Type: Operations Management, Fast Track

Title: Reframing the Education System Crisis: An Untapped Opportunity for Impactful Research to Improve Cost and Access

Exorbitant higher education costs and disparities in access to a high-quality education contribute to a loss of national capacity to solve societal problems, maintain national competitiveness, and increase national prosperity. Though many industrial sectors have benefitted from the focused attention of engineers (e.g. aerospace engineering, computer engineering, petroleum engineering, and more recently, healthcare engineering), the education industry is an exception; engineering research efforts focused on the education services industry have been fragmented at best. This paper is a call to action and intended as one-step toward addressing this oversight and drawing attention to this opportunity. While the education industry would benefit from a broad interdisciplinary approach to its study—one that includes researchers in economics, management, law, and public policy—the focus of this paper is on opportunities to incorporate engineering approaches, in particular operations research and industrial engineering approaches, to address problems unique to the education industry. Though equally applicable to education systems globally, this paper focuses primarily on the United States' education system in its use of examples to demonstrate the need for and potential benefits of pursuing such a research agenda.

1. Motivation for a New Research Discipline

Per the Bureau of Labor Statistics within the United States Department of Labor, the Educational Services sector (NAICS 61) "comprises establishments that provide instruction and training." Such establishments include schools, colleges, universities, and training centers. The Educational Services sector is responsible for educating or training the human capital inputs for most, if not all, other sectors of the US economy, including knowledge workers and technical workers. One recent report by the Council on Competitiveness noted that knowledge- and technology-intensive industries account for 40% of the US GDP, which is one of the highest percentages among major economies (Council on Competitiveness 2016). This is solid justification for former US Secretary of Education Arne Duncan's reference to educators as our "nation builders" (Duncan 2015). Indeed, given its impact and its distinctive connection to knowledge creation and worker development, the education industry is vital to the long-term health of the nation's economy. However, it is also an industry that does not receive an amount of focused engineering research attention commensurate with its importance.

The state of the education industry in the United States has been the subject of several national reports (Council on Competitiveness 2004, National Academy of Engineering 2004, National Academy of Engineering 2005)and the conclusions drawn usually indicate a need for concern. For example, the Council on Competitiveness 2017 Clarion Call (Council on Competitiveness 2017) makes the following observations:

- By 2025, there could be 2 million US manufacturing jobs unfilled due to lack of skills.
- Eighty-four (84) percent of US manufacturing executives say they face talent shortages.

- Seventy-five percent of contractors say that it is difficult to find qualified construction workers.
- Fifty-one percent of small businesses report finding few or no qualified applicants to fill positions.
- By 2024, the US could be short by up to 1.1 million science, technology, engineering and math (STEM-educated) workers.
- Employment growth over the past two decades has been strong for individuals with education or training beyond a high school diploma, but flat or declining for high school graduates or those with less than a high school diploma.
- To compete in a knowledge-intensive global economy and to raise the standard of living, more Americans must earn post-secondary credentials, either from a university, a community college or in a skilled trade.

These observations motivate our call for focused education industry research to enable the future global competitiveness of the United States. One way to address these concerns is to improve the United States' education system. Two key needs in this regard, for which operations research and industrial engineering have the potential to provide solutions, are to: 1) reduce the cost of education, in particular higher education, and 2) enable equal access to a high-quality public education at all levels.

1.1. The Need to Reduce the Cost of Education

The 2015 report from the National Center for Education Statistics (NCES) (Kena et al. 2015) indicates continued increases in the cost of post-secondary education over the last decade. The cost of education has nearly doubled in the last 15 years as evidenced by the cost of undergraduate tuition and required fees at public 4-year institutions (Figure

1). Given that these costs vary significantly across universities, instead of using the average cost, the figures below report the values of the 10th, 50th, and 90th percentile costs at public 4-year universities. An increasing cost trend is seen for each percentile. The most recent total cost of tuition and required fees increased by at least 45% across all percentiles when compared to the cost of tuition and required fees 15 years ago.

