Work in Progress: Visualizing Design Team Analytics for Representing and Understanding Design Teams' Process

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Abstract

Engineers typically approach design in teams, particularly when dealing with complex problems that may need to be decomposed into several parts or subsystems to be designed individually and integrated. Team design projects during students' college years can serve as critical experiences to prepare for professional work on design teams. However, the volume of actions across team members and iterative nature of engineering design makes tracking, representing and learning from design teams' actions difficult and time-consuming. This work proposes developing *design team analytics* as a tool for representing and understanding how students collectively navigate and address complex designs, by leveraging a computer-aided design (CAD) platform with action-logging functionality.

A class of 28 juniors and seniors in a project-based engineering program at a small Midwestern University worked in teams of four-to-five to design a distributed system of solar arrays for their local community while balancing energy need and budgetary constraints. Students were given a suite of 8 solarizable sites including flattop, pitched-roof buildings, and parking lot locations. Students then used these sites to design, evaluate, and select a subset for their final design. Energy3D, a CAD platform for constructing buildings and solar arrays that features many analytical tools, served as the primary design platform. Importantly, Energy3D logs users' actions such as adding a solar panel or running an annual solar yield. The data from these logs was examined in terms of individual and collective contributions resulting in visualizations of the teams' design processes across several metrics including: construction, optimization, and numerical analysis.

Preliminary results for this work-in-progress indicate that students mostly designed sequentially across solarizable sites, with little concurrent activity. Optimization patterns vary between teams and show some relation to teams' final design(s) performance.

Introduction

Real world engineering is typically a complex process requiring a high degree of collaboration. To prepare students for such an environment many faculty members embed team based design work in their courses. In fact, engineering design and teamwork are both required components of ABET accredited engineering programs[1]. Improving the ability to dissect and analyze a team's actions may eventually allow for a better understanding of how effective teams differ from less effective teams. In this study students' used a CAD software called Energy3D that affords construction and analysis of solar array systems while automatically logging user actions. We aimed to develop a series of design team analytics from teams' recorded actions in the platform.

The questions this work-in-progress sought to address were two-fold: 1) How did teams navigate the design challenge? and 2) What, if any, relationships were there between teams' design process and the performance of their design(s)? Data from Energy3D logs was examined through visualizations of teams' design process across several metrics.

More specifically, actions were clustered into three categories: construction, optimization, and numerical analysis. Design teams' actions were further contextualized in terms their design timeline and the sites they explored.

Results from design team analytics have implications not only for teams' design process, but may be re-deployed as reflection tools for students' or progress indicators for teachers or design mentors.

In the next section the paper reviews research in learning analytics and visualization for data analysis. Following this, the context of the study and design challenge are outlined. Energy3D is discussed briefly before reviewing the data collected and participants for the study. Next, our methodological approach for developing and visualizing the analytics are discussed. Following this, the results are presented in three blocks: first, by looking at teams' overall process and artifacts, second, by showing visualizations of teams' process and third, by analyzing teams' performance on the four design criteria (energy production, cost-effectiveness, cost and aesthetics). Lastly, the results are discussed in context of the research questions and a few concluding points are made.

Literature Review

While education has been slower to pursue analytics as a shift in methodology and research[2], it is receiving more attention and has begun to develop into subfields including academic analytics[3] and learning analytics[2,4-5]. Of particular relevance to the work in this study is learning analytics, an emerging subfield focused on the measurement and analysis of learners and their immediate contexts, typically through digitally collected data. Analytics generated from this line of inquiry target our understanding of learners and are applied in ways to improve learning and learning environments[2]. In the setting of engineering education, learning analytics can be leveraged to help teachers or mentors understand students learning, progress, challenges, and to help students track or reflect on their learning through analytics dashboards[6]. The advancement of learning analytics and related areas[5] is due in part to an increasing number of systems that digitally log data, including learning management systems[2], simulations[7-8] and intelligent tutoring systems[9]. As learning analytics and related subfields like educational data mining have grown, more researchers have started to apply these techniques to the study of design [7, 9-14].

Visualization or visual data analysis is a proven method for representing heterogeneous and multi-modal data[15] in displays that can provide a holistic view of some phenomena and reveal important patterns and complex trends[4]. Visualization plays a central role in design as a complex process and in design research. Regarding design as an activity, Dym and Brown[16] argue the design process can be conceived as a progressive series of representations, including mathematical, symbolic and visual representations. These representations help conceptualize and advance a design from the beginning initial problem statement to a final proposed design. Furthermore, in the area of design research visualizations have been used frequently to understand design behaviors or the design process through numerous techniques. For example, linkography[17] and design timelines[18-19], the first of which visualizes an interconnected network

of design moves and the second of which reflect the time spent on different design stages and transitions between stages.

This work builds on the growing application of learning analytics to education, and to design in specific, to employ visualization as a means for representing complex design behavior data.

