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# Multiplayer Physical and Virtual Reality Games for Team-based Manufacturing Simulation

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## Abstract

Familiarity with manufacturing environments is an essential aspect for many engineering students. However, such environments in real world often contain expensive equipment making them difficult to recreate in an educational setting. For this reason, simulated physical environments where the process is approximated using scaled-down representations are usually used in education. However, such physical simulations alone may not capture all the details of a real environment. Virtual reality (VR) technology nowadays allows for the creation of fully immersive environments, bringing simulations to the next level. Using rapidly advancing gaming technology, this research paper explores the applicability of creating multiplayer serious games for manufacturing simulation. First, we create and validate a hands-on activity that engages groups of students in the design and assembly of toy cars. Then, a corresponding multiplayer VR game is developed, which allows for the collaboration of multiple VR users in the same virtual environment. With a VR headset and proper infrastructure, a user can participate in a simulation game from any location. This paper explores whether multiplayer VR simulations could be used as an alternative to physical simulations.

## 1. Background

For many engineers, familiarity with the different manufacturing processes is critical. However, while engineering students are learning the technical skills and theories in classes, the opportunity to practice these skills is lacking. Practice in an actual manufacturing scenario is expensive due to equipment cost, safety concerns, and inventory. Therefore, simulations of manufacturing scenarios with scaled-down toys are common in educational settings. In addition, learning professional skills, such as teamwork, are as valuable as technical skills.

Minimizing production cost is one of the goals that manufacturing companies aim to achieve, thus organizations need to focus on eliminating waste in their processes and implement manufacturing process improvement initiatives. Lean is a process improvement philosophy that has been successfully applied by many organizations to improve their business processes [1]. This continuous improvement approach eliminates non-value-added activities and is defined as “a philosophy that shortens timelines between customer order and shipment by eliminating waste” [4]. In Lean manufacturing, there are eight types of waste: defects, overproduction, waiting, non-value-added processes, transportation, inventory, motion, and non-utilized employee talent. Lean philosophy divides the tasks of a process into: value added, non-value added, and non-value added essential. Value added activities are those that (1) add value to the product or service, (2) customer is willing to pay for, and (3) are done right the first time. Non-value-added activities are those that do not add value to product or service and hence can be eliminated. Non-value-added essential activities are those that do not add value to product or service but are necessary for the delivery of product or service. In order to improve a given process, we should emphasize value added activities, minimize non-value add essential activities, and eliminate non-value add activities.

There is an urgent need for skilled engineers to transform the manufacturing industry. Successful organizational transformations depend on a better understanding of the capabilities and methods that can help to deliver whole system change. According to the Manufacturing Institute, the manufacturing workforce is older and less educated relative to other sectors. U.S. dominance is in jeopardy as relatively few young Americans choose a manufacturing career [2] as the U.S. manufacturing skill gap widens due to retirement, economic expansion, and inadequate education. The combination of these factors will result in two million unfilled jobs in the next decade [3].

In order to fill in the skill gap, emerging technologies are being tested to see whether they can help with providing high quality and lower-cost training for engineering students. Compared to traditional physical simulation, the development of virtual reality (VR) technology brings immersion and presence in virtual environments to the next level by allowing a user to experience a world completely different than their present location. VR technology has been rapidly deployed in simulation and training due to its relatively low cost compared to duplicating new physical simulation environments. The use of VR allows for new perspectives in human-computer interactions that otherwise would be restricted to interactions in two dimensions [5]. With VR, training and education can be done in ways never before.

Synchronous multiplayer gaming in VR has been a relatively new concept due to the demand on bandwidth and real-time communication. In Christensen et al. [6], researchers compared the use of VR and non-VR multiplayer games, as well as two different methods of control in a puzzle game: Xbox controller and HTC Vive hand-tracking controller. They found that the hand-tracking controllers improve player experiences in most aspects. McGrath et al. [7] summarized current research in medical training and assessment with virtual simulations and virtual reality. The survey paper found that multiplayer game-based learning had the advantage of providing lower-cost interactive virtual simulations for trainees to participate in teams. Similarly, Baur et al. [8] found that multiplayer VR gaming can be beneficial in neuromuscular therapy as it could facilitate social interaction and increase performance. Liszio and Masuch [9] provided an approach to integrate social interactions into game design by having one player using VR and two other players using tablet PCs as they worked collaboratively towards their goal. Gugenheimer et al. [10] similarly proposed a prototype to increase social interaction between one player in VR and another player not using VR by projecting parts of the VR world onto the floor. While previous research mostly examined one user in VR, our research differs by exploring a VR game where all users are in VR at the same time synchronously. This paper explores the applicability of multiplayer VR simulation games in an educational setting to teach engineering students the principles of manufacturing systems and teamwork. Simulation experiments were conducted to study the defectiveness of the simulation games. The protocol for the simulation experiments was reviewed and approved by The Pennsylvania State University's Office for Research Protections (IRB #: STUDY00009232).