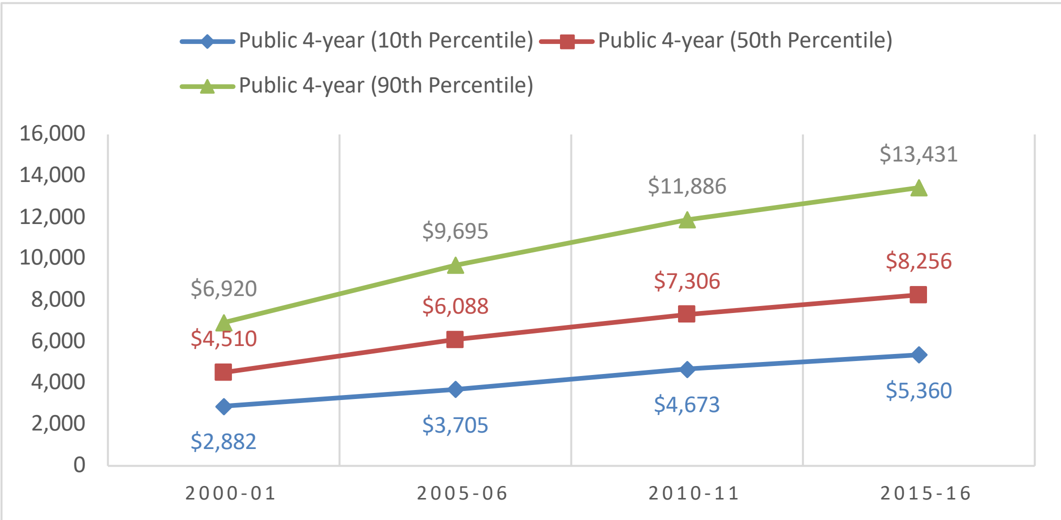

Figure 1: Annual Undergraduate Tuition and Required Fees in Constant 2015-16 Dollars[1]

The severity of such cost increases would be diminished if there were an accompanying increase in income. However, this is not the case as indicated by the cost of education as a percentage of the median annual income of US wage earners. For example, Figure 2 data shows the average cost of tuition, fees, room, and board at 4-year universities as a percentage of median wage earner net compensation. Thus, a household with a single wage earner earning the median wage would need to disburse at least 25% of that compensation in order to independently support the college expenses

[1] SOURCE: U.S. Department of Education, National Center for Education Statistics, Integrated Postsecondary Education Data System (IPEDS), Fall 2000 through Fall 2015, Institutional Characteristics component; and Spring 2001 through Spring 2016, Fall Enrollment component.

of one student attending one of the least expensive 4-year institutions. For private institutions, this figure could potentially reach over 200% of the median net compensation.

