move, resize)	"Move Building": {"Type": "Foundation","Building": 115, "ID": 115, "Coordinates": [{"x": 40.626, "y": 28.856, "z": 0}, {"x": 40.626, "y": 3.856, "z": 0}, {"x": 5.626, "y": 28.856, "z": 0}, {"x": 5.626, "y": 3.856, "z": 0}, {"x": 40.626, "y": 28.856, "z": 1}, {"x": 40.626, "y": 3.856, "z": 1}, {"x": 5.626, "y": 28.856, "z": 1}, {"x": 5.626, "y": 3.856, "z": 1}]}}
Analyze solar performance (using the helidon, solar radiation simulators)	"Compute Energy": true "SolarEnergy": [{"#4": 4987.45}, {"#10″: 11,631.73}, {"#21″: 11,281.82}, {"#27″: 7648.16}, {"#37″: 4804.12}, {"#38″: 12,844.37}, {"#39″: 475.51}, {"#94″: 18,885.67}, {"#113″: 18,792.68}, {"#114″: 20,829.91}, {"#121″: 3298}, {"#130″: 2320.62}]}
Set a value (date, time)	"Change Date": "10/30″
Observe surroundings	"Camera": {"Position": {"x": −238.965, "y": 88.192, "z": 319.885}, "Direction": {"x": 0.59, "y": −0.215, "z": −0.778}}}
Write a note	"Note": "I(313, y)I(314, e)I(315, s)"


```
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Fig. 3 Example of the logged action data

design using the three indicators; and (2) tracking changes in iteration/fixation patterns from Design 1 to 3 for each student to identify the design pathways.

Detecting iteration/fixation patterns with three indicators

Indicator 1: frequency of using energy analysis tools The solar urban planning project required designers to iterate the designs for optimal solar performance of the buildings.

Naturally the first step of iteration is to understand the solar performance of the current design. Using tools to conduct solar energy analysis typically signifies the start of a cycle of iteration. Then the designers can decide how to revise the designs based on results of the analysis. Results from our previous implementation of the project confirmed that all students adjusted their designs after running energy analysis (Xie et al. 2014b). The more frequently a designer uses energy analysis tools, the higher chances that he has performed multiple cycles of iteration.

Java programs automatically counted how many times students used these tools. Median split was performed to identify students who frequently used the tools (iterative designers) and those who seldom used these tools (fixated designers).

Indicator 2: solar performances of the final designs Quality of students' designs reveals direct evidence about whether a design satisfies the requirements. Given the complexity of the design challenge, it is unimaginable for any designers to complete a successful design in just one trial. A successful design probably has gone through cycles of iterations because iterations, which engage designers in goal-directed processes of gathering and filtering new information, can inform the analysis, synthesis, and evaluation of possible solutions (Dym 1994; Adams and Atman 1999). In the solar urban design project, the success of a design was determined by the difference of average daily solar energy density of high-rise buildings in the summer and winter. The average daily solar energy density (ρ) was calculated using the following formula:

$$\rho = \frac{1}{N}\sum_{i=1}^{N}\frac{E(i)}{V(i)}$$

where N is the total number of new construction in the city block, $E(i)$ is the total solar energy radiated on all the surfaces but the roof of the i th building and $V(i)$ is its volume.

Typically, ρ is low in the winter and high in the summer. To achieve optimal energy efficiency, the buildings need to be designed to receive maximal daily sunlight in the winter (on December 31) and minimal daily sunlight in the summer (on June 30). Hence, the difference between ρ in the winter and in the summer ($\Delta\rho$) should be closer to zero in a good design than in a poor one. Normally $\Delta\rho$s are positive because ρ in the winter is smaller than that in the summer. The smaller $\Delta\rho$ is, the better the design is, and the more likely the designer has performed iteration.

$$\Delta\rho = \rho_{\text{summer}} - \rho_{\text{winter}}$$

Java programs were developed to automatically calculate the average $\Delta\rho$s of the designs students created. Median split differentiated students whose final designs had low or high $\Delta\rho$s. A design with a low $\Delta\rho$ indicates that the designer has performed multiple cycles of iteration during design.

Indicator 3: difference in solar performance between prototype and final designs We defined prototype design as the intermediate design when students performed the first energy analysis after fulfilling the minimum construction requirement, i.e., constructing at least two high-rise and two low-rise buildings. Calculating the difference in $\Delta\rho$s between the prototype and final designs can reflect the impact of changes students made. The difference in $\Delta\rho$s was calculated using the following formula:

$$\Delta c = \Delta \rho_{\text{prototype}} - \Delta \rho_{\text{final}}$$

The value of Δc suggested different design processes:

1. $\Delta c = 0$: suggesting fixation in design. Considering the sensitivity of the energy analysis tools, small changes to the design would cause fluctuations in the solar performance in Energy3D. A Δc equal to zero suggested no difference in the solar performance between the prototype and final designs. The designer may perform minor adjustments such as planting trees in a remote blank area, yet such adjustments did not affect the solar performance of the designs.
2. $\Delta c > 0$: suggesting efficacious iteration. A positive Δc meaned that the $\Delta \rho$ of the final design was smaller than that of the prototype design. The solar performance of the final design was better than that of the prototype. The designer must have performed successful iteration to optimize the energy efficiency of the buildings throughout a year.
