Understanding How High School Students Approach Systems Design

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Abstract: Systems thinking is described as the cognition a person uses in the solution and design of large-scale complex systems, often requiring hypothetical and holistic approach. Engineering and systems thinking are commonly part of a K-12 education, particularly in high school. Because systems engineering is a complex process to undertake, it is increasingly difficult to understand how secondary students approach a systems design problem. This work-in-progress presents an exploratory approach for understanding how and to what degree high school students considered multiple systems in an engineering design project in order to develop categories of students for further inquiry. Students (n = 22) completed a systems engineering design task, The Solar Urban Design, in which they worked to optimize solar gains of high-rise buildings in both winter and summer months within Energy3D as a part of their engineering science classroom. Energy3D is a Computer-Aided Design (CAD) rich design tool with construction and analysis capabilities. As students design in Energy3D, a log of all of their design actions and results from analyses are logged. In addition, students took reflective notes within Energy3D during and after designing. We computed percentile ranks for the students' design performance for each of the required design elements (i.e. high rise 1 and high rise 2) for each of the required seasons (i.e. winter and summer). We investigated the degree to which students optimized only one of the buildings or one of the seasons versus how they used a systems engineering approach to incorporate all elements of the complete system as a summation of each of their four percentile ranks. We looked at their reflections to better qualitatively understand their design process. Results suggest different patterns in the ways that students address systems engineering problems. Draft paper results will discuss student vignettes in order to illustrate the differing cases of students.

Keywords: systems engineering, design, K-12

Introduction

Students in the modern world face great challenges in changing the world for the better despite growing populations, climate change, and safety concerns. The National Academy of Engineering has called engineers to action to change the world through the following 14 "Grand Challenges": (1) providing access to clean water; (2) preventing nuclear terror; (3) engineering better medicines; (4) advancing health informatics; (5) making solar energy economical; (6) developing carbon sequestration methods; (7) securing cyberspace; (8) reverse-engineering the brain; (9) managing the nitrogen cycle; (10) providing energy from fusion; (11) restoring and improving urban infrastructure; (12) engineering the tools of scientific discovery; (13) enhancing virtual reality; and (14) advancing personalized learning. None of these "Grand Challenges" can be solved in isolation nor can they be addressed using conventional approaches. Engineers of the future will need to take a systems perspective to understand and solve these issues. Systems thinking is a relatively new term takes many comprehensive definitions from discipline to conceptual framework as synthesized by Shaked and Schecter [1].

"A discipline for seeing wholes. It is a framework for seeing interrelationships, rather than things, for seeing patterns of change rather than static 'snapshots.' It is a set of general principles...It is also a set of specific tools and techniques" [2].

"An epistemology which, when applied to human activity, is based upon the four basic ideas: emergence, hierarchy, communication, and control as characteristics of systems. When applied to natural of design systems, the crucial characteristic is the emergent properties of the whole" [3].

"The ability to see the world as a complex system, in which we understand that 'you can't just do one thing,' and that 'everything is connected to everything else'" [4].

"Systems thinking is utilizing modal elements to consider the componential, relational, contextual, and dynamic elements of the system of interest." [5].

"Systems thinking - includes holism, an ability to think about the system as a whole; focus, an ability to address the important system level issue; emergence, recognition that there are latent properties in systems; and trade-offs, judgment and balance, which enable one to juggle all the various considerations and make a proper choice" [6]

"A set of synergistic analytical skills used to improve the capability of identifying and understanding systems, predicting their behaviors, and devising modifications to them in order to produce desired effects. These skills work together as a system." [7]

Clearly systems thinking is a complex topic but an important skill for engineers. These skills are important before the professional level, and are seen in a form through the Next Generation Science Standards [8] through the cross-cutting concept of systems and system models. Students even as young as the K-2 level should have a basic understanding of systems, knowing: (1) Systems in the natural and designed world have parts that work together, and (2) Objects and organisms can be described in terms of their parts. At the High School level, students should be able to demonstrate knowledge that: (1) When investigating or describing a system, the boundaries and initial conditions of the system need to be defined and their inputs and outputs analyzed and described using models, (2) Models (e.g., physical, mathematical, computer models) can be used to simulate systems and interactions—including energy, matter, and information flows—within and between systems at different scales, (3) Models can be used to predict the behavior of a system, but these predictions have limited precision and reliability due to the assumptions and approximations inherent in models, and (4) Systems can be designed to do specific tasks. This research seeks to understand how high school students approach systems thinking during engineering design.