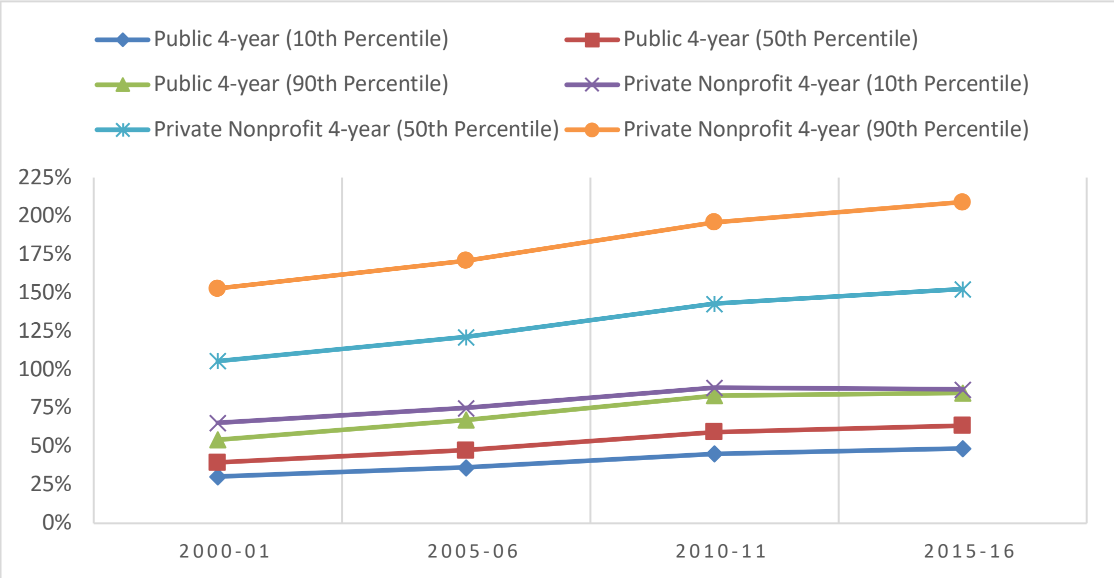

Figure 2: Annual Undergraduate Tuition, Fees, Room, and Board as a Percentage of Median Wage Earner Net Compensation[2]

1.2. The Need to Enable Equal Access to a High-Quality Education

In addition to the exorbitant costs of higher education, the quality of teaching and learning in higher education has also been a concern (2001). These quality concerns, however, are not limited to higher education and, furthermore, access can be affected by factors outside of students' control. For example, College Board data on SAT scores indicate significant differences in average scores based on race and ethnicity (Figure 3). This figure shows that Asians demonstrate the highest SAT performance in math, science and writing with averages at the 61st, 77th, and 68th percentile levels,

[2] SOURCE: U.S. Department of Education, National Center f or Education Statistics, Integrated Postsecondary Education Data Sy stem (IPEDS), Fall 2000 through Fall 2015, Institutional Characteristics component; and Spring 2001 through Spring 2016, Fall Enrollment component. Social Security Administration Wage Statistics for 2016

respectively. In contrast, Black students, demonstrate the lowest SAT performance in math, science, and writing with averages representing only the 28th, 25th, and 29th percentiles, respectively.

