MAKING SENSE OF MULTIPLE OPTIONS FOR THE DESIGN OF A CLASSROOM

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ABSTRACT

The changing nature of education has forced educators to rethink the role of classrooms in student learning. Prior research has shown that the environmental and structural design of education centers impact student learning. With a dozen variables to deal with, classroom designers are faced with the daunting task of selecting one plan from the thousands that are possible. This paper demonstrates how tradespace exploration (TSE), an analytical methodology used by NASA and the DoD to design spacecraft and other complex systems, can be applied to the design of classrooms. To demonstrate the TSE methodology, a predictive model was built based on historical data collected by prior researchers on third and fifth grader test performance and data along 86 descriptive variables that they used to characterize the school and classrooms. An analysis of main effects using a multi-way ANOVA allowed the larger data set to be reduced to 8 composite independent variables that are predictive of student tests scores. This model was then used to generate thousands of possible school and classroom design permutations and predict the resulting student test scores. This allowed the authors to identify the Pareto frontier of designs that yield the greatest benefits for a given investment. The case study described in this paper demonstrates how this approach could be applied to enable decision-makers to identify a more effective allocation of resources or determine when changes in total investment are likely to have a significant impact on desired performance.

INTRODUCTION

Can the designers of classrooms borrow a process used by satellite project managers to select a design that yields the greatest outcome for the investment? In both cases, designers have a variety of features that come in different sizes to choose from: multiple options yield thousands of variations of the final product. NASA and the Department of Defense (DoD) are currently using a process called tradespace exploration (TSE) to model the effects of multiple design parameters and aid in the selection of a plan that best addresses an immediate need. This paper represents an initial attempt to demonstrate how TSE can be utilized to inform classroom design decisions that result in the greatest student achievement for the money invested.

BACKGROUND

The changing nature of education has forced educators to rethink the role of classrooms in student learning. School facility planners need to pay a greater amount of attention to the design of classrooms. Improvements at that level "will directly benefit the young children in schools" (Achilles, 1999, p. 2). Students relate to the built surroundings where they spend a school day. The environmental and structural design of this learning center impacts student learning (Earthman & LeMasters, 2009; Tanner, 2009, 2014).

"Structure must change before culture can change" (Ouchi, 2004, p. 18). There are several structural and environmental factors (controlled variables) that contribute to student success. Among these are: floor space, ceiling height (relates to room volume), area of window glass (relates to natural light), light fixtures, temperature control, air quality, cleanliness, air conditioning, safety, noise level, view of the environment, color of classroom walls, and cost (American Federation of Teachers, 2006; Duncanson, 2014; Earthman, 2004; National Summit on School Design, 2005; Tanner, 2014). With a dozen variables to deal with, classroom designers are faced with the task of selecting one plan from the thousands that are possible.

THEORY OF MAKING CHOICES

People make choices every day without a lot of thought: what to wear, what to eat. Decisions that affect a lot of people or large amounts of money involve a large risk (Buchanan & O'Connell, 2006). Risk is a numbers game that people deal with in different ways. The aim of good decision-making is to choose an available alternative that offers the greatest benefit relative to the cost or other resources that must be given up to achieve it.

Having an excessive number of choices can be a bad thing. That situation leads people to feel they could have done better if they had more time (Tugend, 2010). That is the situation educators face when designing a classroom. Just using the eight variables from the case study shown in this paper, with five different levels for each results in more than 100,000 possible designs. Creating a mathematical model can move people toward making a rational decision. Using TSE has the power to assist classroom planners in the selection of a design that supports educational goals.

TRADESPACE EXPLORATION

Tradespace exploration (TSE) is a process to deal with complex planning problems that include large sets of data. TSE can provide a way to model the effects of multiple design parameters, their impact on test performance and cost to better inform strategic decision-making. Running an integrated model for multiple permutations of different levels of the design variables results in a large set of candidate alternatives (e.g. tradespace). As shown in Figure 1, this allows us to plot each alternative relative to its cost to graphically identify the best alternatives. The alternatives that cannot be improved in terms of the benefit they provide without becoming worse off on the cost axes (or vice versa) are called Pareto optimal solutions (Pareto, 1906). The set of all such solutions define the Pareto frontier. If the design requirements are adequately characterized, the designer wishes only to consider Pareto Optimal solutions because these solutions provide the most benefit relative to their cost.