Context of the Study

This study was conducted at a unique program which may make the sample less comparable to other engineering students at similar points in their academic career. As such, we delve deeper into the context of the study. The study happened in an upper division project-based engineering program which is part of the extended campus of a medium size public university in the Midwest. The course had a total of 28 students and 17 of the 28 fully participated and consented to the research. Each semester the students in the program are placed on vertically integrated teams, meaning first and second semester juniors (J1s and J2s) are working with seniors (S1s and S2s), and assigned a project of the scope and scale of a typical capstone project. Students earn six credits for completing this project: three in Design and three in Professionalism. The Design credits are awarded for project work like scoping, maintaining a technical notebook, and achieving project objectives. The Professionalism credits are awarded for project work like professional development, teamwork, and communication. Topics in Design and Professionalism are discussed in a one credit Seminar. Students learn technical information and skills by participating in one credit courses called competencies which are contextualized and connected to the design projects where possible. In order to graduate students must complete their general education requirements, four Design courses, four Professionalism courses, four Seminars, and thirty-two technical competencies. It is specifically worth noting that S1 and S2 students will have more design training and experience than seniors in a traditional program.

The first two days of each semester in the program is dedicated to an orientation that focuses on creating the student culture we want in addition to onboarding J1 students and updating returning students concerning changes in the program. The updating and much of the onboarding is done through the dissemination of syllabus information, discussion of assignments, and establishment of expectations. Creating the culture includes ice breakers, team building activities, and an orientation design challenge. For the spring 2018 orientation design challenge teams of four/five student engineers were tasked to design photovoltaic installations on a series of public sites from around the community to meet the energy demands of their campus with Energy3D, an open-source CAD tool. An example of some of the models teams could select from is shown in figure 1. The composition of the teams is shown in table 1. The designs were assessed on meeting the specified energy need (.4), cost-effectiveness (.4), cost (.1), and aesthetics (.1). Parenthetical values are the weight given to each criteria. Although four hours of orientation time was explicitly connected to working on the design challenge students could also work on it in the evening or early morning.

Table 1 – Team Compositions

Team	Composition
Team A	J1-1, J2-1, S1-0, S2-2
Team B	J1-2, J2-1, S1-0, S2-1
Team C	J1-1, J2-2, S1-1, S2-1
Team D	J1-1, J2-1, S1-0, S2-2
Team Removed (Did not consent to research)	NA, 4 members.

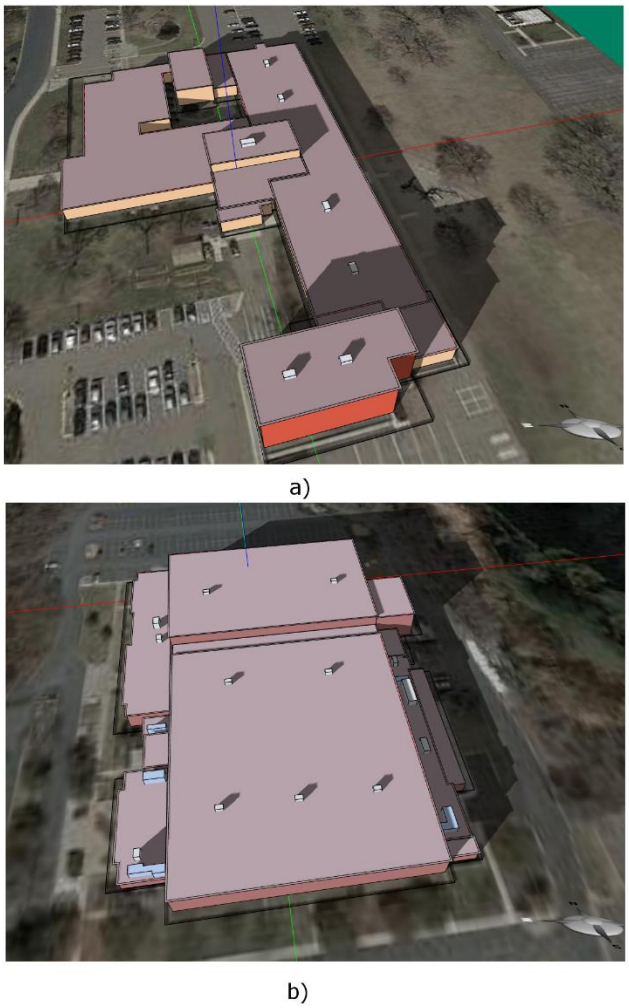

Figure 1- Two of Eight Models Teams could Select to Solarize

Energy3D

Energy3D is a publically available professional-grade CAD software with a built-in physics engine that enables extensive solar simulation and analytical capability for photovoltaic and concentrated solar power energy systems. Furthermore, integration with Google Maps and a database of averaged weather data for over 600 sites around the world allows users to build and test models in their local community or region. When a student opens Energy3D each of the

actions they take from the data schema[20] are logged into a Javascript Object Notation (JSON) file format until Energy3D is closed. JSON is a lightweight data exchange format that is human and machine readable. Each logged action is atomic in the sense that it is the smallest possible action that could either affect the design or the designer(s). For example, adding a new solar panel rack or viewing the daily insolation on a building or rack. Energy3D has been used for several different design challenges (e.g., see[7, 21-22]). The actions relevant to this design challenge are discussed in the methods section below.