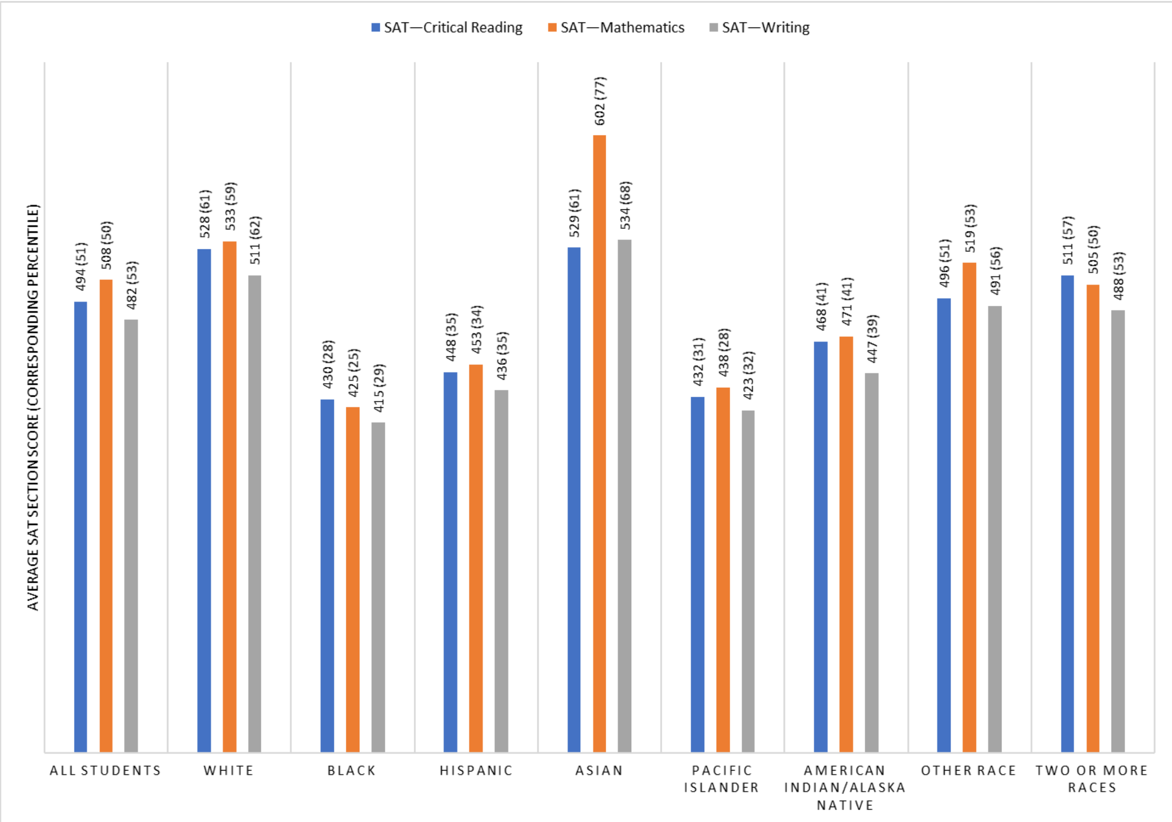

Figure 3: 2015-16 SAT Performance Averages (Percentile) by Race and Ethnicity

As a further example of disparity, Figure 4 shows differences in National Assessment of Educational Progress (NAEP) math readiness for 8th grade students based on the urban district in which the students reside. Despite the short 40-mile flight distance between them, twenty five percent of 8th grade students in Chicago, IL are at or above the proficient level in math versus only four percent of 8th grade students in Detroit, MI. This compares to thirty two percent of 8th grade students nationally who are at or above the proficient level in math.

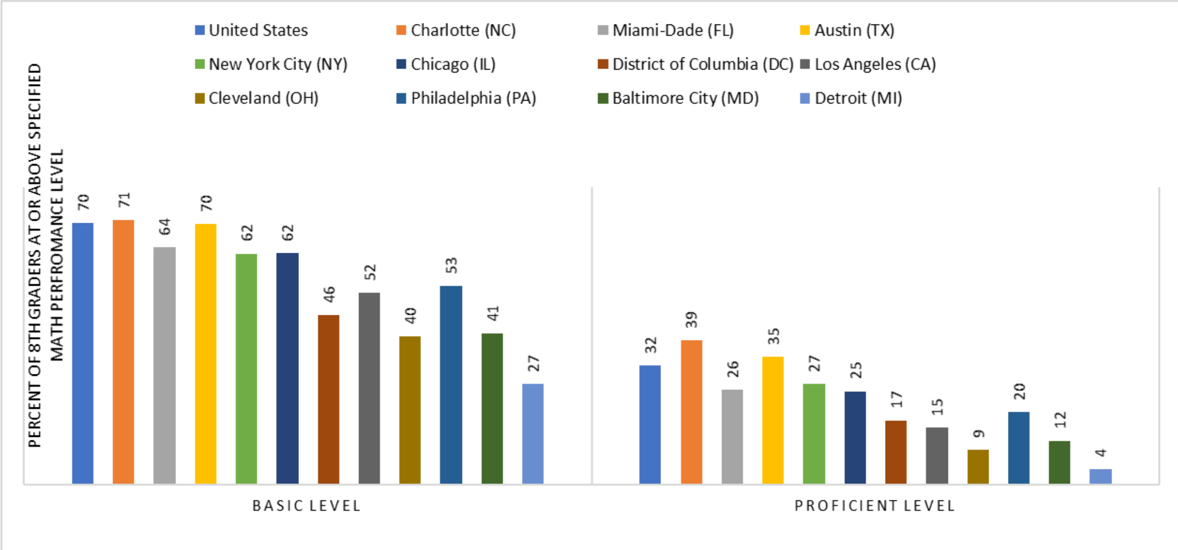

Figure 4: 2015 NAEP 8th Grade Math Scores by Urban District

The disparities present nationally are also reflected internationally. As indicated in Figures 5a and 5b, the 2015 Trends in International Mathematics and Science Study (TIMSS) (Provasnik et al. 2017), published by NCES, indicates a widening gap between the US and the top performing nations of the world in mathematics and science ability at both the 4th and 8th grade levels. These disparities may help explain why many US college graduates are not well prepared to function in the real word of technical work upon graduation and are unable to immediately contribute to organizations as employees to help meet national needs (2001, Cross 2000).