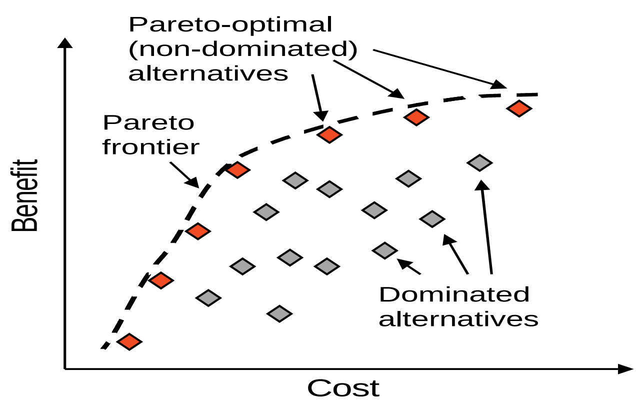

Figure 1. A plot of the permutations of the design variables produces a curved surface called the Pareto frontier. Points along thr curve are the best choices for the product being designed relative to the cost (Curry, 2014).

KEY INDEPENDENT FACTORS

Tanner (2009) reported the results of studies that correlated classroom characteristics to student achievement. These areas will be used in the TSE.

Table 1

Correlations between key factors and student test scores (Tanner, 2009)

Characteristic	Pearson Correlation (R)
Light – window area	0.592
Wall color	0.545
Pathways - % open floor space	0.503
View of environment	0.502
Available technology	0.506
Quiet places	0.478
Display space	0.475
Safety	0.439

Natural Light – Window Area - View of the Environment

A feeling of comfort can be added by the view from the windows. Students need to see outside. Anthes (2009) states:

> …students with restricted views of at least 50 feet outside the window, including gardens, mountains and other natural elements, had higher scores on tests of vocabulary, language arts and math than did students without such expansive vistas of whose classrooms primarily overlooked roads, parking lots and other urban features (p. 56).

Tanner (2009) reported that 25-50 sq.ft. of windows was needed for each 100 sq.ft. of classroom floor. Natural light has a positive effect on student outcomes in Science and Reading Vocabulary scores. Natural light adds to physical and mental comfort. Tanner (2015) noted that "Outside green spaces and "views" and "views overlooking life" are a logical consequence of having windows in classrooms" (p. 7).

Wall Color

Cash & Twiford (2010) found that a focal point in a classroom was best identified through the use of one medium tone of blue, brown or gray with a neutral surrounding. Younger children like bright colors. It contributes to less eye strain and increased attention span. A feature wall with a bright color enhances learning. Splashes of color on the floor, desks and chairs can complement the walls (Barrett, Zhang, Davies, & Barrett, 2015). Dark colors, black, and gray lead to negative feelings for the occupants. Black and gray are the least preferred colors by students. White walls result in under-stimulation leading to restlessness and loss of concentration. Youngsters describe these colors as being weird (Jalil, Yunus, & Said, 2012).

Pathways - % Open Floor Space

Young children are "rug-rats": they look at space horizontally. Given a choice, youngsters will spread out on the floor. They require greater amounts of horizontal space than adults (Achilles, 1999). Open floor space is positively correlated to higher test scores in Science and English Language Arts (Duncanson, 2003, 2009). Open space on the floor is important to provide broad pathways so students can move freely (Tanner, 2009). Narrow pathways between rows of student desks do not count as open floor space. Two youngsters need to be able to pass each other without making contact.

Available Technology

Computers have become a powerful educational tool. It is important to regulate their use so they do not override personal interaction between students (Higgins & others, 2005). Technology has enabled students to collaborate on a global scale. The scope of global problems is now an open area for students where they can involve themselves using problem solving skills to address topics of interest to them. The opportunity to follow their own passion often leads to students staying on an important task and be self-directed: practices valued by adults (Schwartz, 2013). Teachers can empower students when appropriate technology and communication tools are readily available for the students to use (November, 2018).

