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Virtual Reality as a Value Engineering Method in Machine Shop Learning

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Abstract

Utilizing a Value Engineering (VE) approach towards solving educational student throughput bottlenecks caused by equipment and space capacity issues in university machine shop learning, Virtual Reality (VR) presents an opportunity to provide scalable, customizable, and cost-effective means of easing these constraints. An experimental method is proposed to demonstrate applying VR towards increasing the output of the value function of an educational system. This method seeks to yield a high Transfer-Effectiveness-Ratio (TER) such that traditional educational strategies are supplemented by VR sufficiently so that further growth in classroom enrollment is enabled.

Introduction

Educational systems are constrained by capacity and budgetary considerations. To meet the demands of future industrial growth it is necessary to create new techniques for increasing educational capacity within limited resource allocations. Systems engineering offer quantifiable, if sometimes misunderstood, methods to solve this problem. This article will explore a methodology for analyzing and improving the function of an educational system by means of value engineering to create a Value Engineered Educational System.

It will also be proposed how Virtual Reality (VR) technology is a means by which the VE method can be executed to improve function of an educational system. An experimental method will also be described to quantify the capacity increases a well-executed VR system can provide. This quantification shall be shown by utilizing a Transfer-Effectiveness-Ratio (TER) calculation.

Value Engineering (VE)

Value engineering (VE) is a structured approach to improving the value of a product, system, or service by balancing its functions with the costs required to achieve them [1]. The concept of value is often defined as a simple ratio, such as,

$$\text{Value} = \frac{\text{Function}}{\text{Cost}} \tag{1}$$

$$\text{Value} = \frac{\text{Function} + \text{Performance}}{\text{Cost}} \tag{2}$$

$$\text{Value} = \frac{\text{Function}}{\text{Resources}} = \frac{\text{Finished Project Capabilities}}{\text{Project Cost}} \tag{3}$$

The core idea is that the system stakeholders' needs and requirements drive the Value. In VE, functions are described using a "verb + noun" formulation, which expresses what a system should do, while performance defines how well these functions should be executed [1]. For example, a function may be to "brew coffee" and the performance may be defined as "brew 10 cups of coffee in different flavors within 5 minutes."

Cost is the expenditure required to meet the function and performance of the system. It can be more broadly defined to include all resources put towards accomplishing the system objective. This would encompass not just capital spent, but also time investment and opportunity costs.

The goal of VE is to enhance value by optimizing functional performance while minimizing the resources needed to achieve it, considering the entire lifecycle of the system [1] [2].

Despite its technical roots, the determination of value is inherently subjective, as it depends on the perceptions of the customer and other stakeholders. This subjectivity can lead to biases, distorting the true value in many projects. Factors such as organizational focus on internal rather than customer value, outdated assumptions, incomplete project scopes, and changing customer needs can result in suboptimal value. To achieve better value outcomes, VE must integrate not only technical engineering but also social processes that uncover the true nature of value. Key strategies to improve value include focusing on functions, conducting trade-off analysis, and aligning the value with the changing needs and timeframes of customers [1].

The term 'value engineering' in common parlance is typically taken to mean reducing costs of a system towards meeting the minimum threshold of acceptable function of the system [3]. It can be misunderstood as a purely cost-cutting approach in construction, systems design, and systems management. This way of thinking focuses on only a portion of the total relationship of VE. The proper definition as shown by equations (1), (2), and (3), is that Value is taken as the ratio of the function of the system versus the resources the system consumes.

VE is not merely about decreasing costs – but about the overall increase of Value of the system [3]. When a system function includes a term for throughput, a full application of VE means finding ways to increase function of the system when it may begin to reach capacity where additional throughput is desirable.

Value Engineered Educational System (VEES)

Education is one such system that can benefit from a VE analysis. In education, the "verb + noun" with performance can be described as "teach X number of students to meet a minimum level of competency within an academic period."

As population numbers rise and society increasingly demands a highly technically literate population to meet workforce demands, strain is being placed on the traditional educational pipelines that train engineers [4] [5] [6]. These limiting factors include instructors, physical space for students, equipment for students, and competition for laboratory resources between entry level students and senior students [7] [8].

Additionally, education in disciplines (such as mechanical engineering) that involve expertise in heavy-duty moving machinery (such as rotating lathes) poses a clear hazard to inexperienced students and so presents a further constraint on safe, rapid, quality instruction of these students [9].

Colorado State University's (CSU) Engineering Manufacturing Education Center (EMECH) for entry engineering students has been identified as one such example where the rapid growth of the student body has put a strain on the school's capacity to continue its expansion without diminishing the quality of the education. There are several factors contributing to the bottleneck in student throughput in the center.