## 2. Teaching a Physical Team-based Simulation

We developed both physical and VR simulations using the same scenario in physical form and virtual reality for easy comparison. Initially, the physical simulation was developed and tested in classroom setting with institutional review board approval. Then, the same simulation was adapted to a virtual reality application. First, we will discuss the physical simulation in detail so that it may be replicated and the virtual reality application may be better understood.

The scenario is the manufacturing of toy cars as the product. The simulations involve designing a product, identifying manufacturing requirements, and manufacturing and selling the product. In the simulations, four participants work collaboratively. Each participant is assigned a task individually on an assembly line. Only by working together can the entire process be successfully completed.

In this simulation, the participants are first presented with a set of instructions on their tasks. To assemble the toy car, the four participants are given the tasks, respectively:

(a) The selection and assembly of wheels and axels;
(b) The selection and assembly of tires and rims;
(c) The selection and assembly of the base;
(d) The selection and assembly of sides and roof;

Once the participants are ready to start, the car order along with the set of customer requirements are presented to the participants. For example, the requirements could be:

(a) vehicle must have four tires, a windshield, a steering wheel and a roof;
(b) all tires must be of the small-soft type;
(c) vehicle base width and length must be 4 dots and 6 dots, respectively;
(d) vehicle weight must be between 20 and 30 grams;
(e) vehicle height must fit a sitting driver;
(f) there must be a minimum of 5 different colors on the vehicle;
(g) total vehicle cost must be $9 or less.

While each participant has his or her own task, to satisfy the customer requirements, the participants must work together as a team keeping in mind the big picture. Teamwork and communication skills are thus essential to the successful completion of the entire production.

In a traditional physical simulation, the four students must sit in the same room and complete the production together. The simulations are part of an industrial engineering course on manufacturing systems. Figure 1 shows a simulation in action, where students use plastic bricks to build the toy cars following customer requirements on paper.

(a) (b) (c)

Figure 1. Sample pictures from the physical simulations: (a) student participants using physical simulation to complete the production process, (b) inspection, (c) finished goods inventory.

## 3. Physical Simulation Application and Results

We implemented the physical simulation for making toy cars in an undergraduate industrial engineering class, Manufacturing System Design and Analysis. Twenty-three student participants (5 women, 18 men) were involved in the simulation activities and were divided into four groups (sample pictures are shown in Figure 1). Data was collected focused on both conceptual and analytical knowledge as well as problem-solving skills. The conceptual and analytical knowledge is assessed through student's understanding of manufacturing topics. Some key concepts considered in the manufacturing games are included in Table 1.

Table 1. Some key manufacturing related concepts considered in the simulation games.

| Concept | Definition |
|---|---|
| Mass Production | Production of large quantities of identical products. |
| Lead Time | The amount of time between receiving an order and the completion and shipment of the order to the customer. |
| Takt Time | The available production time divided by the units a customer demands. |
| Cycle Time | The average time between successive units of output. |
| Production Cost | Direct materials, direct labor, and manufacturing overhead used to manufacture products. |
| Revenue | Amount of money received by selling the product to the customer. |
| Profit | Revenue – Production Cost. |

To assess the conceptual knowledge, students were asked to answer five multiple choice questions about the Mass production paradigm, high volumes produced at reduced cost, and unskilled or skilled workers after they completed the simulation game (see Figure 2). The questions are related to Mass Production, which is one of the manufacturing paradigms. The main characteristics of the Mass Production paradigm are:

(1) Principle: Based on specialization and division of labor as described by Adam Smith.
(2) Technical Skills: moderate skills.
(3) Non-technical Skills: communication, teamwork.
(4) Business Model: Design–Make–Sell.
(5) Product Design: designed by the Original Equipment Manufacturer (OEM) and constructed assuming enough customers.
(6) Manufacturing Processes: assembly, casting, machining, grinding, polishing, etc.
(7) Production Type: Batch production, production line.
(8) Production Parameters: high quantity vs. low variety. Examples: cars, plastic bottles.

