

White Paper — 21st Century Technology Series

Building Happy Schools: Parametric Modeling for 21st Century School Improvement

A parametric virtual model is a dynamic, multi-dimensional virtual surrogate of an organization and its physical environment. Information about workflow is incorporated into the model so that it can accurately represent both the physical and the strategic reality of the organization. Such models have been used for decades to design commercial structure from jet planes to petrochemical plants. Today, the technology needed to create, manage and use such models has become so inexpensive and ubiquitous that it makes little sense not to use such models for all enterprise planning.

To build a parametric virtual model in today's world of web-enabled technologies is to build a real-time on-line simulation of the organization that operates in the virtual world in every respect as its physical counterpart operates in the real world. Construction ideas can be tested in the virtual world before a single penny is spent in the real world. The model ensures that all stakeholders see the same plan, that all contractors receive a clear and unambiguous definition of their deliverables and, eventually, that what is delivered is what was modeled. The model can also continue to collect and deliver information about how the operating environment delivered by a building meets its original goals and supports the workflow of the organization long after the builder and architect have moved on to other pastures.

The model is a single, interconnected system that correlates intangible values, tangible real constants, operational reality and real and projected costs. It allows different stakeholders to access different viewpoints into the business, from a mile-high bird's eye view to the drill-down view that provides actionable details, and to access these viewpoints through a simple web-based interface that does not require individual desktop licenses. All of the supporting documentation, all of the cost data, all of the detailed design documents are accessible through the same web-based interface. If necessary, security protocols limit access to sensitive information through password or otherwise controlled login.

Building Schools that Work in the 21st Century

It is clear that as teaching modalities are being analyzed and redesigned in response to 21st century issues, technologies and learning modalities, so too school buildings must be analyzed and re-designed to serve the workflow of 21st century education. There are myriad studies, research reports, proceedings, papers, articles and speeches that address the impact of school design on education. Still, a foundation-funded report published in October 2006¹ reports that "Almost no schools are designed with the specific objective of creating healthy and productive study and learning environments." Yet the tools required to design school buildings that substantively contribute to delivering quality education are available now.

The US Department of Education's National Symposium on School Design developed design principles for the 21st century a decade ago that were endorsed by all the major professional associations that work in school construction. The first one: "To meet the nation's needs for the twenty-first century, school learning environments should ... enhance teaching and learning and accommodate the needs of all learners." Still, as recently as October 2006, an expert could say: "Good school design can be defined and it can be measured. This makes it all the more odd that more than 99% of the \$30 billion that the U.S. spends on school buildings each year goes into the construction of schools that will fail the test of

We tame \$10 elephants.



good school design.”² It is not only odd, it is tragic: “While the effects of school and classroom design may be subtle, they are also likely to be highly persistent, influencing the performance of generations of students.”³

A Parametric Approach to Building 21st Century Schools

Parametric modeling is so called because it is driven by parameters, variables or constants that define the dimensions of the organization. Models begin with the basic three dimensions of Euclidian geometry and add dimensions of information to become four-, five-, six- or simply multi-dimensional. Parametric tools can evaluate a proposed school design against any set of standards that can be measured. This means that in addition to the four major environmental parameters that define the comfort of interior space (lighting, indoor air quality, acoustics and temperature), the design can be evaluated for workflow, that is, for its impact on the performance of the students.

Sufficient information exists to very specifically define a host of these parameters. The model can thus evaluate how well or ill these dimensions support the educational mission of the space, which depends on their inter-relationship with not only the people who inhabit the space and those who fund and maintain it, but also the principles that drive their curriculum. With this information in hand, there is no excuse for not deliberately designing schools to support learning. What are the dimensions that should be parametrically driven in a model of the 21st century school? Well, to look at the most obvious:

- ▶ The dimensions and interrelationship of the physical shape of the space
- ▶ The physical characteristics of the environment enclosed in that space
- ▶ The fiscal dimensions of capital and operational costs

The Physical Shape of a School and Its Relationship to Student Success

The links between employee productivity and commercial building environments have been a topic of systematic study since the first assembly lines were built and the first time and motion studies calculated how long it took one worker to fasten one screw. Workflow — the total flow of functional operations through which an organization executes its mission — drives the design of manufacturing assembly lines, power plants and innumerable other complex building structures. Modeling technologies support workflow optimization, allowing engineers to quantify the impact of design decisions. In recent decades, as the focus of productivity improvement has shifted from industrial workers to information workers, research programs began to explore optimizing the workflow of white-collar workers in commercial buildings.