3. $\Delta c < 0$: suggesting ineffective iteration. A negative Δc indicated that the final construction was less energy efficient than the prototype. The solar performance of the design deteriorated after iteration. Students have performed iteration that was ineffective in optimizing the solar gains of the houses.

Each indicator can detect iteration and fixation from one single lens. Sometimes the conclusions drawn from the indicators may conflict with each other. For instance, a student may have performed lots of energy analyses but generated a design with poor solar performance. Triangulation therefore became necessary because it involves supporting claims based on data from multiple sources (Adams et al. 2002; Davies 2011; Mathison 1988; Pellegrino et al. 2001). We triangulated results from the three indicators to not only validate conclusions from one data source alone but also reveal more information about various design patterns students underwent. The triangulation suggested four patterns during design: a) fixation, b) ineffective iteration, c) inadequate iteration, and d) efficacious iteration. Details of the characteristics of each pattern will be discussed in the Results and discussion section.

Tracking changes in iteration/fixation patterns from Design 1 to Design 3

We first calculated and compared the percentages of students with the iteration/fixation patterns during Design 1, 2 and 3. Then we tracked how each individual student's patterns changed from Design 1 to Design 3. The results suggested multiple design pathways students underwent during the solar urban planning project. More details will be discussed in the Results and discussion section.

Results and discussion

Duration of the designs

Students on average spent 15,115 s on the solar urban planning project (approximately 252 min, SD = 2110 s). The computer logs show that students were enthusiastic about the project and some students continued working on it after school hours.

Students spent significantly less time on latter designs than on the first design [$\chi^2(2) = 99.004$, $p = 0.001$]. On average students worked on Design 1 for 117 min, Design 2 for 77 min, and Design 3 for 58 min. One reason for the decreasing time spent on the designs was that students did not spend as much time on problem scoping in Design 2 and 3 as they did in Design 1. Computer logs showed that all students spent at least 5 min on problem scoping in Design 1, e.g., using the camera tool to view the design template and existing buildings from various angles before making any construction. Fewer students in Design 2 and none in Design 3 carried out such actions as they became more familiar with the design challenge and constraints.

Detecting fixation and iteration with indicators

Indicator 1: frequency of using energy analysis tools

All students used the energy analysis tools multiple times ($M = 18$, SD = 16) during design. A median split was conducted: students who performed more than 14 analyses were considered as iterative designers and those who used the tools less than 14 times were viewed as being fixated at certain degree.

A closer look revealed that students performed fewer energy analyses as they proceeded during the project (see Table 2). Statistically significant difference was found in the frequency of using analysis tools during the three designs, $\chi^2(2) = 53.699$, $p = 0.0001$. Over 75% of the participants were identified as being iterative during Design 1, whereas only 27.3% were iterative during Design 3. Nearly three-quarters of the students became fixated at the end of the project. Figure 4 presents the distribution of iterative and fixated designers during each design.

As an example, student F06 used the energy analysis tools 38 times during Design 1, 18 times during Design 2, and 5 times during Design 3. He was iterative during the first two designs and became fixated during Design 3. F06 may have acquired information on where to position buildings for optimal solar gains throughout a year during Design 1 and 2. The new knowledge, however, became an obstacle and blocked him from exploring new ideas in Design 3. By contrast, student C07 conducted more energy analyses in Design 3 (31 times) than in Design 2 (12 times). Figure 5 shows the frequency of analyzing the solar performance of the designs by C07 and F06. C07 became somewhat fixated while working on Design 2, yet was able to overcome the fixation effect in Design 3.

Indicator 2: solar performance of the final design

We calculated the difference ($\Delta\rho$) between average daily solar energy density (ρ) in the winter and in the summer. As noted earlier, a low $\Delta\rho$ indicated that the design was successful and had undergone multiple cycles of iteration, whereas a high $\Delta\rho$ suggested

Table 2 Average frequency of using analysis tools during Design 1, 2, and 3

	Design 1	Design 2	Design 3
Mean	28	16	10
SD	19	12	8

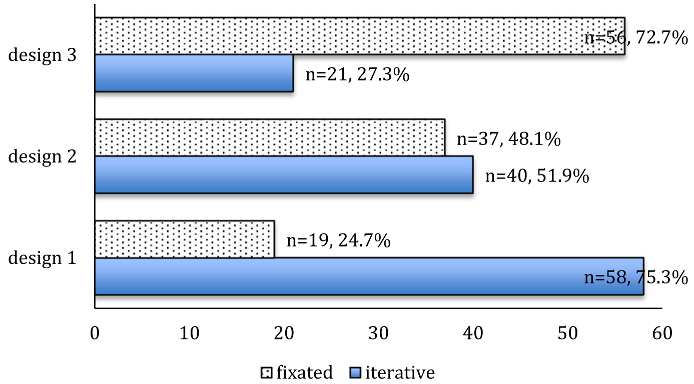


Fig. 4 Distribution of iterative and fixated designers in Design 1, 2, and 3 as detected by the frequency of performing energy analysis (indicator 1)

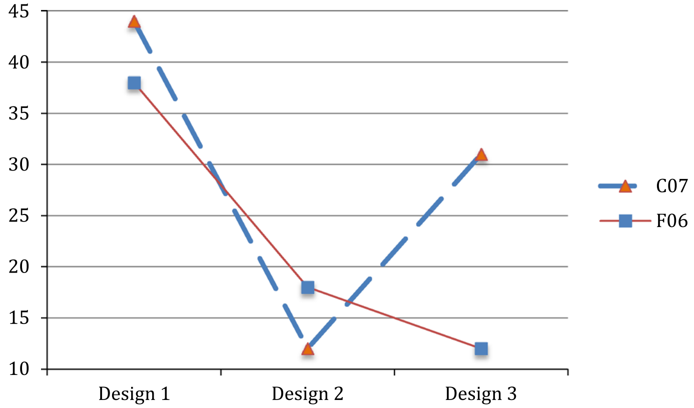


Fig. 5 Frequency of solar performance analysis C07 and F06 performed during Design 1, 2, and 3

fixation in design. The $\Delta\rho$ of the completed designs ranged from 0.08 to 1.28 kW h/m^3 with a median value of 0.22 kW h/m^3. Designs with $\Delta\rho$s lower than 0.22 kW h/m^3 probably have gone through several cycles of iteration whereas those with $\Delta\rho$s higher than 0.22 kW h/m^3 may be fixated.