The student responses to the conceptual questions are shown in Figure 3. It is noted that most students answered the questions correct for after participating in the simulation activities. The analytical skills assessment focused on the manufacturing system performance parameters such as cycle time and production cost. Figure 4 shows the cycle time for the Mass production activity. Cycle time is the average time it took the group to build one toy car. The average cycle time for the Mass Production activity was 0.77 minutes. This is compared to an average cycle time of 6.5 minutes when the students worked individually. The shorter cycle time for the Mass

Production simulation is a result of using the assembly line and performing the tasks in groups. It can also be noted in Figure 4 that groups 3 and 4 were more effective than groups 1 and 2 as reflected by the shorter cycle time for producing the toy cars. This also applies to the production cost shown in Figure 5. Production cost includes the cost of material and labor per one toy car. The average production cost was $6.3 per one toy car as compared to an average production cost of $12.1 if the activity is conducted by students individually. The lower production cost in Mass Production is due to the economy of scale and the assembly line implementation. The total profit for the Mass Production simulation activity was $90.79, an average of $22.7 per group.

**Q1. The business model used in the Mass Production paradigm is:**
a) Sell-Design-Make
b) Design-Sell-Make
c) **Design-Make-Sell**
d) All of the above

**Q2. Workforce in the Mass Production paradigm is:**
a) Highly skilled
b) Moderately skilled
c) **Relatively unskilled**
d) None of the above

**Q3. The manufacturing system used in Mass Production is a:**
a) **Dedicated manufacturing system**
b) Flexible manufacturing system
c) Advanced manufacturing
d) General purpose machines

**Q4. The production volume in Mass Production is:**
a) Low
b) **High**
c) Medium
d) None of the above

**Q5. Which of the following statements best describes the Mass Production paradigm:**
a) Options of customized standard products
b) Market of one
c) **Standard products**
d) Personalized products made with advanced technology

Figure 2. Conceptual knowledge questions for the simulation activity.

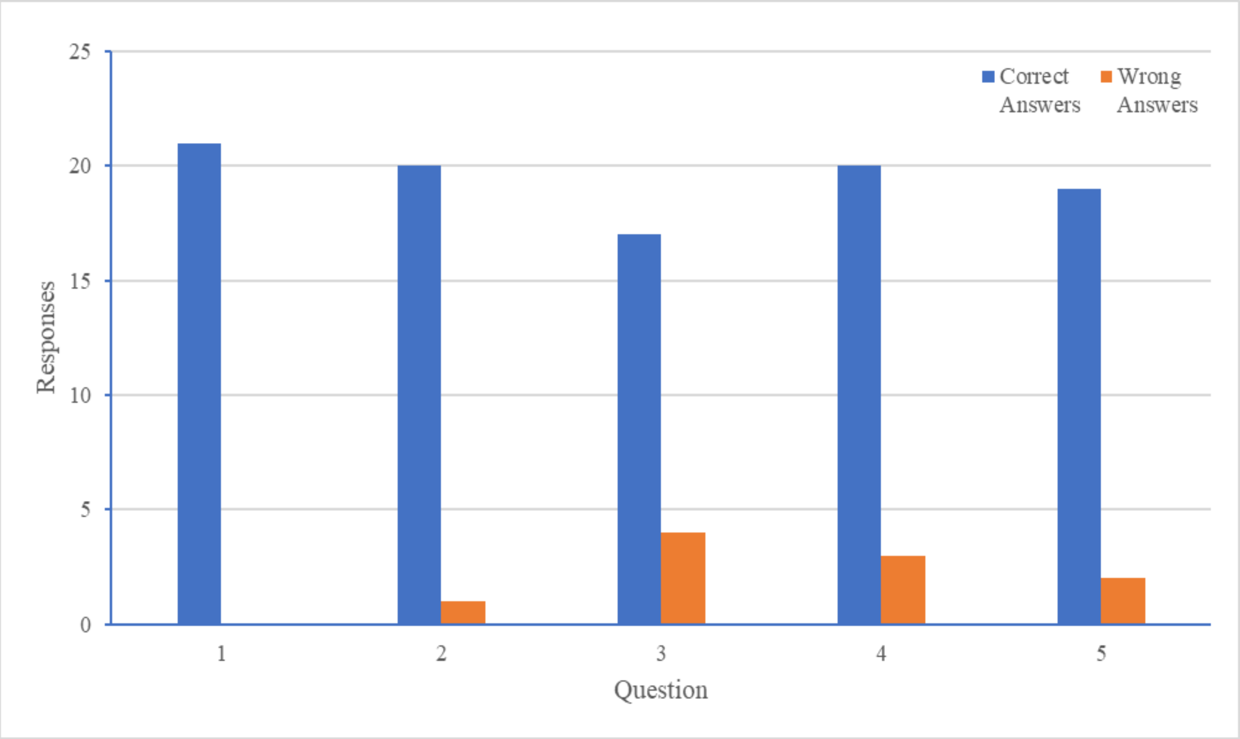


Figure 3. Students' responses to the conceptual questions.