Data

Two forms of data were collected for this study: students' final artifacts and their design logs as captured by Energy3D. First, for their artifacts, each team submitted the set of Energy3D files or community sites they selected for their final design. Each team also submitted graphs of the annual energy production of each site, which were independently verified by the authors by opening their models and running an annual analysis. Models also contained several other useful data points including the cost of the system, cost-effectiveness of the system, and the solar panel models the team selected. Secondly, teams were asked to submit the Energy3D logs from their time designing, which can be retrieved through the menu bar in the system. Energy3D logs JSON files locally, so for each computer the team used they submitted a log file. Figure 2 displays an example of three different logged actions: Add Rack (a), Change Tilt Angle (b) and PV Annual Analysis (c). For each action the timestamp, filename of the current file, name of the action, and unique metadata for that action are recorded. Collectively this allowed us to analyze their design timeline, actions, and what sites they were examining.

Methods

The design process can be represented by different models[23-24] which share many aspects. For example, design process models often have some creation or building step such as modeling[18] or preliminary design[24] and some testing or evaluation stage[23-24]. Another common stage is some form of optimization, such as detailed design[25]. There are many other common stages across design process models, however preliminary design, evaluation and detailed design are a central pillar of the design process representing a cycle of creation, analysis and refinement. For this reason, we developed analytics specifically around these processes.

Due to the large number of actions captured by Energy3D it was necessary to cluster the actions into sets that could represent different categories of design activity. Table 2 depicts our schema for organizing the JSON logged actions into categories. First, construction or preliminary design consists of initial building and creation actions such as adding or pasting solar panel racks, resizing or moving existing racks (both recorded as edit rack) and removing racks. Second, optimization or detailed design, consists of advanced manipulation of solar panel racks parameters including their tilt angle, azimuth angle and what model of solar panels are placed on the racks. Finally, numerical analysis, or evaluation, consists of analytical tools within Energy3D that estimate the annual kilowatt hour production of a given photovoltaic system or subsystem.

```
"Activities": [{
    "Timestamp": "2018-01-09 09:35:15",
    "File": "public-works-department-bloomington-mn.ng3",
    "Add Rack": {
        "Type": "Rack",
        "Building": 20,
        "ID": 168,
        "Coordinates": [{
            "x": 234.359,
            "y": -32.48,
            "z": 14.215
        }]
```


a)


```
"Activities": [{
    "Timestamp": "2018-01-09 09:39:57",
    "File": "public-works-department-bloomington-mn.ng3",
    "Change Tilt Angle": {
        "Foundation": 20,
        "ID": 176,
        "Old Value": 30.0,
        "New Value": -30.0
    }
}]
```


b)


```
"Activities": [{
    "Timestamp": "2018-01-09 10:22:19",
    "File": "public-works-department-bloomington-mn.ng3",
    "PvAnnualAnalysis": {
        "Months": 12,
        "Foundation": "Foundation(2)",
        "Solar": {
            "Monthly": [351.69, 419.99, 664.85, 746.02, 851.68, 957.55,
                        1017.8, 971.03, 636.81, 474.56, 285.33, 234.25],
            "Total": 231518.03
        }
    }
}]
```


c)

Figure 2- Examples of Logged Actions. a) Add Rack, b) Change Tilt Angle, c) PV Annual Analysis

Table 2 – Categories of Design Actions

Name	Types of Actions	Description
Construction	Add/Edit/Rotate/Remove /Paste Rack	Actions involved with the creation or building of the solar array system.
Optimization	Tilt Angle, Azimuth Angle, Change Model, Select Solar Panel Model	Actions involved with modifying parameters of the solar array system
Numerical Analysis	PV Annual Analysis, Energy Annual Analysis, Group Annual Analysis	All actions that produce annual kilowatt hour (kWh) production for a solar array system or a subset of the system

Energy3D logs were processed through a Python script and imported into the R statistics package for visualization with the ggplot2 library. Due to the complexity of the models and size of photovoltaic systems, most annual analysis took 10-20 minutes to complete. Results of teams' analyses are plotted on a subplot that runs parallel with plot of teams' actions. Team visualizations are segmented vertically in two ways: by session and by site the team was working on. Teams' design process was split into sessions depending on a two-hour idle threshold. Teams appeared to often set up an analysis that was part of their current session and leave the simulation and return in 2 or less hours. If a shorter threshold is used, say 1 hour, there would be many one or two action 'sessions' composed of these types of analysis, which is why we used two-hours as the threshold. Plots are segmented into session subsections by a white gap between subsections. Each solarizable site also had a distinct filename, which could be tracked in teams' logs. Plots are segmented into separate file subsections with a dashed vertical line.

Results

The results section has three major components. First, we discuss some general features of students' artifacts, including how many they submitted, how they approached their designs, what models of solar panels they used, and how long they worked on their designs. Second, each team's design process visualization is presented and relevant patterns and contextual information is discussed. Third, we present how each team performed on the design criteria and describe any relationships between their actions throughout the design and their final design(s) performance.