Research Question: How and to what degree do high school students consider multiple systems in an engineering design project?

Research Methods

Research participants & Classroom context

Data for this study comes 109 9th grade students in physical science classes at an urban high school in New England. For this work-in-progress, we focus on one class of 23 students. Six students from the class were removed from additional analysis as they had not adequately recorded their reflections on their design iterations within their journal. Students participated in an in-class design project using Energy3D (http://energy.concord.org/energy3d/), a CAD simulation environment [10]. Energy3D is developed by the Concord Consortium as "a computer-aided engineering tool for designing, analyzing, and constructing green buildings and power stations that utilize renewable energy". The user-friendly software offers a simple 3D graphical user interface for drawing buildings, and evaluating their performance using energy (solar and heat) simulations (see Figure 1).

Design challenge

Students used Energy3D to complete a "Solar Urban Design Challenge" that required students to: (1) add two high-rise buildings, (2) add two low-rise buildings to an existing city block, in order to (3) optimizing solar gains of the high-rise buildings in the winter and summer (See Appendix for full design challenge). Ideal solutions would meet all design criteria for numbers of buildings and would perform well in both winter and summer seasons.

Data sources

While designing in Energy3D, each student design action (e.g. Move Building) was recorded in the background of the program in JSON files. Additionally, the performance of the design artifact is also in those JSON files. Researchers are able to use Energy3D to see all student design actions, the final design artifact, and the overall energy performance of that final artifact.

While designing, students were instructed to take notes on their design process. An electronic journal is embedded within Energy3D and in this particular implementation, students had design prompts in these journals, including:

> *Describe your design ideas and explain why you think they are good ideas.*
> *Describe the changes you have made to the last version (design 2 vs. design 1)*

Data analysis

<u>A Solar Urban Designs Systems Performance Rating</u> was calculated for each student, for each of their two designs out of a maximum 4 points each. Students' designs were ranked into quartiles based separately on their summer and winter performance (i.e. absorbing less energy in the summer and more energy in the winter) with respect to the population sample. Students' designs were then scored depending on where they fell along the quartile range, again separately for summer and winter performance. For example, if a student's design was in the bottom quartile it would receive a .25 and if it was in the top quartile it would receive a 1. If students had more than two high-rises, the design rating was calculated with the two best performing buildings.

Design action visualizations were created for each student. A feature of Energy3D allows researchers to understand the timing and frequency of design actions during a design session (e.g. the number of times and timestamp each time student moved a building or conducted a solar analysis).

Displaying multivariate data in a way that both concise and easily analyzable can be difficult. Radar plots are one useful visualization tool for plotting multivariate data on one compact graph [9]. These plots use one, typically circular, grid with “spokes” representing each variable. These spokes are placed at equidistance across the grid with each spokes length indicative of the value for that variable for a given case relative to the maximum value it assumes across all cases. For students in our sample, radar plots were generated for each of our vignettes, reflecting their key design actions for each design. Actions for their first and second design are plotted on the same plot for ease of comparison.

Results & Discussion

The results show that students vary in the degree to which they consider multiple systems in engineering design. Table 1 provides a summary of each student’s overall Solar Urban Design Systems Performance Rating. Using these scores allowed us to look more closely at the students who: (1) exhibited greater systems focus (Student E2), (2) showed a moderate degree of systems design (Student E10 and Student E17), and indicated a lack of systems design focus (Student E20).

Table 1 Students’ Solar Urban Designs Systems Performance Rating (out of a possible 4)

Student	Design 1	Design 2
E1	2.5	2.5
E2	3	2.5
E3	2.5	2.5
E4	2.25	2.5
E5	2.5	2.75
E7	2.5	2.5
E9	2.75	2.5
E10	2.5	2.5
E13	2.75	2.5
E14	2.75	2.5
E15	2.25	2.75
E16	2.5	2.5
E17	2.5	2.5
E18	2.5	NA
E19	2.5	2.25
E20	2.25	2.5
E22	2	2.75

Table 1 displays students’ performance on their first and second Solar Urban design. Students’ designs were ranked into quartiles based separately on their summer and winter performance (i.e. absorbing less energy in the summer and more energy in the winter).