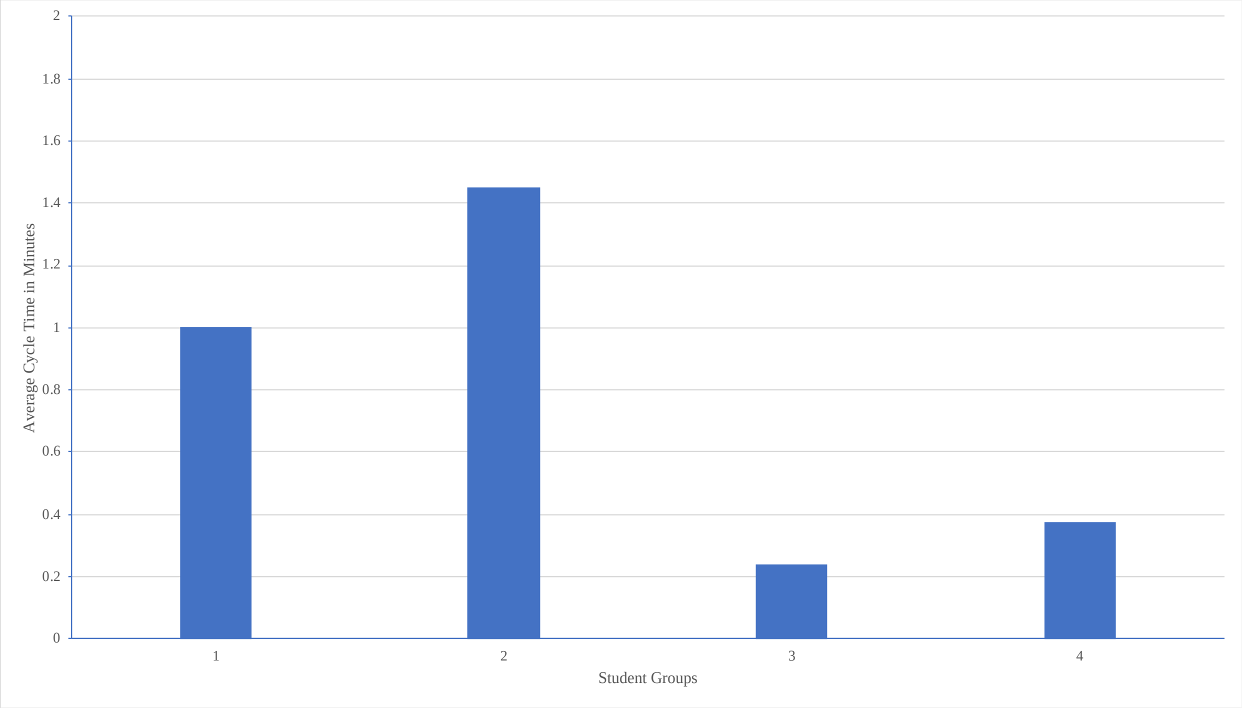


Figure 4. Average cycle time for the Mass Production activity.