First, turning to teams artifacts, Team's A and D submitted 4 and 3 solarized sites, respectively, whereas Teams B and C submitted a single solarized site. Of the four teams, only Team A's log revealed any concurrent design activity or times when two sites were having solar array systems designed simultaneously. We analyzed students' logs to identify any periods where students were working on two or more designs concurrently. Around a fifth of the solar panel models selected by Team A were 6% more cost effective than the normalized cost of panels while the rest were 7.6% less cost effective. Team B's solar panels were slightly more cost effective at about 2.2% while Team C's solar panels were 6.7% more cost effective. Team D was the team that did not select one of the provided models for their design and therefore were penalized for the design challenge.

In order to determine how long teams spent designing we used Energy3D's logs, which is likely to be a conservative estimate as time spent planning, revising plans, or group discussions are not captured through the action-logging of the system. In sticking with a conservative estimate, we subtracted out time in which students appear to idle. The clearest example of this is when students run an analysis, which may take up to 20 minutes to complete on complex designs. Additionally, if students were inactive for 40 minutes or longer their idle time was subtracted out. While we cannot rule that students' may be active at this time, we are unable to definitively ascertain this, so a conservative measure of time designing is used. Using this approach, Team A spent 2 hours and 6 minutes, Team B spent 1 hour and 17 minutes, Team C spent 3 hour and 10 minutes and Team D spent 1 hour and 21 minutes on their design(s).

Next, turning to teams' design process, a few points should be noted. On each teams' graph, the red points on the upper plot indicate the time and performance of their system from an annual analysis. These annual analyses may examine the entire system or a subsection of it, and may be run throughout the entire year or stopped at some month during the analysis. Different red points are used to indicate analyses of different types, e.g. all system partial year. A long, dashed vertical line indicates when students transition from one design site to another. Letter codes, which are defined in Table 3, indicate which site a team was working on at a given time.

Table 3 – Character Codes for Locale Solarizable Sites

Site Name	Character Code
Fire Station	F
Ice Rink	R
High School	H
Elementary School	E
Salt Storage	S
Public Works Department	W

Team A's design process is displayed in figure 3, below. Team A was the only team who designed for two sites simultaneously, as revealed by the timestamps in their JSON logs. This is displayed in figure 3 by stacking the construction and optimization actions for both designs when they were concurrently happening. All instances when students analyzed the Ice Rink are marked with R to distinguish these analyses from the other concurrent analysis. The upper bars represent Team A's work on the Ice Rink and the lower bars represent their work on the Public Works Department. This dual design period lasted for about an hour. Four models were considered by Team A, which were all eventually submitted as designs. Looking at the rest of the display, Team A regularly engaged in optimization actions as they developed their design and conducted analyses toward their end of most of their designs, save for the Salt Storage model. Additionally, for the earlier models they performed intermediate analyses followed by more construction and optimization, suggesting they iterated on their design after the analyses. Many of these intermediate analyses examined only part of the system or part of its yearly production, which may represent seeking a rough analysis in the midst of ongoing design. Team A seems to have spent more time on their earlier designs than later designs.