Quiet Places

Good acoustics – meaning a quiet environment – is essential to support adequate academic performance. Noise distracts attention to the learning process and results in impaired performance particularly in reading proficiency. Children lose track of what they are thinking and thus fail to transfer knowledge into memory. Noise affects mood. This is especially true during times of silent reading when external noise becomes distracting. The use of carpeting can help to alleviate this problem (Higgins & others, 2005).

Teachers are beginning to alter classrooms to increase the number of quiet, comfortable areas for students. The Clearview School in Rolleston, New Zealand, created classrooms so students could sit on the floor on bean bags, ottomans, or at tall desks with whiteboard surfaces they can write on. Staff and students love it. The principal cites higher levels of student engagement. Students are taking more responsibility for their learning. Teachers say they will never go back to an old-fashioned classroom (Law, 2013).

Display Space

Displaying student work is important. Uncluttered displays increase youngster's feelings of ownership and make schools more welcoming (Higgins & others, 2005). Well planned bulletin boards can teach material pertinent to the current curriculum. When students plan and create displays they practice problem solving and learn about important academic topics. Artwork, writing, photos, and 3-D projects should each have their own section to look organized. Bulletin boards need to be visible to all students and the teacher should refer to it each day (Duncanson, 2006).

Safety

Communities expect that students will be safe while in school. School districts are now required to develop a District-wide School Safety Plan designed to prevent or minimize the effects of serious violent incidents and emergencies and to facilitate the coordination of the district with local and county resources in the event of such incidents or emergencies. District personnel must have a plan to deal with violence, natural hazards, and technological incidents. Natural hazards can include dangerous weather conditions (ice, snow, fog, tornado, trees blown across highways), and chemical/biological hazards. Actions of administrators and teachers must be outlined for each category of concern (Pine Bush, 2017).

MODEL DEVELOPMENT

To apply tradespace exploration to analyze school designs we must first build a model that relates the 8 key areas described above and any additional independent variables to student classroom performance. To do so, we can draw upon the source data used to calculate the correlations in Table 1 as originally described by Yarborough (2001). Yarborough collected data student test score data for 24 schools and descriptive data along 86 different dimensions that characterize the school and classrooms. For each of these schools other independent factors such as demographic data and training and experience level of the teachers was also collected.

Using this data an analysis of main effects was performed using a multi-dimensional analysis of variance (ANOVA) to identify the dominant independent variables that contribute to third and fifth grade test scores. Of the 86 variables collected, the ANOVA identified 20 of the 86 variables as the primary contributors to student test scores. These 20 variables could be categorized into the 8 key areas identified above to create 8 composite variables for each of the 24 schools as shown in Table 2. From there, a multi-dimensional regression model was built using the Eureka software package that uses machine-learning to identify equations that relate the 8 composite variables to third and fifth grade test scores for the 24 schools.

To confirm the predictive power of the developed model it was run using the 8 composite variables for each of the 24 schools. As shown in Figure 2 below, when the model outputs are plotted against the actual test scores reported by Yarborough there are a few outliers, but the model generally tracks close to the actual data. For the developed model the average residual (difference between actual test score and score predicted by the model) was around 4 test points.

To apply tradespace exploration to this problem we also need a model of the cost expended for each school design. Since actual cost data was not available for the 24 schools a notional "cost score" was created by summing the 8 composite variables for each school as a proxy measure for cost. This model could be replaced with a more realistic cost model when more detailed data becomes available. As shown in Figure 3, when this notional cost score is plotted against the average predicted test score for third and fifth graders for each school we see that cost generally increases with test scores as might be expected.