The following section provides a descriptive look at all four of the students. First, we provide their overall Systems Design Score with a representative visual of one of their two final design solutions to the prompt. Next, we dive into the design actions that accompany the design artifact performance with pie radar charts that describe the degree to which students made iterations through moving the buildings (Move Building) to or changing the size of the buildings (Size Building), tried to understand the systems through multiple seasons (Change Date), and tested these efforts (Solar Analysis).

Case A: Best Systems Focus

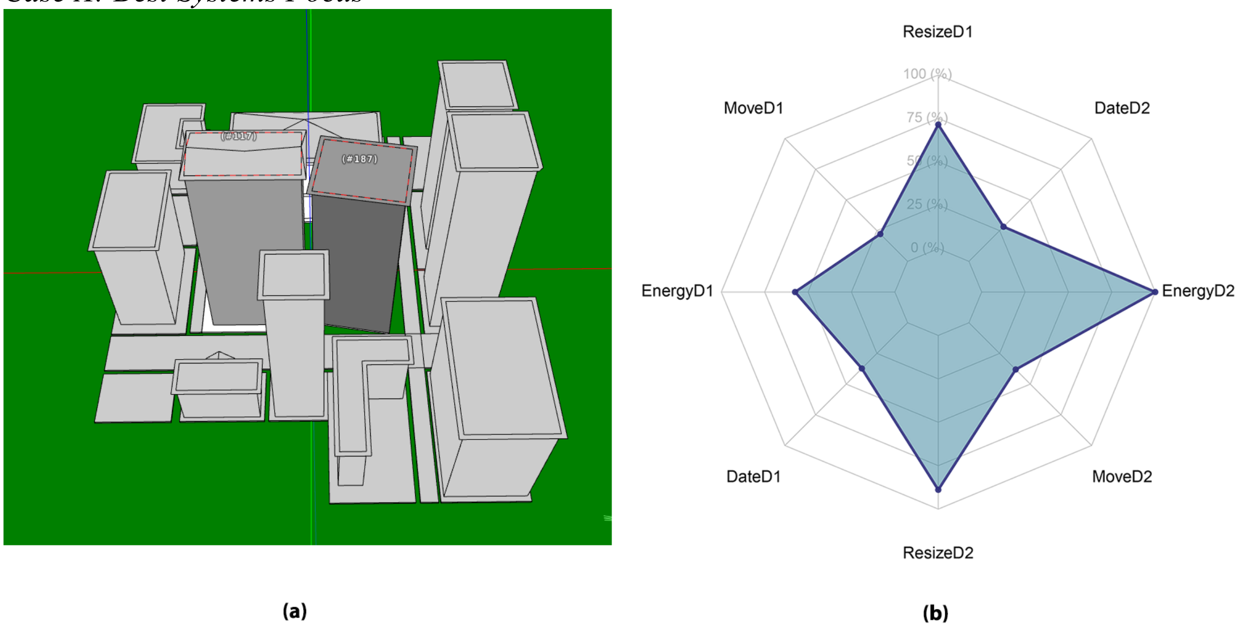


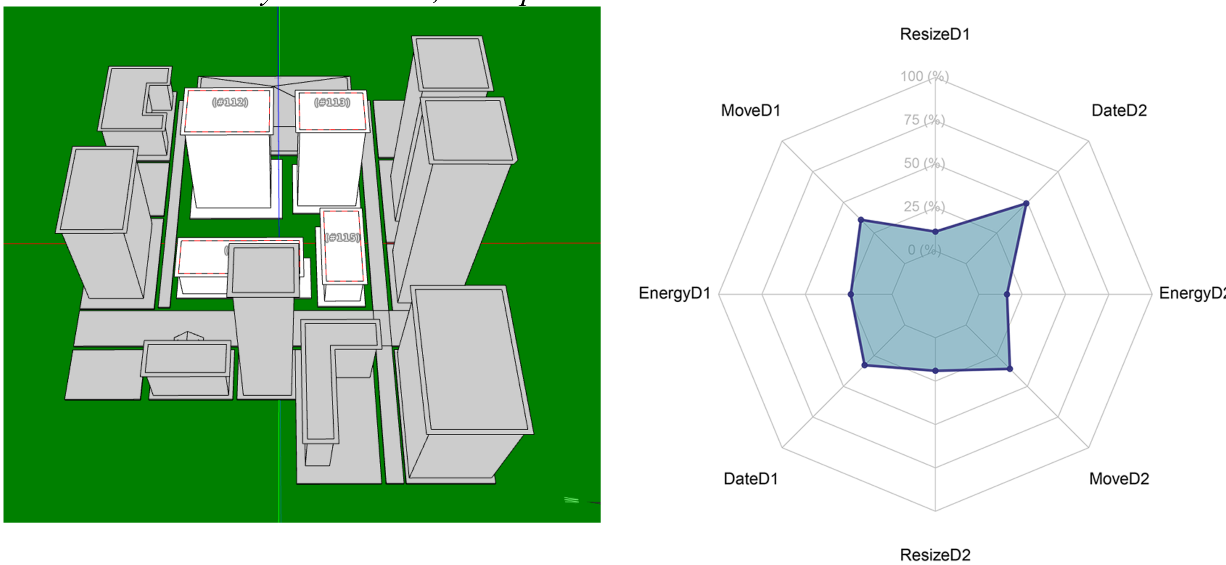
Figure 1 - Student E2. (a) Example Urban Design (b) Design Actions for their first and second design