For instance, student F20's design had a $\Delta\rho$ as low as 0.09 kWh/m^3 (see Fig. 6 for a snapshot of the design). All the high-rise apartments were built along the southern side so that they would receive maximal sunlight in the winter. The surrounding existing buildings were tall, which can provide shade and help reduce the cooling cost of the apartments in the summer. He probably has performed iterations to find the optimal locations, sizes, and orientations of the buildings.

By contrast, student F09's design (see Fig. 6) was not energy efficient ($\Delta\rho = 0.32$ kWh/m^3). The three high-rise buildings were built back-to-back in the middle of the block and the two low-rise buildings were on the northern east and northern west corners. The high-rise apartments were not energy efficient as they would cast shadows on each other, increasing the heating cost in the winter.

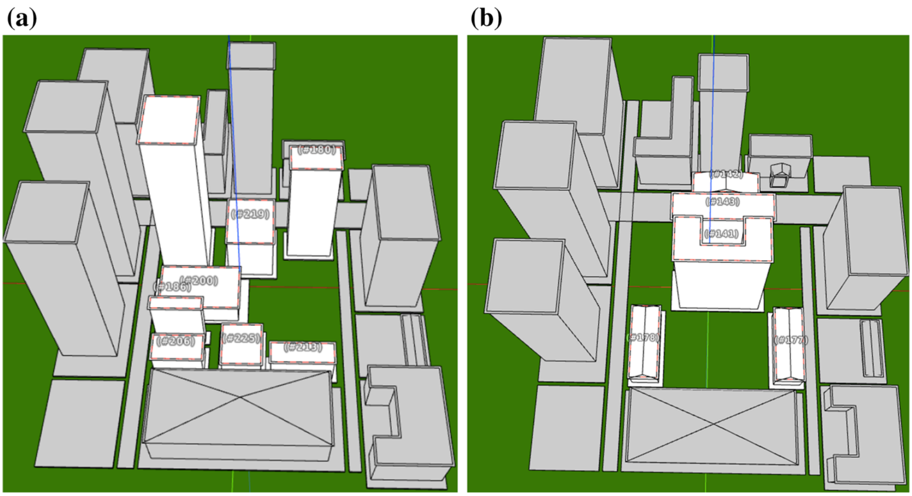


Fig. 6 *Left* student F20's design with high energy efficiency. *Right* student F09's design with low energy efficiency

More students were found to accomplish designs with low $\Delta\rho s$ as they progressed during the project. Thirty-five students (45.4%) in Design 1 and 41 students (53.2%) in Design 3 finished designs with optimal solar gains throughout a year. They may have acquired ideas and experience from Design 1 and 2 and applied them during Design 3. Figure 7 shows the distribution of iterative and fixated designers as identified by the $\Delta\rho s$ of the completed designs.

Indicator 3: difference in solar performance between prototype and final designs

In total, 61 designs (26%) had Δcs equal to zero, suggesting fixation in design. Nearly half of the designs ($n = 104$, 45%) had positive Δcs: the final designs were more energy efficient than the prototype designs. These students probably have performed multiple

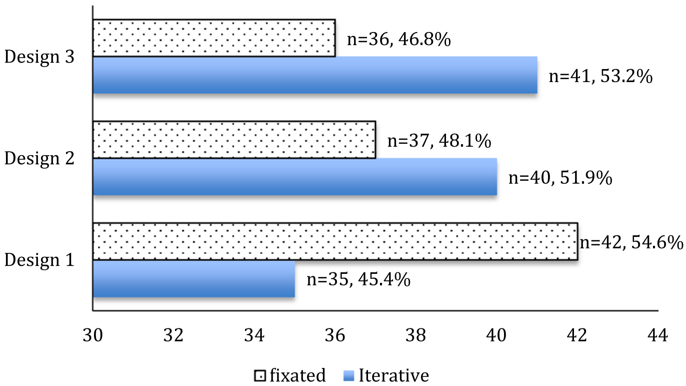


Fig. 7 Distribution of iterative and fixated designers in Design 1, 2, and 3 as detected by the solar performance of the final designs (indicator 2)

cycles of efficacious iteration during design. Sixty-six designs (29%) had negative Δcs, that is, the final designs were less energy efficient than the prototype designs. Designers may have performed iteration to revise the prototype designs, yet the iteration was ineffective or even counterproductive in improving the solar performance of the buildings. Figure 8 shows the distribution of students who performed ineffective iteration, efficacious iteration, and fixation during design.