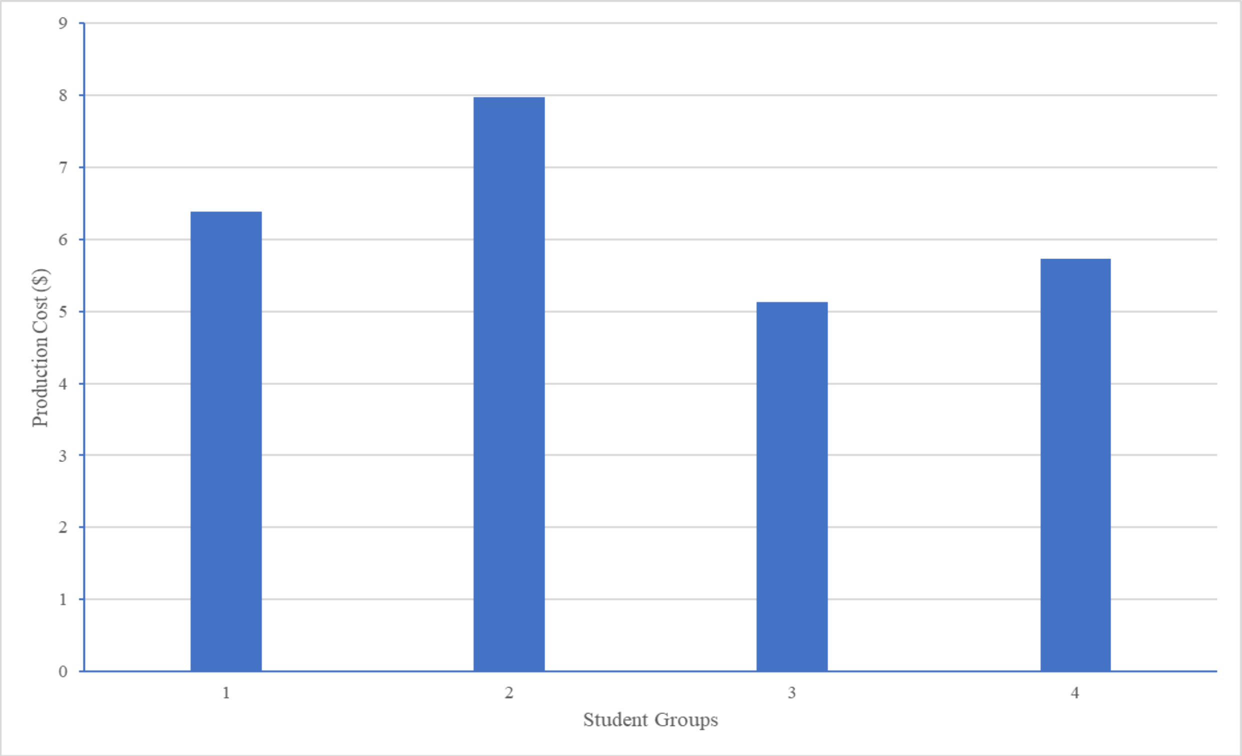


Figure 5. Production cost per toy car for the Mass Production activity.

In order to simulate the forecasting and takt time calculations in the Mass Production activity, each student group conducts an initial market analysis and develops a production plan based on forecasting. This is done as follows: *each student in the group rolls a single die (of 6 faces) five times and calculates the average of the faces for the five trials. This ensures the demand is normally distributed. The group calculates the sum of the four averages and that is their total number of car toys they can sell to customers.* Based on these numbers, the student groups develop their production schedule and obtain the required raw material from the supplier. They also develop their designs for the product and assign the tasks to the group members. Each student creates a design for the toy car and the group picks the best design. Sample designs are shown in Figure 6.

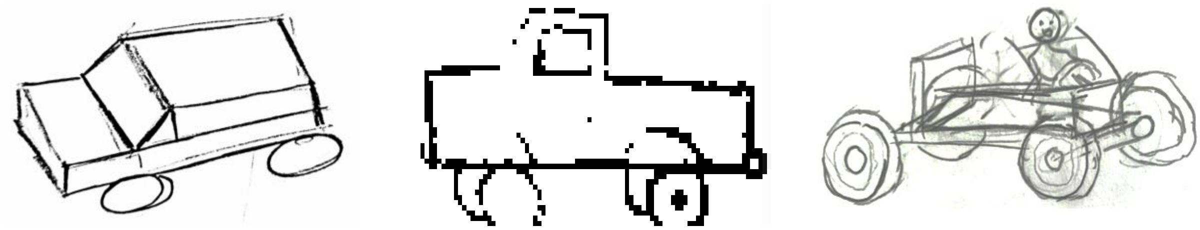


Figure 6. Sample desings for the toy car.

Once the group finalizes the selection of the best design alternative, they identify the raw material needed to assemble the toy car. The team will make sure the total cost of the car and the weight constraints are satisfied. Table 2 shows a sample list of parts for a given toy car design along with the price, quantity, and weight of the parts. The selling price for the toy cars will be determined as: raw material cost + labor hour ($0.25/worker//minute) + profit (20% of [raw material + labor]).

Table 2. List of parts for a given car toy design.

| Type | Size | Weight (per item) (grams) | Price (per item) ($) | Quantity | Total Weight (grams) | Total Price ($) |
|---|---|---|---|---|---|---|
| **Brick** | 1 x 3 | 1.15 | 0.12 | 2 | 2.3 | 0.24 |
| **Brick** | 1 x 1 | 0.45 | 0.07 | 6 | 2.7 | 0.42 |
| **Tires** | small | 0.65 | 0.15 | 4 | 2.6 | 0.6 |
| **Plate** | 2 x 8 | 2.25 | 0.25 | 1 | 2.25 | 0.25 |
| **Slope** | 1 x 2 | 0.65 | 0.11 | 2 | 1.3 | 0.22 |
| **Axle** | Small two-sided | 0.7 | 0.15 | 4 | 2.8 | 0.6 |
| **Rim** | small | 0.25 | 0.20 | 4 | 1 | 0.80 |
| **Steering Wheel** | 0ne size | 0.6 | 0.29 | 1 | 0.6 | 0.29 |
| **Windshield** | 2 x 4 | 2.5 | 0.38 | 1 | 2.5 | 0.38 |
| **Plate** | 4 x 6 | 3.35 | 0.43 | 1 | 3.35 | 0.43 |
| | | | | **Total** | **21.4** | **4.23** |