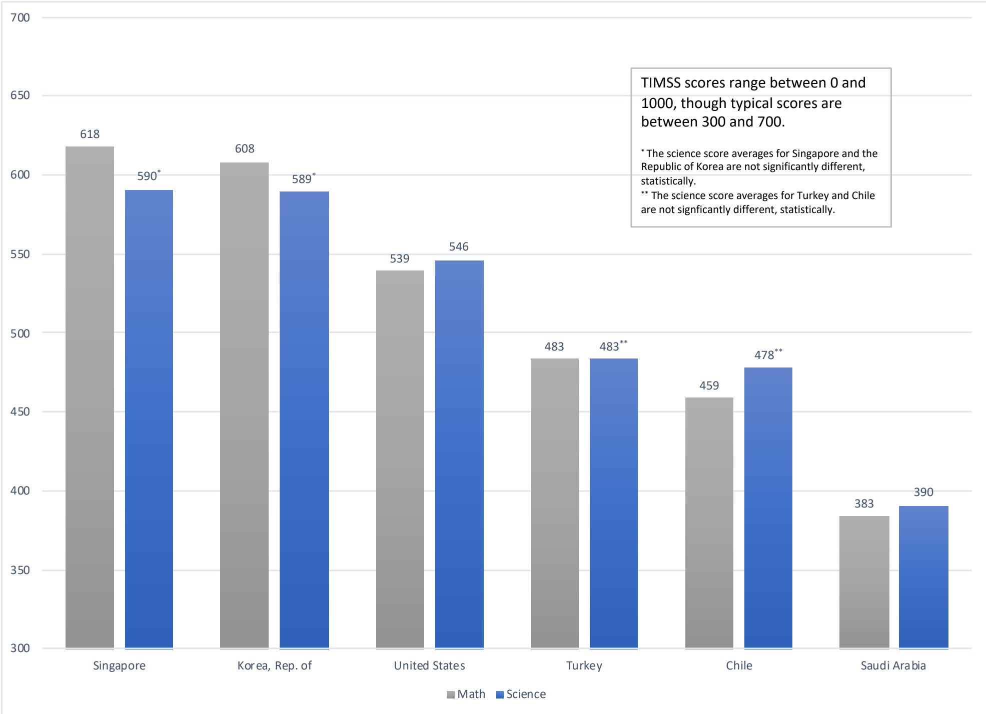

Figure 5a: 2015 TIMSS Grade 4 Math and Science Averages

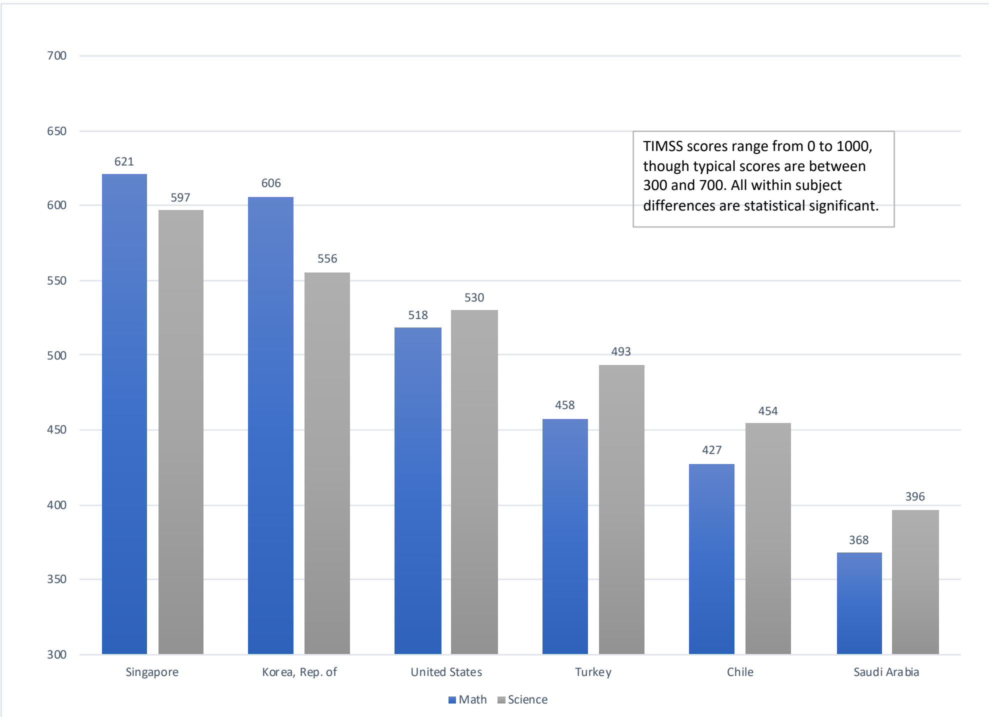

Figure 5b: 2015 TIMSS Grade 8 Math and Science Averages

Another plausible explanation for the lack of preparedness of graduates, which affects access to education, is the presence of individual learning styles and the resultant impact on learning effectiveness. Recognizing this potential problem, the National Academy of Engineering (NAE) has identified "Advancing Personalized Learning" as one of the grand engineering challenges (National Academy of NAE). This is an area where operations research and industrial engineering are expected to make significant contributions.

2. Introducing Education Engineering (EDEN) as a Discipline

Though we believe a multidisciplinary approach—one that leverages the combined efforts of researchers in engineering, management, economics, public policy, and others—is necessary to address the education industry problems highlighted above, we are presently advocating for a new research discipline we are calling education engineering (EDEN). In contrast to the more familiar discipline of engineering education—which focuses on the professional formation of engineers—EDEN is *the application of mathematics and the sciences in service to society to solve problems associated with the complex network of organizations, information or management systems, financing mechanisms, logistics providers and channels, and personnel engaged in delivering education*. Again, this is in contrast to and more expansive than the current discipline of engineering education, which has a more restricted focus consisting of engineering epistemologies, engineering learning mechanisms, engineering learning systems, engineering diversity and inclusiveness, and engineering assessment (Journal of Engineering Education 2006). It is our hope that the growth of EDEN as a discipline will be comparable to the growth that has been experienced by the healthcare engineering discipline. Healthcare engineering, as a discipline, dates back to