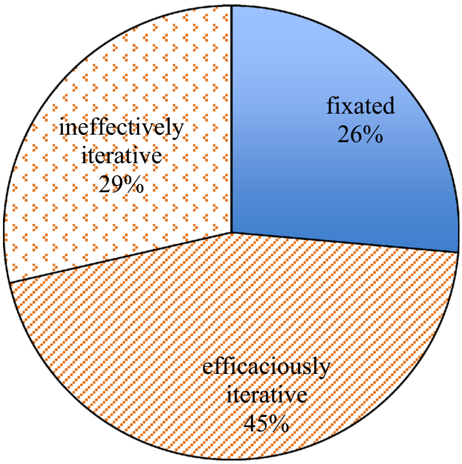
As an example, student F12 substantially improved the solar performance of his design; the $\Delta\rho$ of the design decreased from 0.46 kW h/m^3 (prototype) to 0.18 kW h/m^3 (final). The large Δc suggested multiple cycles of efficacious iteration during design. Comparing the prototype and final designs F12 completed confirmed this; F12 made substantial revisions to the prototype design, including moving the high-rise buildings to the southern side of the block, placing the low-rise buildings along the northern side of the block, enlarging the tall buildings, and increasing the density of the buildings so that the buildings can cast shadows on each other to lower the cooling cost in the summer. The iteration significantly improved the solar performance of the design. Figure 9 shows the snapshots of F12's prototype and final designs.

Another finding is that more students experienced fixation during Design 3 than during Design 1. Only ten students (13%) were fixated during Design 1, i.e., they did not perform any actions that altered the solar performance of the designs upon the completion of prototype designs. Nearly half of the students ($n = 33$, 42.86%) experienced fixation during Design 3. Figure 10 shows the distribution of students who were fixated, performed efficacious and ineffective iteration during the three designs.

Triangulating results from the three indicators

We consolidated results from the three indicators for a comprehensive understanding of the design processes students had gone through. Based on the triangulation results, students' design processes were categorized into four patterns: *efficacious iteration, inadequate iteration, ineffective iteration,* and *fixation*. Table 3 shows the characteristics of the design patterns. Figure 11 shows the distribution of students with different patterns.

Fig. 8 Distribution of students who were efficaciously iterative designers ($\Delta c > 0$), ineffectively iterative designers ($\Delta c < 0$), and fixated designers ($\Delta c = 0$) as detected by the difference in solar performance between prototype and final designs (indicator 3)



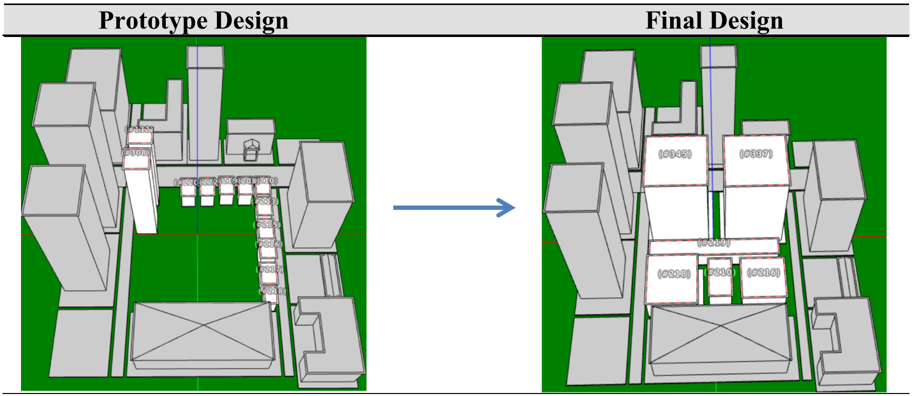


Fig. 9 Snapshots of F12's prototype and final designs

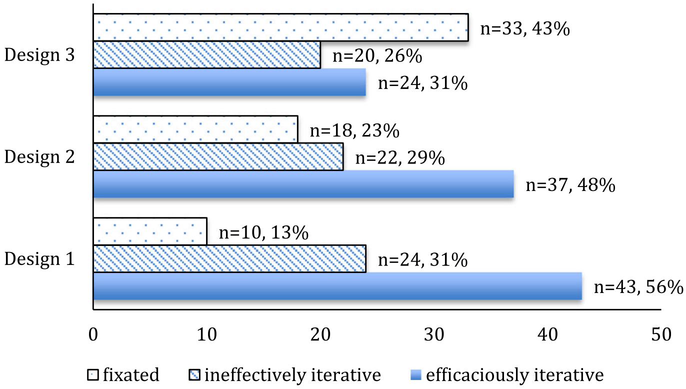


Fig. 10 Distribution of students who were fixated, performed efficacious and ineffective iteration during Design 1, 2, and 3 based on the changes in $\Delta\rho$s from prototype to final designs (indicator 3)

Efficacious iteration

These students were identified as being iterative by indicator #2 and #3, i.e., they carried out iteration that improved the solar potentials of the design ($\Delta c > 0$) and their final designs achieved optimal solar performance throughout a year ($\Delta\rho < 0.22$ kW h/m^3). Among the 231 final designs, students conducted efficacious iterations during 65 designs (28%).