Given the demand forecasts, the participants can calculate the takt time based on the following equation:

$$Takt\ Time = \frac{Total\ Avialable\ Production\ Time}{Average\ Customer\ Demand}$$

For example, if the available production time is 20 minutes and the average customer demand is 36 toy cars, the takt time is 20 minutes / 36 toy cars = 0.55 minutes or 33.33 seconds.

Open ended questions were also used to collect student's responses on the different aspects of the simulation activities. We used Word Cloud to cluster the student's comments and identify the most repeated responses. *For Open Ended Question 1 (OEQ1),* the question was "Did the mass simulation game improve your understanding of the Mass Production paradigm? Explain." The Word Cloud for the responses is shown in Figure 7. All students answered the question with "Yes" and most mentioned "production" in their comments since "product" is the focus of the mass production paradigm. Other terms the students focused on are “inventory”, “process”, and “market” which are associated with mass production.

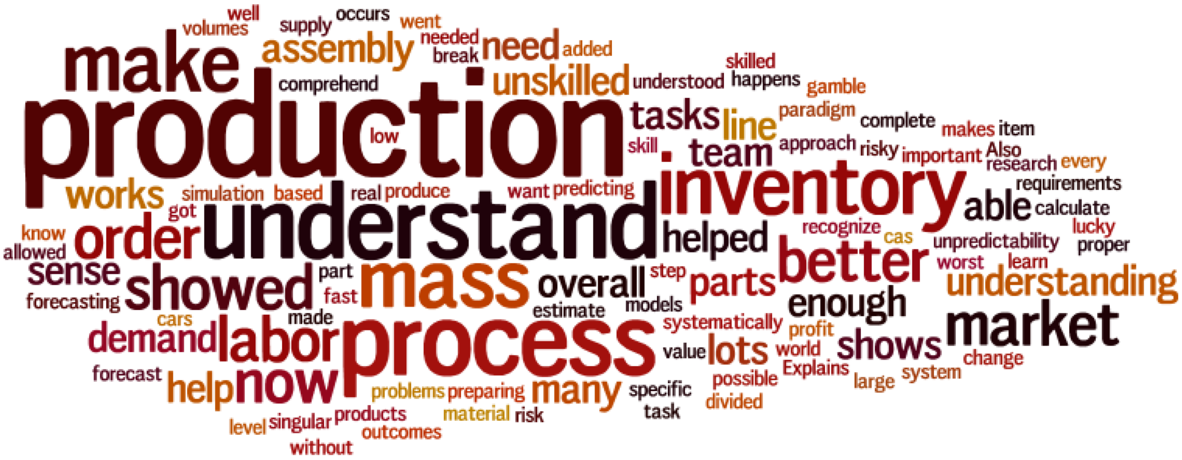


Figure 7. Word cloud for student responses to OEQ1.

*For Open Ended Question 2 (OEQ2)*, the question was “Did the Mass Production simulation game improve your design and manufacturing problem solving skills? Explain.” Responses for this question are shown in Figure 8. All responses were “Yes”, and other words emphasized by the student include “profit”, “problem”, and production”.