Student E2's design 1 is shown in Fig. 1 (a); they placed their two high rises between other tall buildings to the east and the west. Their radar plot shows they resized their buildings and ran many analysis of their energy performance of their buildings for both their first and second design. They reflected in their journal:

> *"I made the tall buildings grey so that in the winter they will absorb heat in the winter, but not too much in the summer. I gave the most surface area to one of the tall buildings so that it can take in as much heat as it can in the winter. I also have the most surface area of the buildings facing the south side because of its position to the sun."*
>
> *"increased surface area, rotated one of the buildings to get more surface area facing sun"*

Student E2's radar chart shows iterations (i.e. resize, move, date) and analysis (i.e. energy) in both of the buildings (D1 and D2). This student is taking a systems approach to in understanding how iterations affect performance such as how moving or resizing a building affects energy performance. Changing Date allows an understanding of how the building performs during different seasons in an attempt to gain a systems outlook of performance. Finally, equal counts of actions between both buildings, D1 and D2, represents a systems approach to looking at both buildings in the system rather than one building as the main focus.

Case B: Moderate Systems Focus, Example 1



(a) (b)

Figure 2 - Student E10. (a) Example Urban Design (b) Design Actions for their first and second design

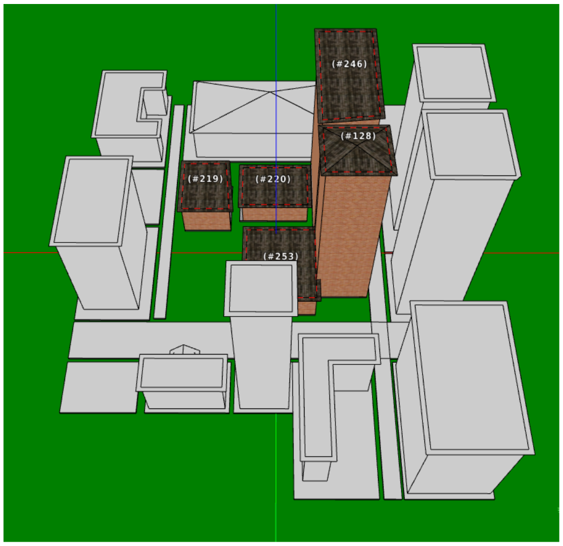
Student E10’s design 2 is shown in Fig. 2 (a); they placed their two high rises adjacent to each other with a taller building to the east and shorter buildings to the west. Their radar plot shows modest but balanced activity in most categories for both designs, with slightly date changing for design 2; however this is not matched by more energy analysis. They reflected in their journal:

> *“The large, low rise building that looks like a mall was the hardest to make cool in the summer. It worked fine in winter, so I used my three high rises to shadow it. My second low rise is also in the shadow, and I placed my high rises so they wouldn't absorb too much heat. I had a large amount of open space for aesthetics, and three high rises for the same reason. Fiddling with shadows gained me more solar energy in the winter, and less in the summer.”*