The business community easily recognized decades ago that, in a service-driven economy, spending money on improving the work environment is the most cost effective way of improving productivity. Since a small percentage increase in productivity can yield dramatic improvements in profitability, a number of research studies have offered ways to define the parameters of the productive work environment and quantify the return on investment (ROI) for improvements. A seminal whitepaper⁴ by [Gensler](#), a leading global architecture, design, planning and consulting firm, estimated that, accumulating the impact of workflow-aligned design on white-collar job satisfaction, recruitment and retention, **workflow-aligned building design can potentially increase productivity up to 19 percent**. What if we could bring this order of improvement to the productivity of our teachers — and to our students’ performance?

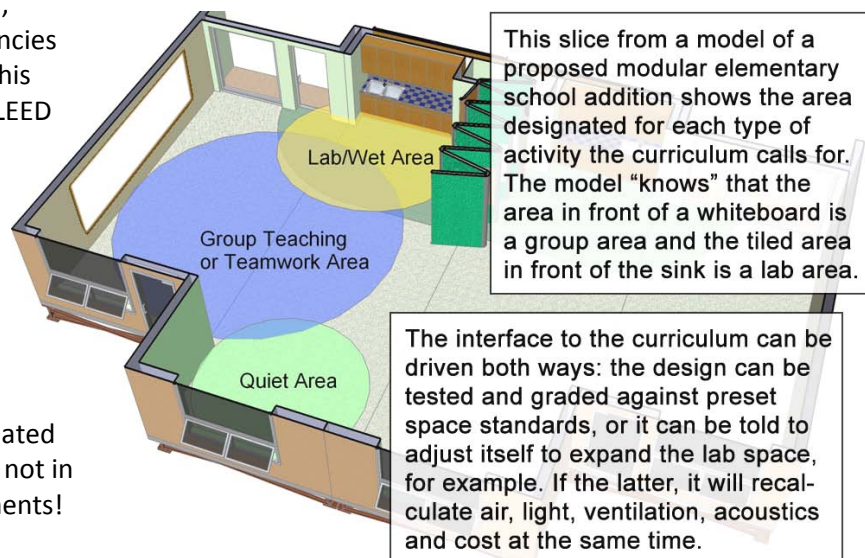
State standards mandate “x square feet of [type] space per student,” spelling out in minute detail the minimum number of square feet of classroom space, hallways, closets, etc., etc. a new school must have for each student — but they say nothing of its shape or quality. Yet the expert community has been ready for years to define with clarity what makes a school layout effective. “There are certain recognizable ‘patterns’ that define healthy spatial relationships [within the purview of school planning and design] both at a micro and a macro level.⁵”

Why, then, stop at meeting minimum square foot requirements? If a pattern can be defined, a design modeled parametrically can be evaluated against it. The model can shine a green, amber or red light on the spatial relationships of any proposed collection of spaces based on the intended academic purpose. As the model is integrated in all its dimensions, what ifs can recalculate their own costs, in terms of capital dollars invested, yes, but also in terms of student performance — which should be the driving ROI calculation for any school building.

The Physical Characteristics of the School Environment

Workflow-aligned design must address not just the layout of the floor plan, but all the parameters of an indoor environment — air quality and ventilation, lighting, acoustics, temperature, etc. There is overwhelming evidence that these indoor environmental characteristics impact productivity. Yet addressing them has too often been seen as purely the realm of energy-efficient design,

increasingly sought after as agencies promote LEED^{®6} certification. This focus on energy-efficiency and LEED certification has hurt school design because it has narrowed the scope of “building performance” to mean the performance of energy-saving designs and equipment. Far too often, the ROI for optimizing the indoor environment of schools is calculated only in terms of energy savings, not in terms of productivity improvements!



The official standards for environmental parameters within schools range from non-existent to distressingly vague to apparently (and dangerously) ignorant. It’s hard to understand why this disconnect between healthy school building design and student performance persists. There is ample acceptance of the impact of *unhealthy* buildings on both student and teacher performance. Innumerable research studies support the inference that the physical environment has a significant impact on student performance. One set of studies concludes “Variables describing the physical conditions of classrooms, most notably the window characteristics, were as significant and of equal or greater magnitude as teacher characteristics, number of computers, or attendance rates in predicting student performance.⁷”

If I were to go to a pet store to buy some fish and an aquarium, I'd get very precise instructions about the temperature, amount, salinity and pH of the water; the nature and arrangement of the tank accessories; and the nature, frequency and quantity of food and light required to keep the fish in optimal health and spirits. A comprehensive aquarium test kit that periodically assays 12 different characteristics of the water would be included to help me ensure that I maintain an optimal environment for my school of fish. While there is a widely published expert consensus about what defines the