First, there is the limited quantity of machinery available for students to use. The machinery available in the lab includes drill presses, mills, and lathes. In particular, there is a low number of lathes available for the students, with each new lathe costing tens of thousands of dollars and requiring significant physical space to be used. A student spends approximately 10 hours on a lathe to complete the introductory course project [10]. Most of the student's time is not spent machining parts – but in familiarizing themselves with the operation of the equipment.

Second, there is the limitation of physical space in the laboratory. Expansions to the campus lab are projected to cost upwards of $2,000,000 and, once they are complete, there is no opportunity for further expansion [10].

Third, even with physical lab space expansion, there is the issue of procuring qualified instructors to meet the growth of the student body. Between Fall 2022 semester and Fall 2024 semester, the student body increased by 71.8% from 149 students to 256 students (see Fig. 1) [10].

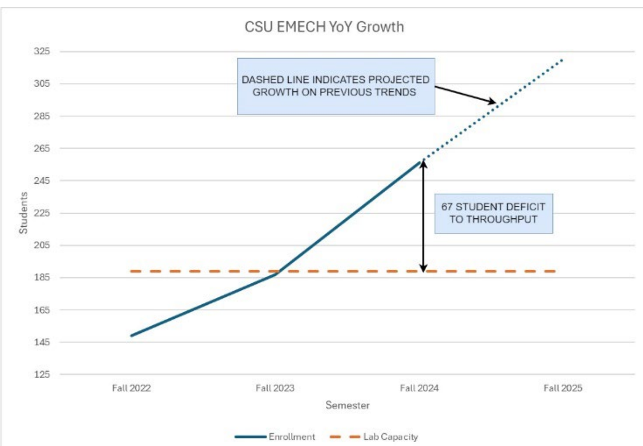

Figure 1. *CSU EMECH Lab Year-over-Year Growth with Student Throughput Deficit Increasing Over Time Increase as Capacity Stagnates*

With these factors in consideration, the CSU EMECH machine labs are a prime candidate for the application of a VE approach that solves the educational challenges presented above, namely:

1) Cost-effective expansion
2) Scalable expansion
3) Quality expansion

Here, we propose, using the VE formula to formulate what we shall call the Value Engineered Education System. The definition of the Value Engineered Education System (VEES) is,

$$S = \frac{\text{Function}}{\text{Cost}} = \frac{C}{A+E+P+D+M} \quad (4)$$

Where,

S = Student Throughput (Students/Dollar)
C = Capacity (Students/Semester)
A = Space Costs (Dollars/Semester)
E = Equipment Costs (Dollars/Semester)
P = Personnel Costs (Dollars/Semester)
D = Development Costs (Dollars/Semester)
M = Maintenance Costs (Dollars/Semester)

In short, the value of an educational system is the ratio of its function (the capacity to educate students) versus the cost (the costs of organizing a program).

It is implicitly assumed that the quality and competency standards for advancing students through the educational system are maintained. That is, the upward limits on Capacity are informed by how many students can be accommodated with a reasonable expectation that there is successful knowledge transfer in the program such that they can pass the assessments.

Virtual Reality Applied to the VEES

A VE approach points towards the usage of novel emergent technologies that provide students verisimilitude to the equipment, operations, and procedures they are required to know by the completion of their course. Virtual Reality (VR) is one such technology ideally suited for integration into a traditional laboratory educational workflow. VR has the following distinct advantages for educational formats:

1) Fully customizable experiences
2) Repeatable experiences
3) Flat-rate spatial and budgetary requirements for the system
4) Capability for built-in assessments of aptitude

Thus, it is in alignment with a VE approach to utilize VR as a supplementary system for enhancing the throughput of a traditional educational system. That is, VR provides a means of increasing the value of the overall system if the meaning of value is defined appropriately.

As previously shown, space and equipment for traditional instruction methods are limited in their scaling potential. The curve showing the relationship to increase value by cost reductions will saturate and only minor additional gains in value can be obtained by marginally reducing costs. This is because cost reductions cannot increase actualized student capacity as shown by the VEES expression (4). Cost increase is necessarily required to increase maximum throughput potential, and hence, the value of the VEES (see Fig. 2).

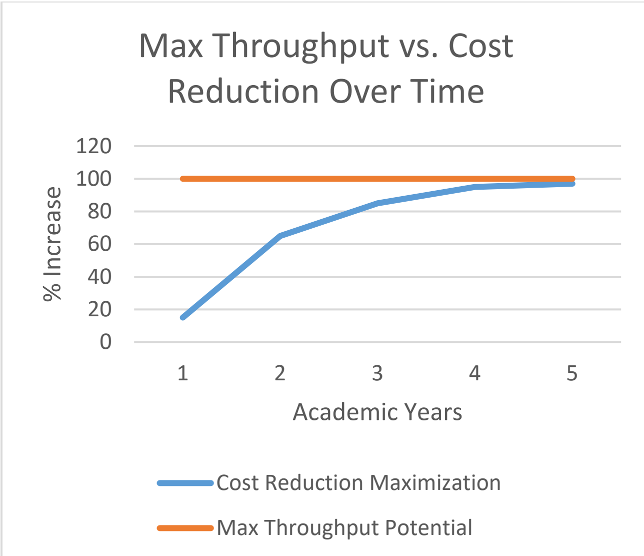

Figure 2. *Capacity Held Constant Shows that Value % Increases Reach a Saturation Over Time Even as Cost-Reductions Are Maximized*

Instead, VR offers a potential for near-term and long-term value increase by means of increasing capacity at a reduced cost than traditional lab expansion methods. Let us consider the following graphs which show two scenarios for increasing capacity.