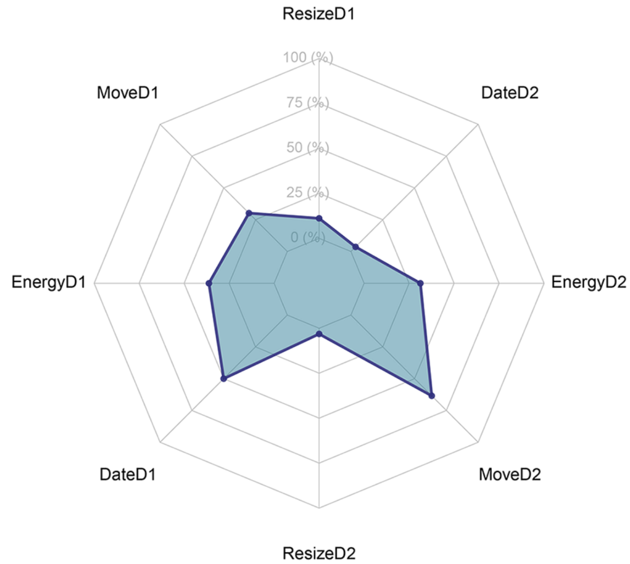
> *“I put the high rise that got the least solar energy in the sun so that it would heat up more in the winter, but it's in a shadier spot in the summer.”*

Student E10’s radar chart shows low to moderate iteration focus (i.e. resize, move, date) and analysis (i.e. energy) in both of the Buildings (D1 and D2). The student seemed to iterate more in building D2 as seen from the date and move commands. Changing Date allow and understanding of how Building D2 performs in different times of the year. However, this student did not accomplish a similar analysis with Building D1.

Case C: Low Systems Focus



(a)



(b)

Figure 3 - Student E20. (a) Example Urban Design (b) Design Actions for their first and second design

Student E20's design 1 is shown in Fig. 4 (a); their two high rises about the eastern high rises on the city block. Their actions, displayed in Fig. 4(b), show a modest amount of energy analysis and building movement and somewhat more date changing for design 1. Their actions for design 2 show a modest number of energy analysis and substantial number of building movements. They reflected in their journal:

> *"I put the tall buildings under the shadow of the already tall buildings that were there so that they would be blocked by the sun. I also made the building pretty tall because then they are the most efficient."*
>
> *"I realized that taller buildings do worst in the summer but better in the winter."*

Student E20's radar chart shows low iteration focus in terms of resizing for both designs and moderate analysis (i.e. energy) in both of the buildings (D1 and D2). In Building 1 the student changed the date moderately to understand performance and different times of the year but did not resize or move the building to change the performance. In Building 2, the only moved the building to change energy performance rather than resizing or changing the date to understand impact. This implies that the student used Building 2 to help the performance of Building 1 and did not look at the design challenge as a systems problem to accomplish energy efficiency for both buildings.

All three student examples showed variation in how the students addressed the design challenge and the extent to which they considered the challenge from a systems perspective. Those with pie radar charts with a larger "web" tended to represent those who spent more time on iteration and analysis. Pie radar charts with actions in iteration and analysis for both buildings reflect designers with a more sophisticated systems goal in working with multiple seasons and multiple buildings. Interestingly, there is not apparent relationship between student reflections and design outcomes. While Case A and Case B showed more thoughtful reflections than Case D, we would need a larger sample size to better understand trends of reflection.

Conclusions & Future Work

Iteration and analysis are hallmarks of informed designers and design behaviors that we as educators hope to help develop in students. Moreover, systems thinking through making trade-offs, judgement and balance are valuable skills not only for engineers but for humans in general. This work attempts to visually represent the degree to which students are behaving as informed, systems thinking designers. Future work will expand the analysis and visuals to a larger data set in order to understand further variation in similar design challenges.

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Appendix

SOLAR URBAN DESIGN

Design Specs

The Boston Redevelopment Authority has opened bids for redesigning a city block (100 m x 100 m) in the downtown area. As the chief engineer of a startup company focusing on sustainable city planning, winning the bid is important to you. Your job is as follows:

1. Design new construction buildings in the empty, leveled city block:
   - **At least two high-rise buildings**: These are for residence and offices. They should be at least 60 meters tall but *should not be taller than the highest existing building in the neighborhood.*
   - **At least two low-rise buildings**: These are for shops or services such as restaurants, book stores, or pharmacies. They should not be taller than 20 meters.
   - **A balance of built and open space**: Approximately ⅓ of the block must be constructed with high-rises and ⅓ with low-rises. The remaining ⅓ must be open space.
   - **At most eight new buildings** (including high- and low-rises) in total are allowed in the block.
   - **Don't add windows**: We assume that windows will be added proportionally to the total surface areas of each building later.
   - **Don't add solar panels, doors, floors, and any interior structures**. You may add trees and people in the open space or on the street if that makes your design look nicer.
   - **Parking areas, subway, or bus stations** need not be considered.