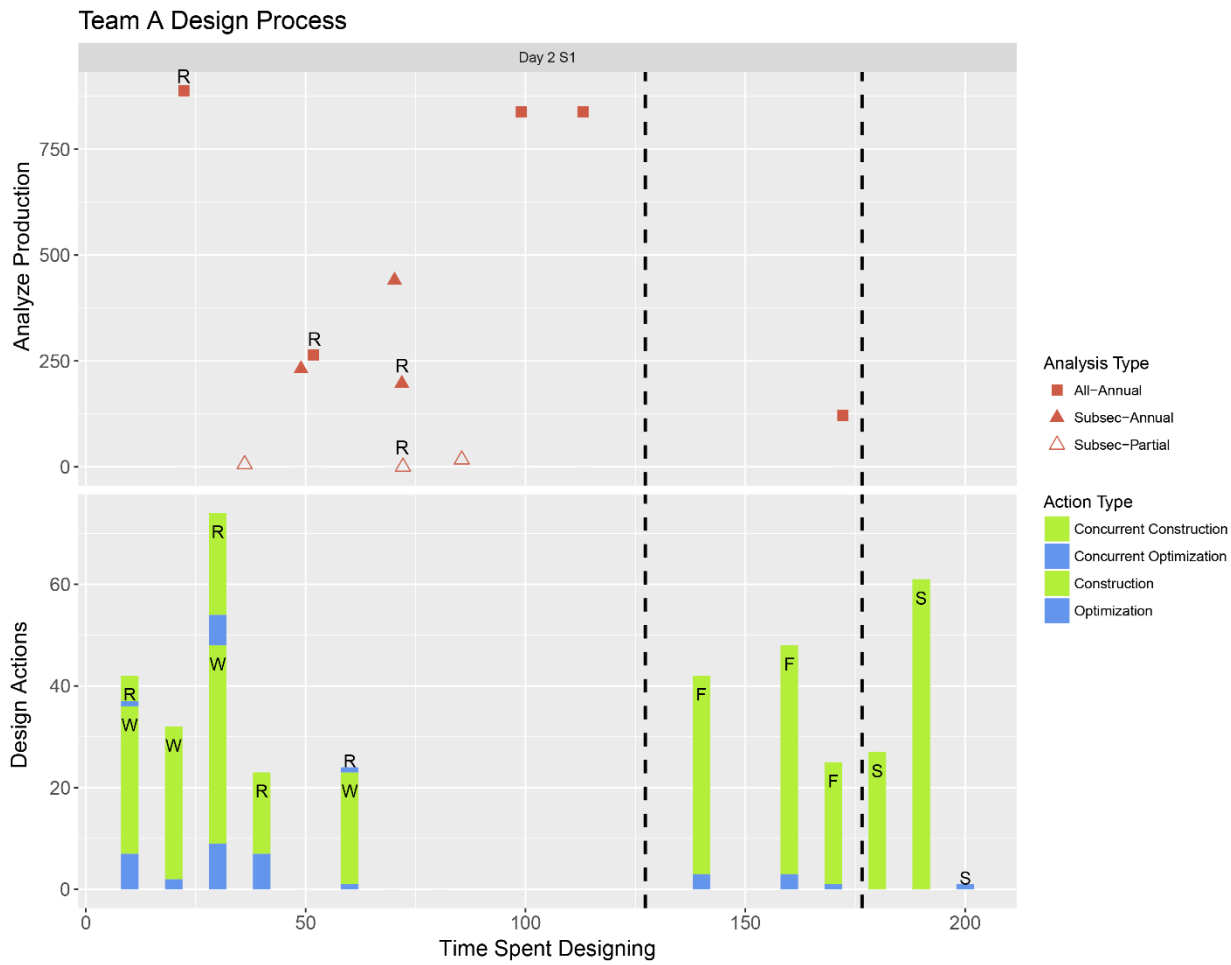

Figure 3 – Team A's Design Process. The lower plot displays their actions on their designs and the upper plot displays the timing and outcome of their analyses on part or the whole of their system. They spent 2 hours 6 minutes actively designing.

Team B's design process is displayed in figure 4. Team B only considered a single site, the Ice Rink, and submitted a solar array design for that site. They engaged in regular optimization intermixed with their construction and analyzed their design after it was mostly completed. Their total active time on the design challenge was relatively short at around an hour and a half.

Team C's design process is displayed in figure 5, below. Team C graph reveals a large number of optimization tasks near the beginning of their first two design sessions. Part of the explanation for Team C's high level of optimization is that they applied changes to individual racks instead of applying to all racks on the scene and then analyzed the changes with a daily analysis (not plotted here). The unusual distribution of optimization actions pushed the authors to inspect the teams original design logs which revealed this pattern of optimization changes and daily analysis. In contrast to the annual analysis, daily solar analysis is quick, but only provide a limited picture of an arrays production as production varies substantially throughout the year, particularly for locations at greater distances away from the equator.