Table 2
Actual test scores and composite descriptive variables for 24 schools (0 – 10 scale)

School	3rd Grade Scores	5th Grade scores	Light	View	Color	Paths	Tech	Quiet	Display	Safety
1	29	24	5.5	4.3	6.3	7.0	0.0	2.3	0.0	8.0
2	35	32	8.0	6.3	7.3	7.0	5.0	2.3	10.0	10.0
3	27	33	2.0	1.7	3.5	7.0	0.0	2.3	0.0	10.0
4	60	37	3.0	2.7	6.3	8.0	8.0	0.7	0.0	10.0
5	33	38	6.5	7.0	9.5	9.0	6.0	3.3	2.0	2.0
6	33	41	3.5	4.3	6.7	6.0	7.0	3.3	0.0	10.0
7	34	43	6.0	3.7	7.3	8.0	7.0	4.0	0.0	8.0
8	51	48	5.0	5.0	6.3	5.0	7.0	0.7	5.0	8.0
9	52	49	5.0	7.3	7.2	7.0	4.0	5.3	0.0	10.0
10	43	51	4.5	4.0	6.3	8.0	4.0	1.7	0.0	10.0
11	35	51	5.0	5.0	7.5	8.0	3.0	2.0	2.0	8.0
12	70	53	9.5	7.3	6.8	10.0	10.0	3.3	0.0	10.0
13	48	54	6.5	7.3	9.2	10.0	8.0	5.0	6.0	10.0
14	60	56	3.5	4.3	5.8	6.0	10.0	2.0	0.0	10.0
15	56	57	7.5	4.7	6.5	8.0	5.0	0.3	0.0	10.0
16	63	57	6.0	8.7	9.2	8.0	5.0	4.7	0.0	10.0
17	44	58	7.5	5.0	5.7	10.0	10.0	4.0	10.0	10.0
18	47	59	6.5	6.3	7.2	7.0	4.0	0.7	8.0	10.0
19	54	60	7.0	3.3	5.5	8.0	5.0	2.7	0.0	7.0
20	63	62	7.5	7.0	4.8	10.0	8.0	0.0	0.0	10.0
21	57	64	5.5	6.0	3.8	10.0	5.0	2.7	8.0	10.0
22	62	64	7.0	6.0	8.0	8.0	8.0	1.3	0.0	10.0
23	59	68	6.0	3.0	9.2	7.0	8.0	1.7	0.0	10.0
24	72	72	5.0	5.7	5.8	9.0	4.0	3.3	0.0	10.0

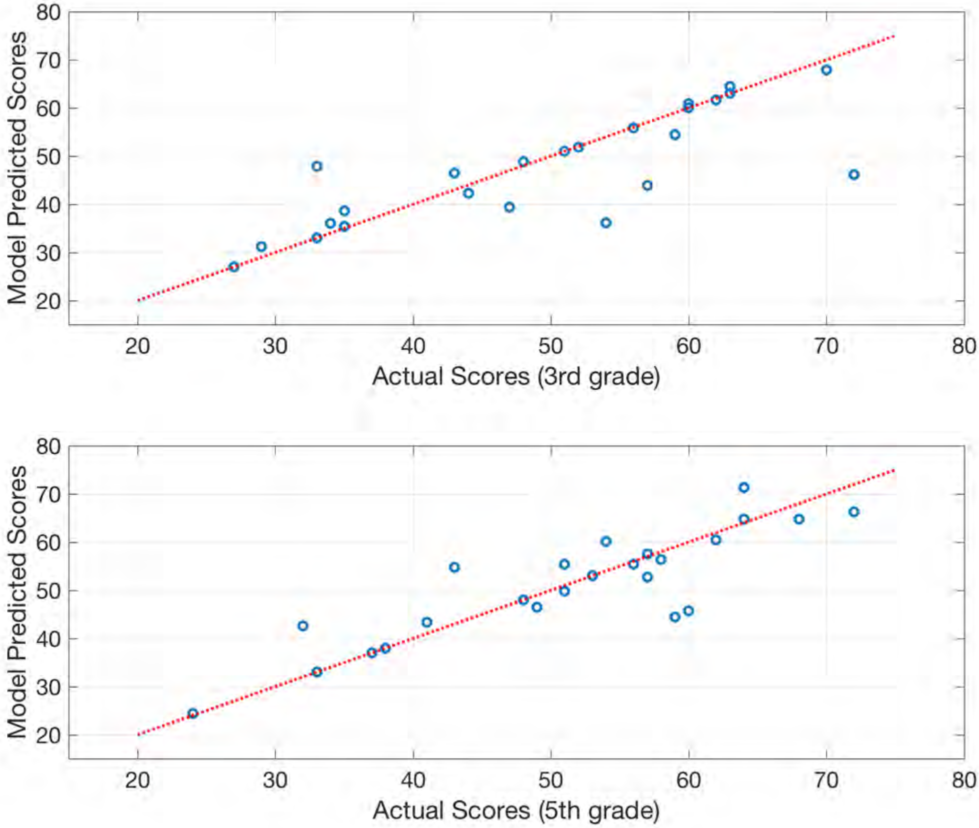

Figure 2. Comparison of model predicted test scores with actual test scores for third and fifth grade students.