1960 when the American Society of Healthcare Engineering was established. In 1989, the term “healthcare engineering” first appeared in the scientific literature. In 2010, five years after the influential joint report by the National Academy of Engineering and the Institute of Medicine entitled Building a Better Delivery System: A New Engineering/Health Care Partnership (Fanjiang et al. 2005) was published, The Journal of Healthcare Engineering was launched. A year later, the IIE Transactions on Healthcare Systems Engineering was launched. More recently, in 2015, the term “healthcare engineering” formally defined. Again, it is our hope that we will see a similar, if not expedited, growth in the new field of EDEN. The education industry is fertile ground for engineers to further our work in service to, and for the benefit of, society.

To highlight some of the opportunities that EDEN affords society, we now turn our attention to the possibilities that may be of interest to operations research and industrial engineering researchers in particular. The Institute for Operations Research and Management Science (INFORMS) defines *operations research* as: “a discipline that deals with the application of advanced analytical methods to help make better decisions.” The Institute for Industrial and Systems Engineers (IISE) states that: “industrial and systems engineering is concerned with the design, improvement and installation of integrated systems of people, materials, information, equipment and energy.” Table 1 shows several operations research and industrial engineering research areas relevant to EDEN. A brief description of each research area along with representative research questions follows. We have further organized the questions into one of three categories based on the ability of the question, if answered, to address the need to: 1) reduce the cost of education, 2) enable equal access to a high-quality public education, or 3) both reduce cost and enable equal access to high-quality education.