Copperbanded Butterfly Fish: Environmental Parameters (partial list) ⁸	Human Schoolchildren: Environmental Parameters ⁹
<p>Aquarium type: Saltwater Reef Tank size: 75 gallon (284 liters) minimum Temperature: 75°F – 82°F (25°C – 28°C) Water quality: Water changes: 20%/week Water flow level: high pH: 8.1 – 8.4 Specific gravity: 1.020 – 1.025 Carbonate hardness (dKH): 8 – 12° Ammonia: 0 Nitrite: 0 Nitrates: 0 Phosphates: < 0.05 ppm Magnesium: 1200 – 1400 ppm Iodine: 0.06 meq/L Oxygen: 5 – 7 ppm Calcium: 350 – 450 ppm Light: 4 – 10 watts/gal., depending on depth T5-HO/metal halide/VHO fluorescent/ actinic Actinic to full spectrum ratio: 1:1 CRI: 90 – 99 Color temperature: 5500 – 10,000K Cycle: On 10 – 12 hrs, off 12 – 14 hrs</p>	<p>Classroom type: <i>Not specified</i> Classroom size: Varies by state and grade Temperature: By state; most 68 – 75°F Air quality: Air changes: By state; most <i>not specified</i> Nitrogen (N2): <i>Not specified</i> Oxygen (O2): <i>Not specified</i> Argon (Ar): <i>Not specified</i> Carbon dioxide (CO2): By state; most <1000 ppmv [OSHA limit] Neon (Ne): <i>Not specified</i> Helium (He): <i>Not specified</i> Methane (CH4): <i>Not specified</i> Krypton (Kr): <i>Not specified</i> Hydrogen (H2): <i>Not specified</i> Water vapor (H2O): <i>Not specified</i> Carbon monoxide (CO): <i>Not specified</i> Light: By state; typical = 50 foot candles at work surfaces, <i>type not specified</i> Acoustics: Noise: By state; most < 55 dBA Reverberation: By state; typical = 0.4 – 0.6 seconds in classrooms</p>

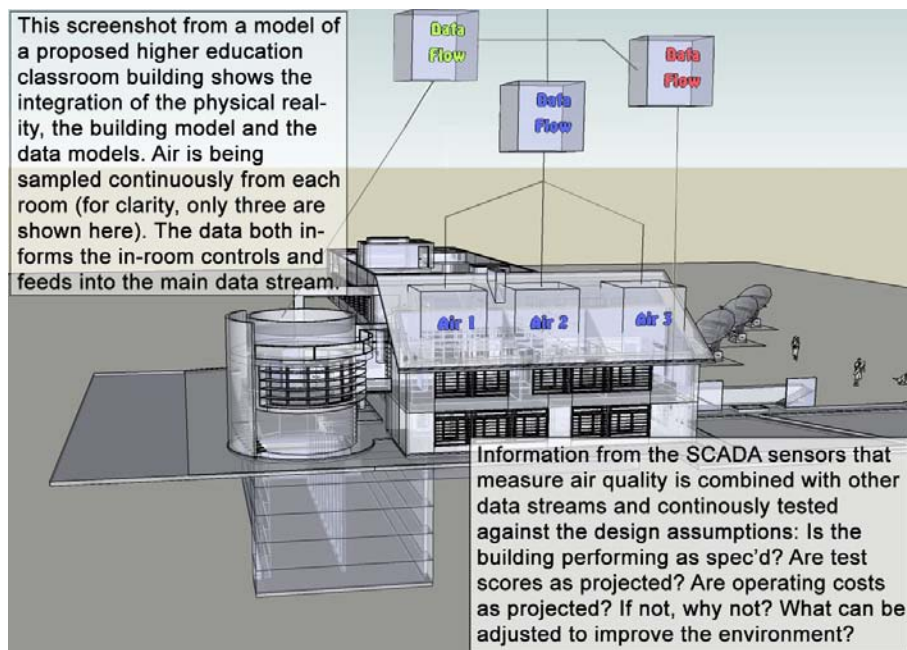
optimal environment for my school of Copperbanded Butterfly Fish, there appears to be an appalling reluctance to specify or even recommend the optimal environment for a school of humans.