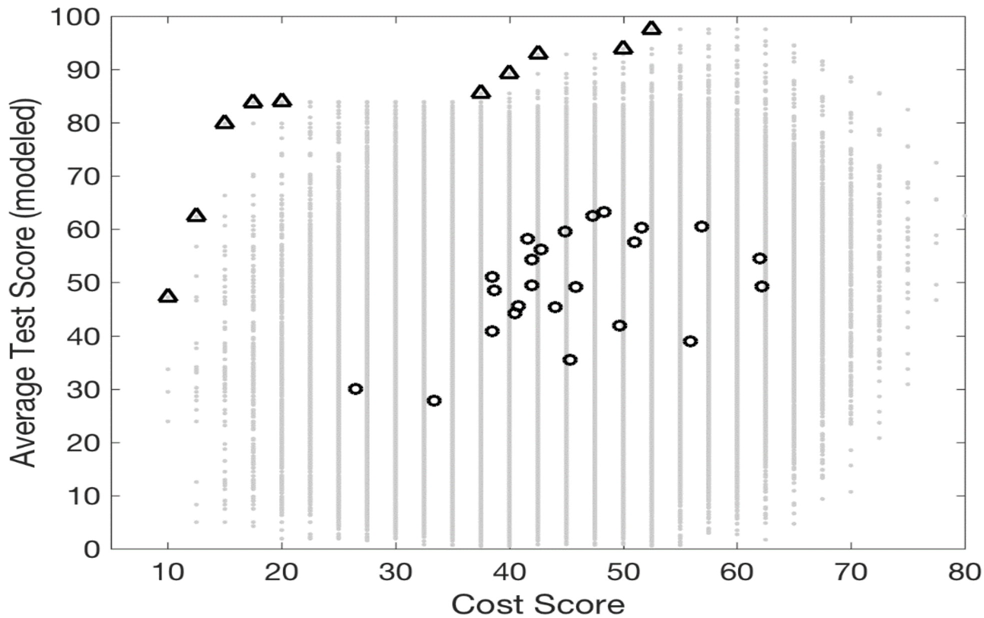

Figure 3. Average test scores versus a notional cost score for the 24 schools.

RESULTS

Applying the model described in the previous section a large number of theoretical school design concepts can be generated. If we consider 5 different levels (ranging from a minimum score of 0 to a maximum of 10) for each of the 8 model input variables we can enumerate 5^8 combinations and run the model to predict third and fifth grade test scores and associated cost score for each design concept. Eliminating the infeasible designs leaves us with approximately 150,000 combinations of schools that could be built.

Figure 4 shows the tradespace of all enumerated designs on a cost versus average test score scatter plot. Examining the tradespace in this way allows several important insights about the various alternatives to be observed. First, it can be observed that cost expenditures below 15 result in a steep decline in test performance. Conversely, cost expenditures about 50 show diminishing returns on further investments. Second, for each of the original 24 designs there exists a theoretical design concept at the same cost score that achieves higher test score performance. This implies that if the same level of resources were allocated differently theoretically higher test scores could be achieved without any additional cost expenditures. Alternatively, the same test scores could be achieved at lower cost expenditures.