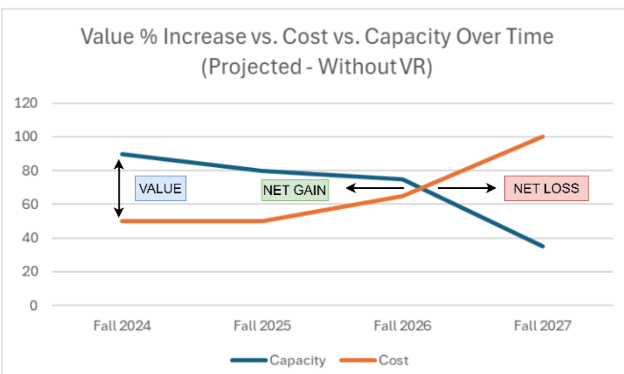

Figure 3. *Value % Increase vs Cost vs. Capacity Over Time (Projected – Without VR Implementation)*

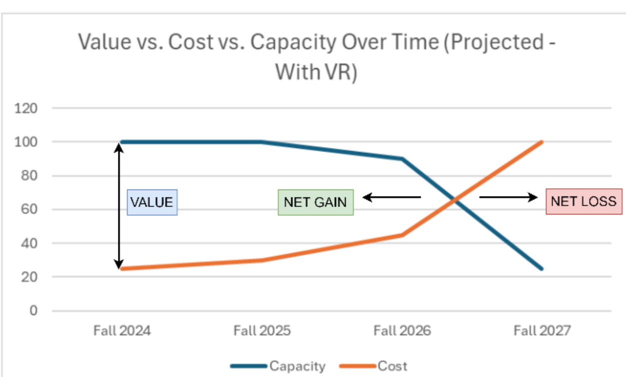

Figure 4. *Value % Increase vs Cost vs. Capacity Over Time (Projected – With VR Implementation)*

Fig. 3 shows the projected percent value increase versus the cost expenditure versus the capacity increase over time without using VR to increase educational capacity. As costs rise, and capacity increases are realized by traditional means to increase capacity, such as lab expansion, procuring new equipment, and hiring new staff, the potential for future capacity increases diminishes. There is a narrowing of the potential to add further value to the system even with higher costs. Eventually, the percentage of capacity that can be added reaches a threshold of diminishing return. This is shown as a net loss of value over time in future academic years.

Fig. 4 shows the projected percent value increase versus the cost expenditure versus the capacity increase over time with VR used to increase capacity. As this projection shows, the capability to increase capacity with cost increases, and hence system value net gain, is maintained for a longer period of academic years. The utilization of the scaling capabilities of VR experiences to train students and increase educational capacity could be pushed into future academic years with efficient program management.

Quantification of VR to Increase the VEES

Since value engineering has an inherently subjective assignment of value by stakeholders, it is desirable to have a method for analysis of the effectiveness of technology used to increase value. Here it is proposed a means to quantify in the VE formula how significant VR is for increasing VEES. One formula that allows this to be done is the calculation of the Transfer-Effectiveness-Ratio (TER) [11] [12]. The TER determines the value of time spent training in a simulator by calculating the efficacy of the virtual training session or simulator [11]. It is expressed as,

$$TER = \frac{Y_C - Y_X}{Y_C} \times 100 \qquad (5)$$

Y_C is the time spent or number of trials to train an individual on a specific task by traditional methods and Y_X is the time spent or number of trials to train someone who has already trained on a simulator.

A TER of 0.5 means that training on a simulator reduces in-person training time by half. Higher TER values suggest that students trained in VR will permit university laboratories to increase student throughput on the same amount of physical hardware and lab space.

Thus, it is possible to prove the utility of a VR system applied to an educational environment by calculation of the TER for experimental trial groups of students versus an experimental control.

Experimental Method Proposal

To demonstrate the efficacy of utilizing VR to execute the VEES strategy to increase throughput of the CSU EMECH laboratory, the following steps are proposed.

First, focus the development of a VR experience focused on the key bottleneck identified by faculty to the educational pipelines, which in this case, is the lathe machine.