2. Consider energy from the sun in different seasons (you will use the Solar Radiation Simulator in Energy3D to investigate these issues and make design decisions) :
   - **Optimize solar gains of the high-rise buildings in the winter and summer:** The locations and shapes of the high-rise buildings should be chosen such that they receive **as much total solar energy on December 31st as possible** to lower the heating costs in the winter ***AND*** **as less total solar energy on June 30th as possible** to lower the cooling costs in the summer. (Note: Do NOT use the Annual Energy Analysis Tool in Energy3D to do this analysis.)
   - **No need to consider the solar gains of the low-rise buildings**: They do not need a lot of sunlight because they accommodate business facilities that usually do not have many windows.

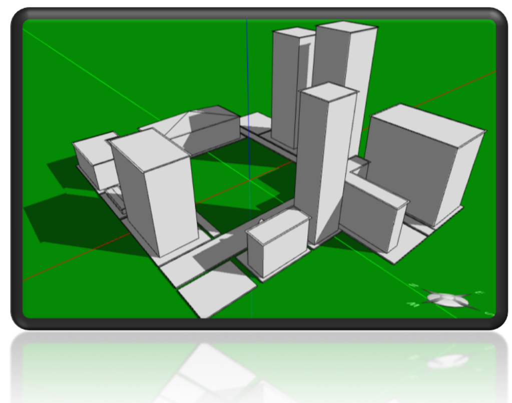
3. You must come up with **three DIFFERENT designs** and choose the best among them to represent your firm. There are many different ways in which you can design your city block. For example, you

can explore the solar performances of different shapes, such as L-shape, T-shape, U-shape, or courtyard, in each design. Once you decide on the shapes, you can also test different layouts to optimize their solar gains both in the winter and summer. If you have a number of design strategies that may not be compatible to one another, you should try to use them separately in different designs and then make a trade-off decision based on comparing their overall quality.

4. You should spend **1-2 class periods** to plan, construct, experiment, analyze, and document each of the three designs. Until this project is over, you can always revisit and improve a previous design.

Instructions

The Boston Redevelopment Authority has provided a computer model of the city block with existing surrounding buildings. Three identical copies of this model can be found on your USB drive and can be opened using the Energy3D software. The image to the right shows how this computer model looks like within Energy3D (the existing buildings in it are grayed out because they cannot be modified).



To get started,

1) Write your name on the tag attached to your USB drive.
2) Connect the USB drive to the computer and then open the USB folder on the computer.
3) Double-click *energy3d.jar* on the USB drive to run Energy3D.
4) Use the "File > Open" menu to open *cityblock-design1.ng3* on the USB drive. Start working on your **first design** using this file as the starting point. While designing, use the "Edit > Show Note" menu to open a text area below the 3D view window. **The text area provides some instruction, questions, and a check list to guide you through the design process**. **You must answer those questions based on your design**. Save everything you have done in this file—do not save your work into a different file unless you want to keep a backup copy.
5) Open *cityblock-design2.ng3* to work on your **second design**.
6) Open *cityblock-design3.ng3* to work on your **third design**. Note: The three *ng3* files contain exactly the same model initially—the surrounding buildings are identical in all three files.
7) Each of your three designs should feature different buildings and layouts. For the design you pick as the best one for the bid, explain why you make that choice in the text area. Refer to the buildings using the numbers on top of them as if they were street addresses.
8) At the end of each session, **remember to save your design**. You MUST save all your work in the USB drive (as you may use a different computer next time). Do NOT just pull the USB drive—use the EJECT function of the computer to safely remove it.

Important Notes

- **Each building must have its own platform**. Don't put multiple buildings on a platform.
- **A building can be resized or rotated as a whole at any time**. You can concentrate on designing its shape initially and resize or rotate it as you wish later.
- **Always document your work**. Your notes will be saved when you save your design.