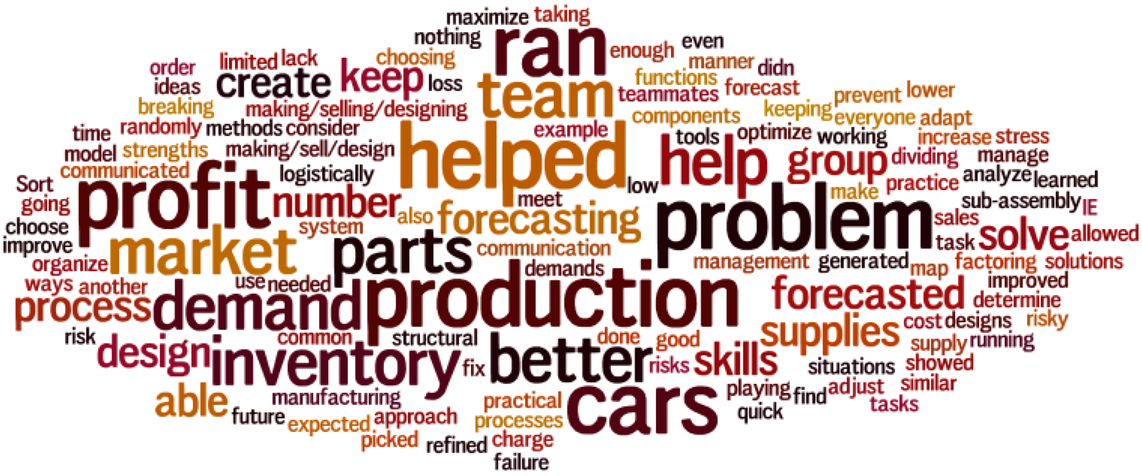


Figure 8. Word cloud for student responses to OEQ2.

The simulation game is used to teach Industrial Engineering students the manufacturing systems as well as the basics of lean manufacturing, optimization, ergonomics, and teamwork. Given the set of customer requirements and simulation activity constraints presented in Section 2, the students are asked to optimize the toy car assembly line by minimizing the assembly time and cost as well eliminating awkward postures. Properly designed workstations can help minimize awkward postures and ergonomic risks. Awkward postures like kneeling, reaching, and bending cause fatigue to the operators, decrease their performance, and can result in injuries. Such postures can result in wasted motions that increase the time to perform the tasks and reduce the quality of the work. In production assembly, well designed and presented information is important for effective assembly operations. In this research, lean manufacturing and ergonomic principles were considered to redesign the assembly processes of the toy cars in order to minimize ergonomic risks and reduce the total cost of the toy car assembly. The 5S lean approach was used to reorganize the workstation layout (see Figure 8). Given an initial workstation layout with a variety of plastic components, we sorted the plastic components into plastic storage containers based on the type and size of the components. With an organization of the plastic components, motion waste was eliminated, and more surface space was given which can be shown in Figure 9. The containers are labeled by size and type of plastic component to make identification easier during simulation. During the first trial of toy car assembly (layout 1), participants were moving around trying to figure out what they needed which caused them to waste time in their allotted time of 20 minutes. With careful consideration of what component types and sizes the participants needed, the layout was reconfigured to improve participants' focus on their tasks. This new layout focuses on putting all the necessary components at their point of use. By allowing the necessary components to be nearby and easy to find, the participants can either choose to assemble while sitting or standing, which will decrease the ergonomic risks associated with the assembly process.

Workstation layout 1 (before)

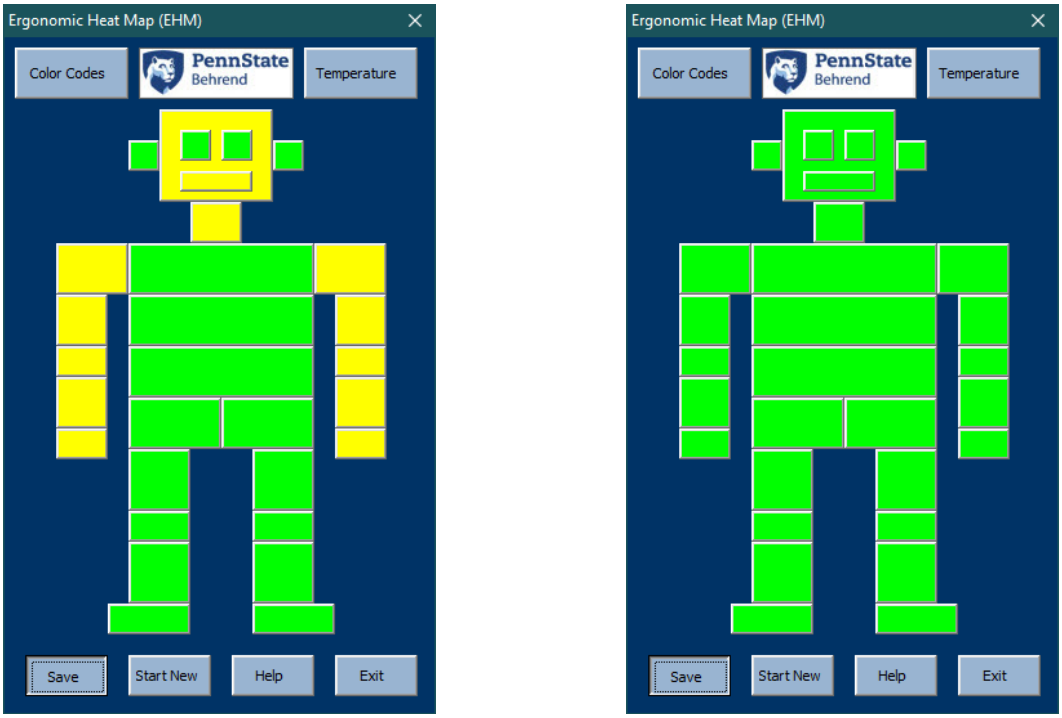
Workstation layout 2 (after)

Figure 9. Before and After workstation layout.