Most of these students frequently used tools to perform energy analysis when revising the prototype designs ($n = 44$). Results from the analyses may have helped them make informed decisions for future revisions. The remaining 21 students seldom used the energy analysis tools yet completed designs with optimal solar performance throughout a year. Such students may have high prior knowledge and everyday experience about the solar path and urban design. The iterations they carried out succeeded in improving the solar performances of their designs.

Table 3 Categorization of design patterns as revealed by the three indicators

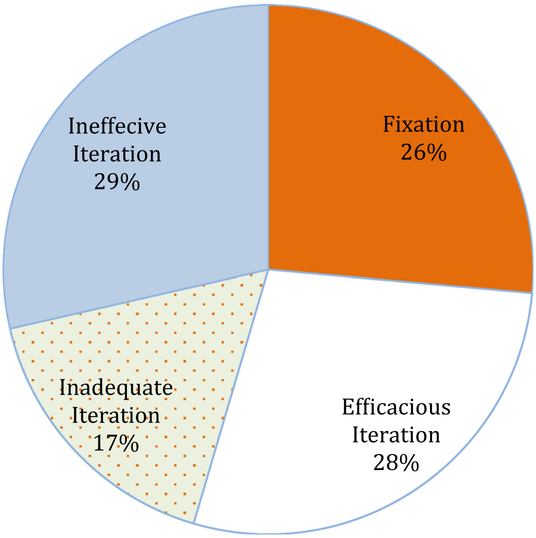
Design patterns	Indicators		
	Performing energy analysis	Solar performance of the final design	Changes in solar performance from prototype to final design
Efficacious iteration	Iterative	Iterative	Efficacious iteration
	Fixated	Iterative	Efficacious iteration
Inadequate iteration	Iterative	Fixated	Efficacious iteration
	Fixated	Fixated	Efficacious iteration
Ineffective iteration	Iterative	Fixated	Ineffective iteration
	Iterative	Iterative	Ineffective iteration
	Fixated	Fixated	Ineffective iteration
	Fixated	Iterative	Ineffective iteration
Fixation	Iterative	Iterative	Fixated
	Iterative	Fixated	Fixated
	Fixated	Iterative	Fixated
	Fixated	Fixated	Fixated

Note For the action of performing energy analysis, if the frequency is <14, the designer was viewed as being fixated. If the frequency is more than 14, the designer was viewed as being iterative

With regard to the solar performance of the final design, if the $\Delta\rho$ is greater than 0.22 kW h/m^3, the design did not meet the design goal and the designer was viewed as being fixated. If the $\Delta\rho$ is smaller than 0.22 kW h/m^3, the designer was viewed as being iterative

With regard to changes in solar performance from prototype to final design, if the change (Δc) equals to zero, there was no change made to the prototype design and the designer was fixated. If the change is positive ($\Delta c > 0$), the iteration improved the solar performance of the buildings, and the designer performed efficacious iteration. If the change is negative ($\Delta c < 0$), the solar performance of the buildings became deteriorated and the iteration were ineffective

Fig. 11 Distribution of designs that were completed with different patterns



Inadequate iteration

These students carried out iteration that improved the solar potentials of the houses (detected as being efficaciously iterative by indicator #3, $\Delta c > 0$), but their final designs did not achieve optimal solar performance throughout a year (detected as being fixated by indicator #2, $\Delta \rho > 0.22$ kW h/m^3). The iterations they carried out were not adequately effective in meeting the design goal. Altogether 39 students conducted inadequate iteration during design. They needed to consider other innovative ways to revise their designs more efficiently in order to achieve satisfactory solar performance.

Ineffective iteration

These students ($n = 66$) performed iteration that led to a decline in the solar performance of the designs (detected as being unproductively iterative by indicator #3, $\Delta c < 0$). Some of them ($n = 32$) still performed multiple energy analyses, but their interpretations of the analysis results probably were incorrect. Hence their revisions resulted in a decrease in the solar performance of the designs.

Fixation

Students who were fixated did not make any revisions that would affect the energy efficiency of the designs upon the completion of the prototype. They might make minor changes yet the Δcs of their designs were equal to zero ($\Delta c = 0$). Students were fixated during 65 designs (28%). Most of the fixation happened when students worked on the third design. Some students still performed energy analyses to evaluate the solar performance of their designs, however, the results of the analysis did not prompt them to revise the solar potentials of their designs at all.