Certainly, schools of children are not like schools of fishes: researchers are not generally free to experiment upon them in controlled laboratory conditions and dispose of the adversely impacted organisms. It is difficult to control the conditions of a study sufficiently to be able to say with 100 percent certainty that one particular variable impacted performance and to what degree. Still, one of many is a 2002 study¹⁰ that reports the then 10-year old case of a group of students whose test scores improved by 19 percentage points (from 10% below norm to 9% above norm) the year they were moved from a portable campus to a new, daylit school. The National Clearinghouse for Educational Facilities says it clearly: “School facilities affect learning. ... [W]e already know what is needed: clean air, good light, and a quiet, comfortable, and safe learning environment. This can be and generally has been achieved within the limits of existing knowledge, technology, and materials.”¹¹

Enough data exists to set clear quantitative and qualitative goals for environmental parameters. And if parameters can be set, a parametric model can test the design against them. With SCADA technology, the parametric model can further test the execution against the design. The methodologies exist to hold school buildings to a higher standard: only the will appears to be lacking.

Consider only two of our four environmental parameters: air quality and acoustics. With regards to air quality, the EPA says: “In the mid-1990s, studies¹² show that 1 in 5 of our nation's 110,000 schools reported unsatisfactory indoor air quality, and 1 in 4 schools reported ventilation — which impacts indoor air quality — as unsatisfactory. Students are at greater risk because of the hours spent in school facilities and because children are especially susceptible to pollutants.” Yet most states require schools to measure only one aspect of air — carbon dioxide, which is what humans exhale into their environment — and it's measured at ceiling height when the classroom is unoccupied. Spot measurements at breathing height in a full elementary classroom just before lunch have found levels as high as twice the OSHA standard for adults. No wonder these students struggle!

HVAC is one of the few construction disciplines that has integrated parametric modeling tightly with their engineering process. We know what air is composed of and what the appropriate ranges are for children, teens and adults. With inexpensive SCADA technology, it is an easy matter to set a positive standard for air quality and monitor air at breathing height on an ongoing basis, signaling the HVAC system to refresh the air appropriately as necessary.



Now consider acoustics. Acoustics are of critical importance particularly in situations where teachers are trying to communicate with young children and with non-native English-speakers. There have been many studies of acoustics in school environments and the impact on learning. The Acoustics Society of America (ASA) concludes that “Young children are ineffective listeners for speech in noise until they reach adolescence, when they achieve levels of speech understanding similar to those of adults. Young children do not effectively listen and understand speech in reverberant conditions.”¹³ Another study concludes “[C]ommonly-reported classroom acoustics have a detrimental effect on the speech perception of ESL children and therefore may compromise a student’s academic achievement.”¹⁴

The acoustic performance of a room is easy to measure and monitor. As a society, we invest enormous amounts of energy and money into the acoustical engineering of concert venues. The American National Standards Institute, Inc. (ANSI) and the ASA released a comprehensive standard for schools¹⁵ in 2002. Yet the acoustic standards for schools generally allow almost 60 percent more background noise in classrooms than the ANSI standard. One suspects that this is done so as to allow builders to use conventional materials and methods and still meet standards, likely as a “cost-savings” measure. However, consider this conclusion by the presenters of a 2001 paper: when you compare the incremental cost of upgrading a classroom ceiling during construction by installing a “better acoustical ceiling” with the cost of educating one child, positing a 3 percent improvement in auditory comprehension due to the improved acoustics, the return on investment is 200 to one.¹⁶

The Fiscal Dimensions of Capital and Operational Costs

Educational authorities are notoriously and chronically short of funds, and so we hear that they must settle for the buildings they can afford. No educator would settle for early 20th century textbooks in the classroom, yet those classrooms are being built under early 20th century purchasing conditions. The construction industry is one of the last to promote the paradigm that increases in scope and quality are inextricably yoked to increases in time and cost — and they have done an excellent job of selling this

paradigm to educational facility purchasers. In virtually all other industries, however, rigorous process engineering continues to drive down costs and time, while product features and quality continue to improve, because today the market will stand for no less. This 21st century paradigm drives the purchase of computers for the classroom, why should it not drive the purchase of the classroom?

Wise use of integrated parametric modeling technologies can lead to lower costs and higher quality facilities, both by containing capital costs during the design and construction stages and by containing operating and maintenance costs after the buildings are occupied. In the earliest stages of the project, efficient use of parametric modeling technologies can drastically reduce “soft” costs of construction, allowing more bond dollars to be realized as brick and mortar rather than drawing and reports. While on-site school construction costing formulas today allow over 45 percent for design and engineering costs, Boeing maintains soft costs for designing and engineering jumbo jets under 22 percent!