Table 1: Representative EDEN Areas of Research

Representative Research Areas	Representative Publications
Education Analytics Predictive and Prescriptive Analytics Student Data and Informatics Operations Research and Optimization Social Network Analysis Data Envelopment Analysis Descriptive Analytics and Data Visualization Information Systems Management Multicriteria Decision Making	(Aires et al. 2018, Bailey and Michaels 2019, Baker 2018, Brennan et al. 2014, Cimenler et al. 2015, Dejaeger et al. 2012, Hardman et al. 2013, He et al. 2018, Hoffait and Schyns 2017, Korhonen et al. 2001, Liu et al. 2013, Nandeshwar et al. 2011, Peña-Ayala 2014, Reamer et al. 2015, Zimmermann et al. 2017)
Education Quality Management and Process Improvement Lean Six Sigma Quality and Reliability Engineering	(Akkan et al. 2016, Bessent and Bessent 1980, Budish et al. 2017, Faudzi et al. 2018, Lopez-Torres and Prior 2016, Phillips et al. 2017, Phillips et al. 2015, Saltzman and Roeder 2012, Souza Lima et al. 2017, Vermuyten et al. 2016, Wang et al. 2017)
Education System Operations Management Facilities and Capacity Management *Student Flow* *Classroom Assignment* Supplychain Management and Logistics *Bus Routing* System Simulation Production Planning and Control	(Essid et al. 2014, Sunder M. 2016, Sunder M. and Antony 2018, Tari and Dick 2016)
Education Financing Financial Engineering	(Berlanga-Silvente and Guardia-Olmos 2017, Chung 2017, James and Rachelle 2016)
Education Ethics Control	(Atoum et al. 2017, D'Souza and Siegfeldt 2017, Köksalmış et al. 2014, Northcutt et al. 2015)
Complexity and Systems in Education Systems Engineering	(Cruz 2019, Cruz et al. 2019, Ghaffarzadegan et al. 2017, Heileman et al. 2018, Mital et al. 2014, Shepherd 1965)

2.1. Education Analytical Decision Support (EADS)

The EADS area focuses on the process of deriving insights from patterns and correlations found in education industry data and using analytical models to: 1) enable better-informed and timelier decision making and, 2) improve education system outcomes. The objectives of EADS are to exploit both historical and real-time data to understand, make predictions about, and develop strategies regarding education processes. Some examples of the types of questions that EADS can help answer are:

To ***reduce the cost*** *of education:*

- Which courses should be targeted for revision in order to decrease average time to graduation without diminishing student learning outcomes?

To enable equal ***access*** *to a* ***high-quality*** *education:*

- What are the characteristics of students who are at risk of not persisting to graduation and how can such students be identified sooner?
- What is the best strategy to assign students to K-12 classrooms accounting for variability in student academic levels, anticipated learning outcomes, and the impact on subsequent teacher evaluations?
- What admissions criteria should be used to attract a diverse and well-prepared cohort of students based on capacity constraints?

2.2. Education System Operations Management (ESOM)

The ESOM area focuses on the design, operation, and value improvement of the systems involved in the delivery of education services. It is concerned with ensuring that the right resource levels are available where and when they are needed at the right price and quantity. The objectives of ESOM are to improve the efficiency, effectiveness, quality, value, and timeliness of the core operations of the education system. Some examples of the types of questions that ESOM can help answer are:

*To **reduce the cost** of education:*

- How can school busses serving a county level K-12 public school system be scheduled to cost effectively transport students to schools in a timely manner without requiring excessively early morning pickup times or late afternoon drop-off times?
- How can university courses be effectively scheduled to maximize space/room utilization?
- How can the curriculum be restructured to facilitate students in engineering graduating in four years?

*To enable equal **access** to a **high-quality** education:*

- How many students should be admitted into a particular degree program given the number of faculty and the desired quality levels?
- What number of course offerings should be made per year based on enrollment projections?

*To **reduce cost** and enable **equal access** to **high-quality** education:*

- How should faculty assignments be determined considering faculty availability and workload, classroom availability, equipment availability, and scheduling conflicts?

2.3. Education Quality Management and Process Improvement (QMPI)

The QMPI area focuses on the design, monitoring, and continuous improvement of the processes involved in the delivery of education services including the identification and reduction of wastes and improvement of process efficiency. Whereas ESOM is focused on strategic decisions, QMPI focuses on tactical activities to aid mid-term planning. The objectives of QMPI are continuous improvement in the quality of education delivery and education systems including improvement in the cost, quality, and efficiency of delivery of education services so that more value is delivered with reduced waste. This requires that data be collected and analyzed to understand and characterize processes and to be able to quickly identify outcomes that indicate abnormal performance of a process or the system so that the root causes of such behavior may be identified and solutions to address the causes proposed, validated, and implemented. Some examples of the types of questions that QMPI can help answer are:

*To **reduce the cost** of education:*

- What are "value added" and "non-value added" elements in the education process?
- How can textbooks and other course materials be redesigned to deliver more value at a lower cost?
- How can quality management techniques be used to quickly identify anomalies at a student, course, school, college, university, or system level in order to trigger timely intervention?