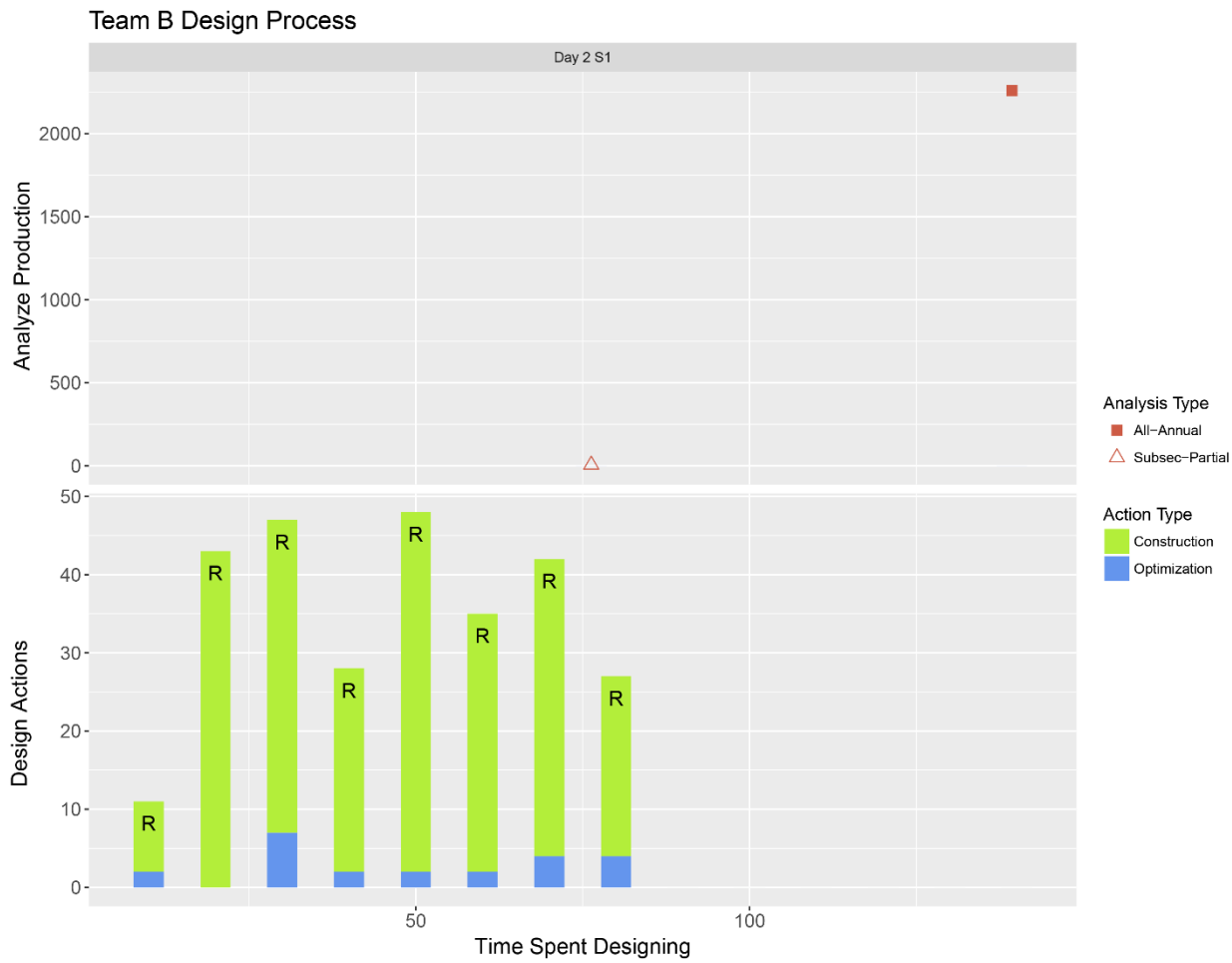

Figure 4 - Team B's Design Process. The lower plot displays their actions on their designs and the upper plot displays the timing and outcome of their analyses on part or the whole of their system. They spent 1 hour and 16 minutes actively designing.

Like Team B, Team C only submitted one model, however they originally designed on the Elementary School site before abandoning that site for the High School. Team C conducted intermediate and final analyses of their designs and seem to have a series of small additions and analysis that occupy their final design session. The modest change to their systems production and small number of actions taken on the system suggests the team is refining their design before completing it.

Team D's design process is displayed in figure 6. Like Team A, Team D submitted 3 sites, which were the only sites they considered: Ice Rink, Elementary school and the Public Works Building. Their time on each design was relative short and optimization only appears to have happened at the beginning of each of these sessions. Team D mostly analyzed their systems at or near the end of their design. For their second and third designs their final analysis examined only part of its annual production and/or part of the full system of panels.