Second, develop a 'digital twin' of the lathe machine in an accessible VR space (see Fig. 5). In this digital space, include the interactive elements upon which a student is trained for operation of the lathe (switches, mounts, rotation axes, terminology, etc). Special attention shall be paid to maintaining a thematically consistent sense of presence in the environment.

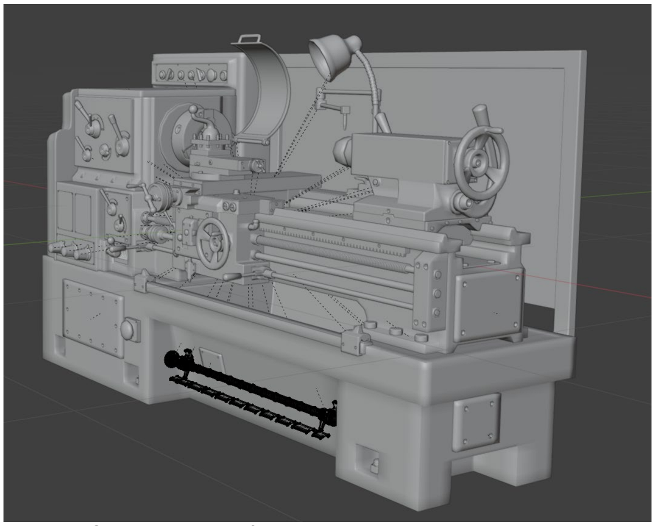

Figure 5. Generated Model of Machine Lathe Digital Twin

Third, develop guided virtual instruction and practice modules for students. These are to include safety tutorials, controls tutorials, and procedural tutorials for the operation of the lathe. Special attention should be given to the utilization of VR haptic controls to provide intuitive user inputs and feedback for successful operation of the lathe in the virtual space.

Fourth, deploy these modules in an academic semester to a teaching section in the CSU EMECH introductory machining lab. From the sample of participating enrolled students, generate randomized control groups of students who undertake traditional instruction only. And, generate a randomized group of students who undertake VR training as a supplement to their traditional assessments of competency (i.e. in-person assessment of competency by their course instructor). Care should be taken to ensure students are comfortable with VR systems to avoid known limitations of motion sickness associated with VR experiences.

Fifth, collect data of the performance of students who underwent VR supplemented training versus the control group who underwent traditional training methods only. Data included shall be objective competency metrics already in use by the CSU EMECH faculty and additionally data on how much time is required to achieve machine competency by each experimental group.

Sixth, calculate the TER. It is desired to know whether students who underwent VR supplemented training obtained an appreciable gain in their comprehension, how much this gain is, and if this gain required less time spent in a physical lab.

With a calculated TER, it will then be possible to create a reasonable projection of the potential growths to lab capacity by the widespread implementation of VR supplemented training.

Sample VR Implementation Projection

Approximately 189 students per semester require 2079 machine hours of training to achieve competency for unsupervised work [10]. This is the maximum number of students the laboratory can physically support due to limitations on the number of operating hours of the lab with the given quantities of equipment available (3 lathes).

If two hours of in-person traditional orientation training could be offset by supplemental VR training (reducing the hours of physical training from 10 hours to 8 hours), then by applying equation (5), throughput can increase to 230 students per semester. This is a nearly 21% increase in student throughput per semester.

Discussion of Theoretical Results

The application of VR to machine shop learning environments is largely unexplored and ripe for research into the efficacy of VR to increase the value of educational systems. The usage of systems engineering principles and value engineering methods towards analyzing VR in educational systems is also an opportunity for further study.

It has been shown here that even a modest reduction to time spent in a physical laboratory space, without sacrificing competency, can lead to substantial gains to laboratory throughput for only the cost of the VR system hardware, its development, and continuing maintenance. In comparison to traditional laboratory capacity expansion methods, there is also a greater flexibility in deploying a VR system, such as by using on-campus computer labs (or even remote deployment of VR systems to dorms and homes) rather than costly and difficult to operate machine shops and procurement of new lab equipment.

One of the significant challenges to widespread adoption and research of VR is the difficulty in creating application specific digital twins and environments that maintain a strong sense-of-presence for users. The usage of enhanced programming acceleration tools, such as artificial intelligence, to rapidly create digital spaces for educating students is yet still largely unexplored and offers another avenue for further research [13].

Conclusion

In this article, the principles of value engineering were described and misconceptions surrounding the concept of value were discussed. A method for quantifying the value of an educational system was proposed and an experimental process for determining an analytical transfer-effectiveness-ratio for assessing value of a VR system in education for stakeholders was discussed.

There is tremendous opportunity for exploring the deployment of VR as a technology implementation of a value engineering method. Subjects of further study include the streamlining of the development of digital twins with artificial intelligence tools and the collection of data to determine real-world transfer-effectiveness ratios.

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