To sum up, triangulating results from the three indicators can determine whether a students experienced fixation or performed iteration in design. The results suggest that the impact of students' iterative activities varied at the degree of efficiency and effectiveness in satisfying the design requirements. Our findings show three types of iteration: efficacious, inadequate, and ineffective. Compared with those who were fixated in design, students who performed ineffective or inadequate iteration recognized the importance of iteration and actively revised their artifacts during design. They struggled to find more efficient and effective ways to solve design problems.

Investigating design pathways during the project

To explore if students became more fixated or iterative as they proceeded in the solar urban planning project, we first tracked the changes in the percentages of students who were fixated during the three designs. Second, we examined how iteration/fixation patterns changed from Design 1 to Design 3 for each individual student and suggested multiple pathways of students went through during the solar urban planning project. Third, we presented a case student to illustrate the most popular pathway.

Percentages of fixated designers in Design 1, 2, and 3

Overall more students became fixated as they progressed in latter designs. Nearly half of the students (47%) became fixated during Design 3, whereas only 14% of the participants experienced fixation during Design 1 (see Fig. 12 for the changes in the percentages of students with various design patterns from Design 1 to Design 3).

This finding resonates with prior findings about fixation effect when designers were exposed to examples (Jansson and Smith 1991; Purcell and Gero 1996; Chrysikou and Weisberg 2005; Viswanathan and Linsey 2010). The completed Design 1 and 2 became obstacles that prevented students from coming up with alternative ideas to solve the design challenge. Meanwhile high school students, without much prior experience of design, may not appreciate the value of alternatives and open-endedness of design problems (Atman et al. 1999; Sadler et al. 2000). Students may stop seeking other possible solutions once they achieved the goals.

Design pathways from Design 1 to Design 3

Tracking how the patterns change from Design 1 to Design 3 suggested four different pathways students underwent during the solar urban planning project. Figure 13 presents the distribution of students with different design pathways during the solar urban planning project.

- *Becoming fixated during latter designs* As the most popular pathway among the participants, over half of the students ($n = 42$, 55%) became fixated during latter designs. These students performed multiple cycles of iteration in Design 1 and became stuck in Design 2 or 3. By the end of Design 3, the effect of fixation was too deep for them to overcome—they seldom made revisions to the prototype designs. Students' completed work in Design 3 typically was a repetition of their prior designs.
- *Becoming iterative during later designs* Less than 10% of the students became more iterative as they progressed during the project ($n = 7$). They were fixated or ineffectively iterative in Design 1. As they became familiar with the design constraints and the software, they were able to carry out iteration that successfully improved the designs to meet the design goals.

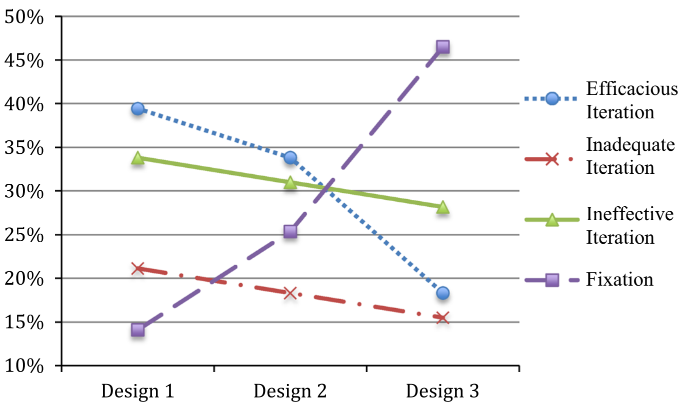


Fig. 12 Changes in the percentage of students with different design patterns during Design 1, 2 and 3

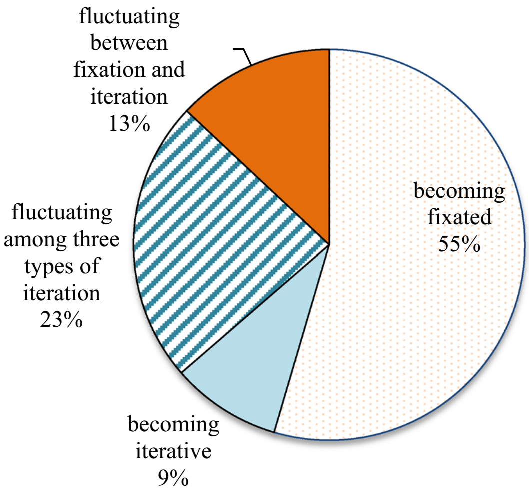


Fig. 13 Students with various design pathways during the solar urban planning project

- *Fluctuating among different types of iteration* Nearly a quarter of the students ($n = 18$, 23%) were consistently iterative during three designs. However, their iteration was efficacious during one design but not the others. These students understood the necessity and importance of iterative design, yet they struggled with solving the design challenge effectively and efficiently.
- *Fluctuating between fixation and iteration* There existed students who were fixated during Design 2 yet became iterative in Design 3 ($n = 10$). In Design 3, these students overcame fixation and experimented with new ideas.

Case study

In this section we presented student C04 to illustrate his design processes. C04 was chosen because he demonstrated the most popular pathway—becoming fixated during latter designs. This section showed how evidence from multiple sources can shed lights on students' complex design processes.