Parametric modeling allows the requirements to drive design from within the model. There is no need to produce 200-page reports packed with tables demonstrating that all the closets meet the state’s standards, and to re-issue them after each minor modification: the model calculates compliance on the fly and flags exceptions. If a written report is required, it can be extracted from the model’s data repository and simply re-formatted for print output. The ability to have all the stakeholders walk through the simulated structure throughout the design stages drastically shortens decision-making. Design acceptance in virtual walk-through before the first nail is ordered virtually eliminates change orders.

Trade-offs and ROI are transparent and easily re-calculated. What will be the impact on cost and functionality of modularizing part or all of the construction? Of purchasing stock rather than custom components? Substitute one material or component for another and the model will adjust on the fly. This is especially important when considering the so-called “LEED premium.” There is a strong engineering argument to be made that LEED-compliant construction need not be more expensive. LEED is a scored valuation, easily quantified and thus easily modeled; interfacing the score sheet with the bill of materials and the project timeline makes it simple to identify the most cost-effective implementation strategies.

Finally, a building whose design model becomes the building information management interface and is integrated with embedded SCADA sensors becomes an organic, self-improving intelligent building. There is no time lag between what happens in the building and when management sees it. Operating costs can be monitored as they are incurred and adjustments made to contain them. Of particular long-term value, the real consequences of deferred maintenance decisions are easily modeled and quantified. The building can report its own maintenance needs and prioritize them to meet preset criteria.

The Bottom Line

A 1995 GAO study concluded “In short, most of America’s schools do not yet have key technologies or the facilities required to support learning into the 21st century. They cannot provide key facilities requirements and environmental conditions for education reform and improvement.¹⁷” We are almost a decade into the 21st century and the situation appears hardly changed. It does not have to be this way! Our students are the future, and they should be housed in buildings designed and constructed using the most modern technologies available. These technologies are now cost-effective for any size organization: in fact, they are highly likely to save the organization money. Einstein is reputed to have said that insanity is “doing the same thing over and over again and expecting different results.” If we build schools with early 20th century methods and designs, how shall we expect to graduate from them citizens who will lead us into the second half of the 21st century?

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- ² Prakash Nair, CEFP, Fielding Nair International, as quoted in [Design For Learning Forum: School Design and Student Learning in the 21st Century — A Report of Findings](#), © 2007, American Architectural Foundation, page 24.
- ³ [Integrated Energy Systems: Productivity & Building Science](#), Publication Number: 500-03-082 (a.k.a. CEC-500-2003-082), California Energy Commission: Public Interest Energy Research Program, October 2003, page 38.
- ⁴ [These Four Walls: The Real British Office](#), Gensler, London, UK, July 21, 2005.
- ⁵ Nair, Prakash and Fielding, Randall. *The Language of School Design: Design Patterns for 21st Century Schools*, © 2005-2007, DesignShare.com, Prakash Nair and Randall Fielding, page 8.
- ⁶ The Leadership in Energy and Environmental Design (LEED®) Green Building Rating System™ developed by the U.S. Green Building Council (USGBC) is a nationally accepted certification program that evaluates the design, construction, and operation of high performance green buildings against national benchmarks.
- ⁷ The cited project is one of six research projects that focus on integrated design topics to save energy, improve the indoor environment, and reduce operating and maintenance costs funded by the California Energy Commission's Public Interest Energy Research (PIER) Program. [Integrated Energy Systems: Productivity & Building Science](#), Publication Number: 500-03-082 (a.k.a. CEC-500-2003-082), California Energy Commission: Public Interest Energy Research Program, October 2003, page 38.
- ⁸ Sample data compiled from various on-line resources, principally [www.fishlore.com](#) and [www.algone.com](#).
- ⁹ Sample data compiled from various on-line resources.
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- ¹² The statement is from EPA's introduction to the *IAQ Tools for Schools (TfS)* program. The text does not cite the study; however, the statistics are likely quoted from [Condition of America's Public School Facilities: 1999](#), National Center for Education Statistics, Institute of Education Sciences, US Department of Education, NCES 2000032, June 2000. Ventilation, at 26 percent "unsatisfactory" or "very unsatisfactory," led the list of six environmental conditions public schools were asked to rate in a survey conducted through the agency's Fast Response Survey System.
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- ¹⁵ [Acoustical Performance Criteria, Design Requirements, and Guidelines for Schools](#), Approved 26 June 2002, American National Standards Institute, Inc.
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- ¹⁷ [School Facilities: America's Schools Not Designed or Equipped for the 21st Century](#), US General Accounting Office, GAO/HEHS-95-95, April 4, 1995, page 20