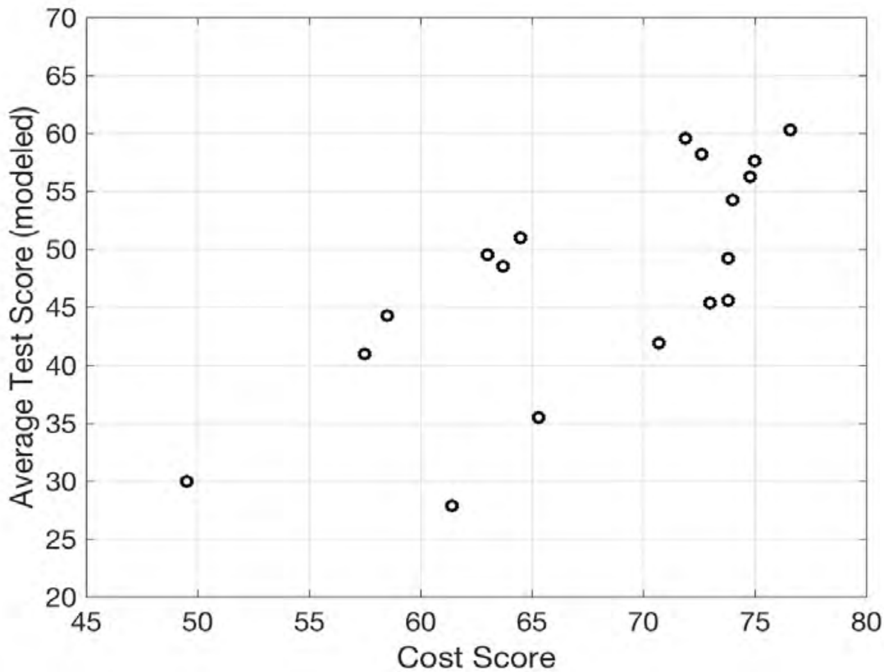

Figure 4. Tradespace of 150K school designs (gray points). Pareto optimal designs (black triangles). Original 24 actual designs (black circles)

CONCLUSIONS

The results from the case study described in this paper show the potential benefits and insights that can be derived from applying a tradespace exploration approach to the design of schools. Modeling school performance and the key factors that impact it parametrically allows a broader range of possible design choices to be explored. This enables decision-makers to select a design that yields the greatest benefits for a given investment. As shown in the case described here this allows decision-makers to potentially identify a more effective allocation of resources or determine when changes in total investment are likely to have a significant impact on desired performance.

A limitation of the current approach shown here is the assumption that decision-makers have a “blank slate” from which to select school design parameters. In reality, various additional constraints would be imposed by existing infrastructure, regulations, and other exogenous factors. Future research could relax these assumptions and build upon the basic methodology to enable the development of decision-making support tools that provide prescriptive guidance to school administrators and other stakeholders seeking to improve classroom performance.

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APPENDIX

The empirical model developed for this study can be expressed as follows:

3rd grade test scores $= a_1 + a_2{*}x_5 + a_3{*}x_2{*}x_6 + a_4{*}x_6{*}x_8 - a_5{*}x_6 - a_6{*}x_3{*}x_7$

5th grade test scores $= b_1{*}x_4 + b_2{*}x_5 + b_3{*}x_1 + b_4{*}x_8 + b_5{*}x_1{*}x_5 - b_6 - b_7{*}x_4{*}x_5 - b_8{*}(x_1^2)$

Cost score $= x_1 + x_2 + x_3 + x_4 + x_5 + x_6 + x_7 + x_8$

Where $\mathbf{x}_N$ are the composite independent variables that describe the school and classroom characteristics (Table A1), and $\mathbf{a}_N$ and $\mathbf{b}_N$, respectively, are coefficients for the third and fifth grade test score models (Table A2 and A3). These coefficients were derived from the machine-learning algorithm that was used to determine the underlying regression model.

Table A1
Variable names for model independent variables

Variable	Name
x_1	Light
x_2	View
x_3	Color
x_4	Paths
x_5	Tech
x_6	Quiet
x_7	Display
x_8	Safety

Table A2

Coefficients for 3rd grade test score model

Coefficient	Value
a_1	44.3649610890026
a_2	2.51129941159534
a_3	1.26592538696679
a_4	0.721787209003415
a_5	16.9361574119665
a_6	0.239948773781894

Table A3

Coefficients for 5th grade test score model

Coefficient	Value
b_1	21.8213900739134
b_2	16.7906506111824
b_3	11.7025344365418
b_4	3.14960935810029
b_5	1.46096479555781
b_6	168.067628065439
b_7	2.9792013033419
b_8	1.6458063302796