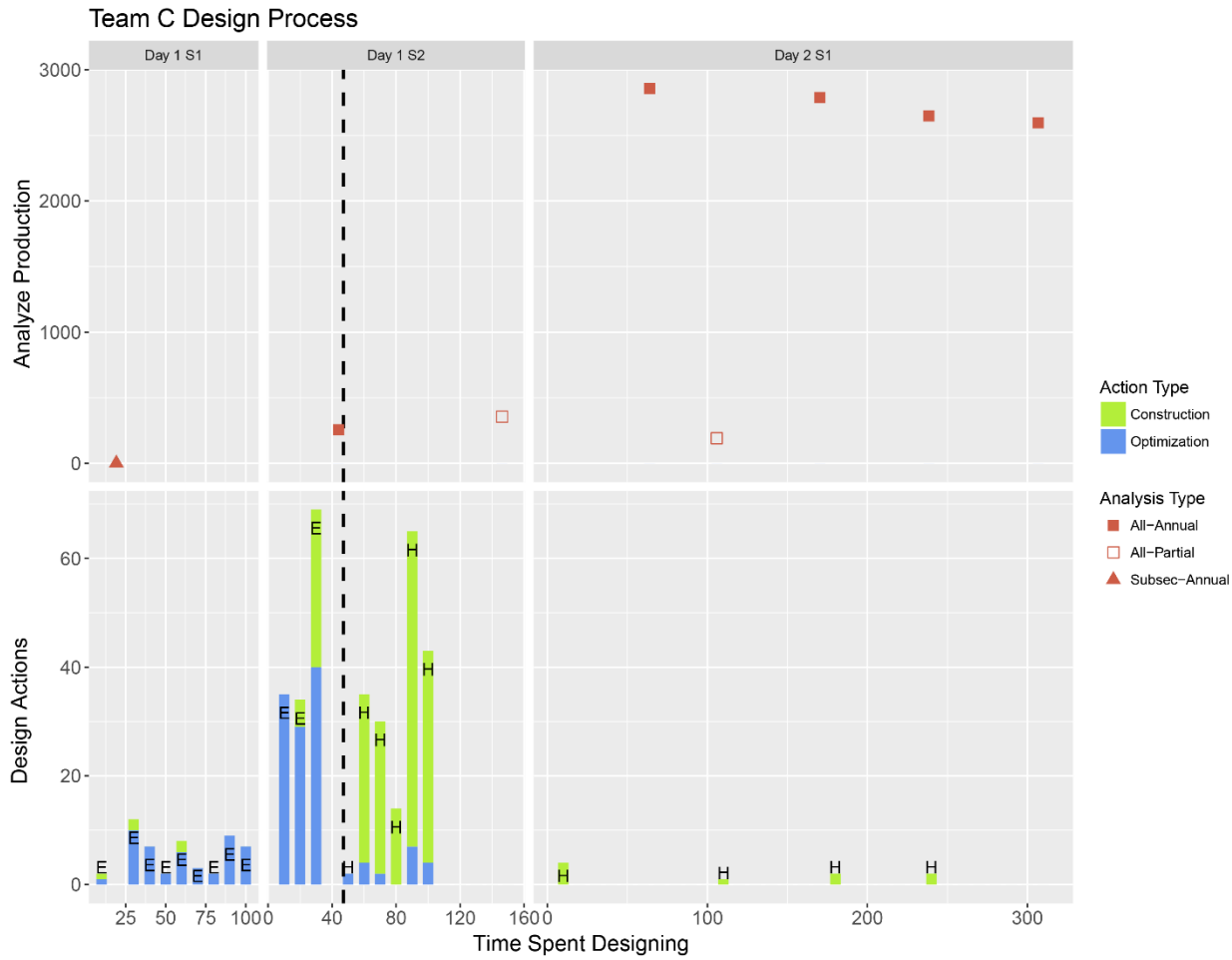

Figure 5 - Team C's Design Process. The lower plot displays their actions on their designs and the upper plot displays the timing and outcome of their analyses on part or the whole of their system. They spent 3 hours and 10 minutes activley designing.

Finally, turning to students' performance on their final designs, teams' energy production, cost effectiveness, cost and aesthetics are displayed in Table 4. The final score is achieved by rank ordering categories, multiplying the category weights by the rankings, and summing category scores. Looking across teams' most of their plots showed a regular pattern of alternating between construction and optimization on their solar array systems.The only team who did not, Team D, showed lower cost-effectiveness on their final models cost/production. This may have been further complicated by Team D only conducting partial analysis of their second and third system, meaning they lacked full information on its performance before submitting them. Due to trade-offs between costs and energy production, Teams A, B, and C had similar final scores as A emphasized cost and cost effectiveness whereas B and C emphasized energy production over cost. Lack of regular optimization across several designs may have led to suboptimal placement of racks and lower cost-effectiveness of their designs, overall. In the case of Team C, a heavier emphasis on optimization on earlier designs,