*To enable equal **access** to a **high-quality** education:*

- How can the efficiency of education systems be compared to identify and benchmark the best systems or units within systems?
- How can design of experiments or data envelopment analysis techniques be used to develop effective assessment of pedagogical innovations?
- How can real-time detection of the impact of pedagogical changes on student learning, identity, motivation, grit, etc. be implemented?

2.4. Education Financing (EF)

The EF area focuses on the use of finance theory, financial engineering, and mathematical methods to address issues of revenue and cost allocation, investment theory, and other aspects of capital budgeting. The objectives of EF are to improve the efficient and effective use of capital resources in the education system. Some examples of the types of questions that EF can help answer are:

*To **reduce the cost** of education:*

- What portion of a municipality's budget should be allocated to education?
- How should public education be financed?
- What is the return on investment for education?

*To **reduce cost** and enable **equal access** to **high-quality** education:*

- How should financial resources be allocated across academic units, schools, or school districts?
- What is the long-term economic cost to a municipality of not investing in its public education system?
- How can post-secondary education be made available free or affordable to all?

2.5. Education Ethics Control (EEC)

The EEC area focuses on maintaining the integrity of the education process. The objectives of EEC are to detect and prevent ethics violations, particularly in online environments. Examples include remote proctoring of online environments during examinations and effective detection of contract writing and plagiarism. Some examples of the types of questions that EEC can help answer are:

*To enable equal **access** to a **high-quality** education:*

- What methods may be employed to expose contracted writing and plagiarism?

- What are the leading factors that predict cheating behavior and how can they be eliminated or mitigated?
- What systems can be developed to detect cheating during exam administration?
- As technology and distance learning increases, how can analytics be used to identify dishonest students through analyzing student behavior?

To ***reduce cost*** *and enable* ***equal access*** *to* ***high-quality*** *education:*

- How can a massive online proctoring be developed to mitigate the cost associated with remote testing centers?

2.6 Complexity and Systems in Education (CSE)

The CSE area focuses on the application of systems thinking and systems dynamics to the study of education systems. The objective of CSE is to leverage mathematical models that capture the complexity of education systems and provide insight to better understand and solve complex problems associated with these systems. Some examples of the types of questions that CSE can help answer are:

To enable equal ***access*** *to a* ***high-quality*** *education:*

- How could public K-12 education be transformed into a yearlong activity?
- How can personalized learning be implemented to adapt to students' learning growth and individual learning styles?

To ***reduce cost*** *and enable* ***equal access*** *to* ***high-quality*** *education:*

- How can the progress of students through the curriculum of an educational unit be modeled using real-time data in order to reduce complexity, quickly identify at-risk students, continuously monitor learning outcomes, and warn of system level anomalies?

3. Envisioning the Future of Education Engineering (EDEN)

The aforementioned problems are daunting and complex. The precipitating questions are important and the implications of answering (or not answering) them are significant. A critical mass of focused research attention on the education industry may help provide such answers. Thus, "[the] purpose [of] this paper is to invite management scientists and operations analysts to add education to their agenda. Education is a system and a set of subsystems potentially offers rich problems. Rich in this case means that the susceptible of analysis, design, and perhaps eventually a little optimization. Education policy-making issues are both non-trivial and complex." (Platt 1962, p. 408)

Though written over five decades ago, this invitation and description of the education system are equally applicable today and the words read as though Platt were one of our contemporaries. The need to have an educated citizenry to address problems of society has not diminished, nor has the need to solve the problems of the very educational system that will educate these citizens. Our understanding of how to leverage the diversity of our nation by lowering the cost of higher education and by providing equal access to a quality education remains a significant challenge.

Our objective is to renew Platt's call to action. Our goal for developing these six research areas is to draw focused attention on this national (and global) opportunity. Our hope is that the development of EDEN will generate economies of scale in research that will accelerate the improvement of educations systems both nationally and worldwide.

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