First, C04 performed much fewer energy analyses in Design 2 and 3 than in Design 1 (Design 1: 58, Design 2: 8, Design 3: 5). With the plummeting frequency of examining the solar potentials of the buildings, it is difficult to imagine C04 would solve the design challenge with novel solutions during Design 2 and 3.

Second, the $\Delta\rho$s of C04's prototype and final designs were the same during Design 3, suggesting no modifications were made that would change the solar performance of the design. In contrast, the $\Delta\rho$ declined from 0.25 kW h/m^3 (prototype) to 0.18 kW h/m^3 (final) during Design 1. C04 successfully improved the solar performance of the designs through iteration. The change in $\Delta\rho$ was 0.01 kW h/m^3 during Design 2, which indicated minor changes made to the prototype design.

Further, C04 performed fewer behaviors that would affect the solar potentials of the houses in Design 2 and 3 than in Design 1. Upon the completion of the prototype design, <10% of his actions during Design 2 and 3 would change the solar energy received by the buildings, such as changing the orientation, revising the height of the walls, and enlarging or shrinking the buildings. By contrast, 20% of his actions in Design 1 focused on revising the solar performance of the design (542 out of 2684 actions after finishing the prototype design).

Third, C04 made fewer revisions to the prototype designs in Design 3 than in Design 1. Figure 14 shows the snapshots of the prototype and final designs completed by C04. He made lots of successful revisions to the prototype design during Design 1. For instance, all the high-rise buildings were initially built along the southern side of the city block, which was energy inefficient because the high existing buildings near the southern side would cast shadows on the new construction in the winter and the heating cost would increase. In the final design, all the high buildings were relocated to the northern side, where the surrounding buildings were low and would not affect the sunlight in the winter.

During Design 2, C04 made inadequate adjustments to the prototype design. His prototype design featured a large rectangular high-rise building #112, a building elongated along the south-north axis. The building would have high heating and cooling requirements because of the small wall area that faces south. The most effective way to improve energy efficiency of the design is to revise the orientation of #112. However, C04's revisions focused on making changes to the low-rise buildings. He shortened the buildings #126 and #132 and planted a few pine trees in the southeastern corner to provide shade on the buildings. His revisions did increase the energy efficiency of the design, but were not sufficient to meet the design goal. The final design has a high $\Delta\rho$ of 0.23 kWh/m^3.

During Design 3, C04 barely made revisions that would change the solar performance of the buildings. The prototype and final designs appeared the same. Further, the final design bore a strong resemblance to the final design in Design 1; the high-rise buildings were built along the northern side of the city block and the low-rise buildings were placed next to the high-rise ones. C04 may have felt frustrated about the failure in Design 2 and became

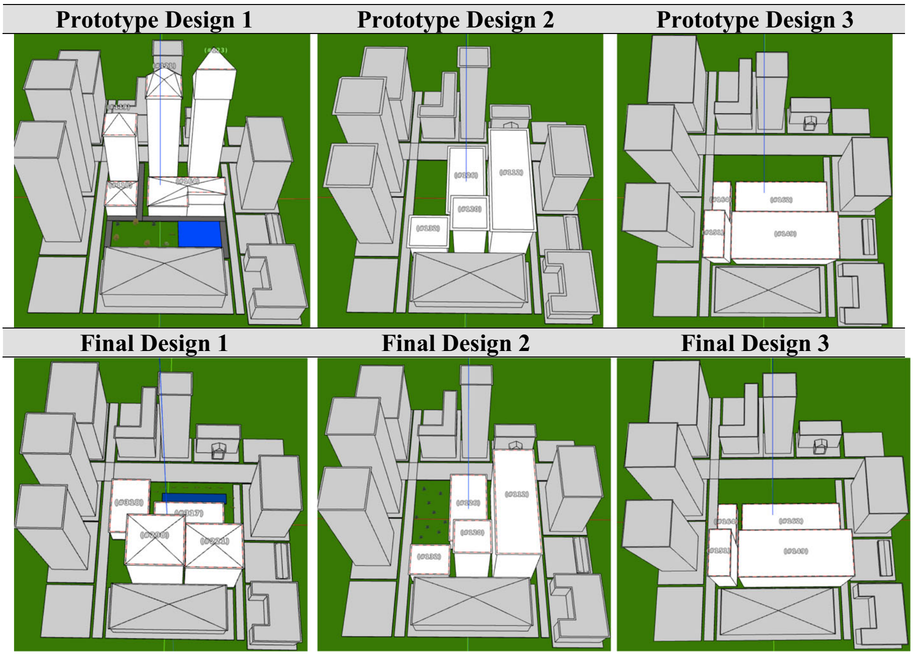


Fig. 14 Snapshots of the prototype and final designs completed by C04

reluctant to explore new design ideas. Knowing that Design 1 succeeded in meeting the design goal, he applied the same layout in Design 3.