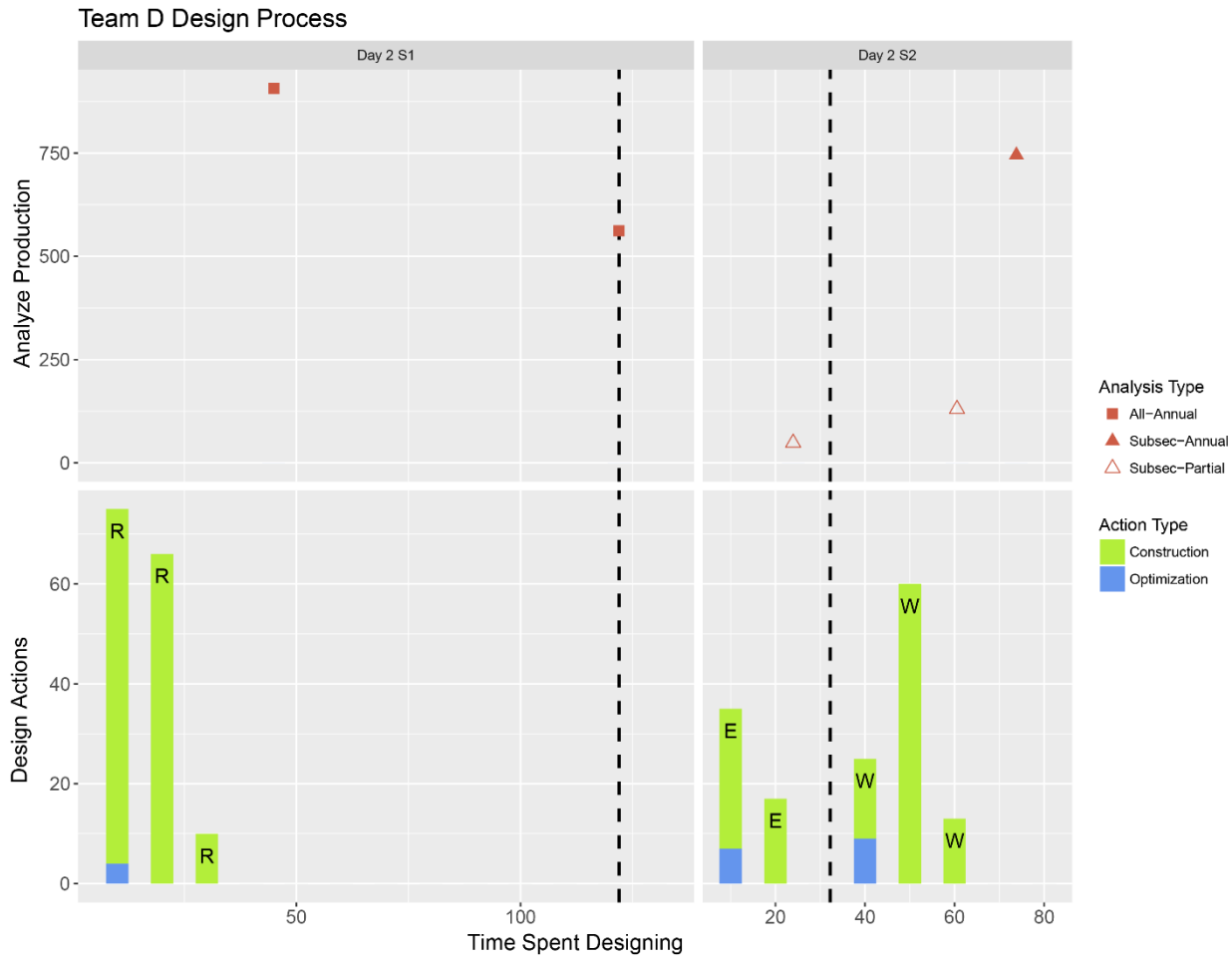

Figure 6 - Team D's Design Process. The lower plot displays their actions on their designs and the upper plot displays the timing and outcome of their analyses on part or the whole of their system. They spent 1 hour and 20 minutes activley designing.

Table 4 - Teams' Rank by Design Criteria

Team	Energy Production (.4)	Cost Effectiveness (.4)	System Cost (.1)	Aesthetics (.1)	Final Score
Team A	1.30 GWh	2.63 $/kWh	$3.29 mil	Second	2.3
Team B	2.26 GWh	2.82 $/kWh	$6.37 mil	Third	2.1
Team C	2.59 GWh	2.88 $/kWh	$7.44 mil	First	2.1
Team D	2.21 GWh	3.25 $/kWh	$7.41 mil	Last	3.5

particularly on sites that were ultimately abandoned may lead to increased cost and lowered cost effectiveness, as optimization is contextual to a given sites attributes. In a similar vein, Team D only optimized at the beginning of their designs at each site and their designs showed lower cost effectiveness and higher costs. On aesthetics, teams who spent less time on their designs, namely Teams B and D, performed the lowest on this measure. Team B covered the Ice Rink with racks, obfuscating the HVAC systems on the top of the building, whereas Team D placed their racks in unusual diagonal patterns that were not aligned with any roofline.

Discussion

This preliminary analysis revealed several interesting findings. First, in addressing research question 1, which examines how teams approached their design, despite the potential gains of designing on several sites, only one team exhibited concurrent designs as revealed by their logs. This may reflect that teams preferred to work collectively on their designs or that not all members were engaged in the design as others. Teams also varied in how and when optimization was used to develop their designs. Furthermore, half the teams submitted designs for multiple sites whereas the other half submitted a design that was concentrated on one site. Second, in addressing the research question 2, about relationships between teams' design patterns and their design(s) final performance, a regular pattern of alternating between construction and optimization throughout their design process appears to be related to cost effectiveness. Alternating between these processes can happen at a global and site/session level and appears to be important at all these levels. Optimization may help students understand properties of the systems they are working with in general (i.e., solar array systems) and will help attune their designs to the contextual factors at play at any given site, such as shading from roof structures in different seasons. Conducting only partial analysis throughout or at the end of teams' design(s) also appears to be related to lower cost-effectiveness. Partial analysis, either by subsection of the entire design or of an entire production year leaves the team with less information to accurately judge the efficacy of their design and may lead to less optimal decisions.

Lack of optimization throughout the design of a particular site may also affect the aesthetics of the design. Finally, time spent designing appears to be related to the aesthetics of teams' designs. Less time spent on the design process leaves less time for addressing the form of their design(s) and may lead to rushed functional designs that rank lower on aesthetics.

Limitations

Due to the unique nature of the engineering program where this research data was collected, the senior students had considerable design experience entering into this design challenge. As such, the sample in this study may be less comparable to engineering students at other engineering colleges.

Conclusions

Team-based design experiences are a critical component of an engineer's education but the large volume of actions, iterative process and open-ended nature of engineering design can make tracking, representing and learning from them challenging. This work-in-progress proposes visualization of design team analytics, focusing specifically on construction, optimization, analysis and their distribution over time to make sense of teams' design processes. We found that only one team worked on multiple sites concurrently, that optimization patterns varied between teams and that optimization across teams' entire design process and within site/session work seems to be related to their final design performance. Learning analytics such as these are quickly and stealthy captured by automatic logging systems, such as Energy3D, and not only provide insight into teams' design process but could be deployed as reflection or dashboard tools

for design teams or as input to design teachers or mentors to inform them of teams' progress and status.

Future work aims to continue to develop the visualizations while incorporating more analytics. We also aim to extend this work to other populations to enable cross-group comparisons on design team analytics and consider how the findings may be redeployed for learning and teaching purposes.

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