Overall the case of C04 exemplifies how triangulating results from multiple indicators helps establish a comprehensive understanding of the design processes students went through. Over half of the students had similar experience as C04. They completed successful designs through efficacious iteration in the first design and became fixated in latter designs. Some students may have experimented with new ideas in latter designs, yet failure, which is common in design, impelled them to previous ideas. This finding resonates with previous studies on the pervasiveness of fixation among professional designers and undergraduate students majoring in engineering (e.g., Linsey et al. 2010; Sadler et al. 2000; Smith and Blankenship 1991). To support iteration, teachers need to emphasize the value of iteration in instruction (Gertzman and Kolodner 1996; Hmelo et al. 2000), so that students recognize the important role failure plays in design and be provided with more opportunities to revise designs.

Conclusions

This study investigated design processes students went through during a solar urban planning project by analyzing logs of their design behaviors and artifacts. Compared with traditional ways of analyzing qualitative data such as observations, interviews, and videotapes, our approach had more advantages: (a) unobtrusive data collection (Baker and Clarke-Midura 2013; Feng et al. 2009; Shute and Ventura 2013). Students did not notice that their design behaviors and artifacts were recorded. Their designs would not be distracted or interrupted. Researchers can work on more "authentic" data. (b) Fastened research process. Using computer algorithms to analyze students' designs can significantly reduce time spent on data analysis. The Java programs we developed can automatically calculate the frequency and duration of design behaviors and the properties of students' designs, and return the results in within seconds. The computerized data analysis can save time so that researchers can focus on interpreting the results.

Overall the finding is that over half of the high school students became fixated at the end of the project, consistent with prior research on fixation effects among professional designers (e.g., Atman et al. 2005, 2007; Linsey et al. 2010). Fixation is especially detrimental to K-12 students because fixated students do not fully explore the conceptual space and develop limited understanding of the underlying science and engineering concepts. Teachers should design interventions and instructional activities to mitigate fixation in classrooms. For instance, asking students to reflect and share their design processes allow them to realize the prevalence of iterative design among classmates and prompts them to consider making more revisions to their prototype designs. Such scaffolding is necessary to help reduce the impact of fixation among novice students.

Another finding is that students went through multiple iteration/fixation pathways during the solar urban planning project. Despite the fact that 55% of the participants became fixated in Design 3, nearly a quarter of the students (23%) fluctuated among three types of iterations—efficacious, inadequate, and ineffective. We view these types of iteration as three of the many design patterns existing between fixation and iteration (see Fig. 15 for the continuum of design patterns). Inadequate and ineffective iteration may be the handmaiden of future success and innovation (Petroski 1985). The existence of the

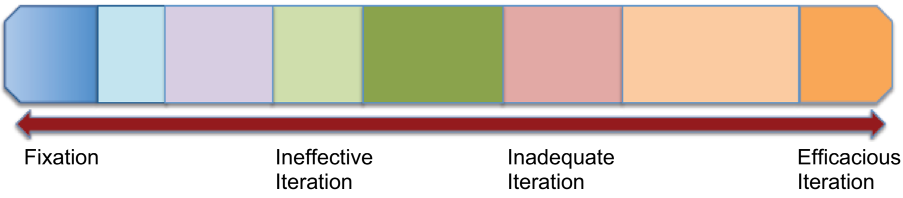


Fig. 15 Continuum of design patterns, with fixation and successful iteration at two ends. We recognize that the use of a continuum is an artificial, oversimplified construct, but we believe that it provides a visual and conceptual model that is useful for envisioning complex design processes. The *blocks* represent various design patterns students experience during design

three types of iteration exemplifies the complex nature of iteration, and confirms the value of data mining in investigating complicated design processes. This result also calls for support on helping students become efficaciously iterative designers, as it shows a substantial number of students appreciated the importance of iteration yet struggled with finding effective ways to perform iterative design. It is crucial to provide guidance to support these novice designers, otherwise they may become frustrated and fixated.

Finally, the way we analyzed design behaviors and intermediate artifacts to infer internal design processes can shed light on research in this field. Design projects are criticized for being difficult to score because researchers cannot determine the design processes students have gone through based on the appearance of the final designs (Bailey and Szabo 2006). Combining design actions with intermediate and final design artifacts and triangulating results from the three sources can lead to in-depth understanding of the cognitive processes that drive the actions. This approach is applicable to any other design projects although the details of the data analysis may vary in designs with different specifications, e.g., selecting which behaviors and what property of the designs can be indicative of the cognitive process.

Limitations and future work

One limitation of this study is that the solar urban planning project was implemented among 9th graders in a public school in northern east USA. The teacher was recruited to participate rather than randomly selected. The data were collected from students in physics classes (82% of the participants were from working-class families). The results may differ from situations involving participants, settings, and conditions different from those in the study. Another limitation is that this study investigated fixation and iteration by mining the computer logs of students' design actions and artifacts. Logging is currently not widely supported by CAD tools as most CAD programs have been developed for professionals to solve engineering problems, not for educational researchers to conduct research.

As our next step, we will focus on understanding whether and how learning and design intertwine during the project. This paper analyzed student design practices yet did not investigate how and whether student design actions are correlated to their conceptual understanding. Conducting pre- and post-test would provide more information about whether and how students achieve learning gains. In addition, examining students' design notes and journals can reveal information to answer questions such as how students made design decisions? Were the decisions driven by science? Our future work will be centered around identifying the relationship between cognitive processes underlying design with those underlying conceptual learning.

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