A qualitative ergonomic assessment was also conducted, and the results are used to make improvements to the production layout. Specifically, we used the Ergonomic Heat Map (EHM) to evaluate the ergonomic risks as shown in Figure 10. After the assessment of the original layout was completed, improvements were implanted to make sure the ergonomic risks are minimized. The EHM software application was designed by the research team; it visualizes ergonomic risks on different parts of human body by dividing the body is divided into 24 parts in addition to the eyes, mouth, and ears. Noise is represented by ears, illumination is represented by eyes, mouth represents stress and work pace, and posture/force are represented by other body parts. To assess the ergonomic risks, EHM uses the Occupational Safety and Health Administration (OSHA) guidelines for noise, temperature, and illumination. For example, for noise level, EHM uses the following equation for evaluation:

$$D = 100 \sum_{i=1}^{n} \frac{C_i}{T_i}$$

*D* is the noise dose, $C_i$ is the total time of exposure at a specific noise level measured in hours, $T_i$ is the reference duration recommended by OSHA, in consideration to sound level. EHM also uses the guidelines developed in the literature for lower and upper extremities ergonomic risk assessment. The different colors on the heat map represent the risk level where green means no risk, yellow means low risk, brown means medium risk, and red means high risk.



Ergonomic Heat Map for layout 1 Ergonomic Heat Map for layout 2

Figure 10. Ergonomic assessment results.

To improve kitting process and optimize the production performance, a mathematical model was developed for the assembly of toy cars. The model takes into consideration the customer requirements of the vehicle as well as availability of resources and other constraints. The objective function of the model is set as:

$$\max \quad \sum_{k=1}^{K} Z_k \left( p_k - \left( \sum_{i=1}^{I} \sum_{j=1}^{J(i)} \sum_{r=1}^{R} c_{ij}\, X_{ijrk} + h \sum_{i^*=1}^{I^*} \sum_{i=1}^{I} \sum_{j=1}^{J(i)} \sum_{l=1}^{L} X_{ijrk}\ \left( t_{ii^*} + t_{il} \right) \right) \right)$$

$Z_k$ and $X_{ijrk}$ are the decision variables. The colors codes for the toy car components used in the optimization model are shown in Table 3. The notation used in the optimization model is shown in Table 4. The decision variables are defined as:

$X_{ijrk}: if\ \ part\ i\ with\ size\ j\ and\ color\ r\ is\ used\ in\ order\ k, then 1, otherwise 0$

$Z_k$: *if order k is produced, then 1, otherwise 0.*

Table 3. Color codes for the toy car components.

| Color | Yellow | Red | Green | White | Black | Gray | Orang | Blue |
|---|---|---|---|---|---|---|---|---|
| R (index r) | 1 | 2 | 3 | 4 | 5 | 6 | 7 | 8 |

Table 4. Optimization model notation.

| Component / part, *I* | Size, *J(i)* |
|---|---|
| Brick (*i* = 1) | *j* = 1,2,3, 4,5 |
| Plate (*i* = 2) | *j* = 1,2,3, 4,5,6 |
| Slope (*i* = 3) | *j* = 1,2,3 |
| Axle (*i* = 4) | *j* = 1,2,3 |
| Steering Wheel (*i* = 5) | *j* = 1 |
| Wind Shield (*i* = 6) | *j* = 1,2 |
| Tire (*i* = 7) | *j* = 1, 2, 3 |
| Rim (*i* = 8) | *j* = 1,2,3 |

The model parameters are:
$c_{ij}: cost\ of\ component\ i\ with\ size\ j$
$p_k: selling\ price\ of\ order\ k\ (fucntion\ of\ no.\, o\ components\ and\ assembly\ time)$
$h: operator\ cost\ per\ unit\ time$
$t_{i\,i^*}: time\ to\ assemble\ part\ i\ with\ another\ part\ i^*, i \neq\ i^*$
$t_{il}: time\ to\ move\ part\ i\ from\ location\ l\ (\ where\ l = 1{,}2{,}3, \ldots 17\ locations)$
$W_k: total\ weight\ of\ toy\ car\ for\ order\ k\ (assuming\ only\ one\ car\ per\ an\ order)$
$w_{ij}: weight\ of\ part\ i\ with\ size\ j$
$V_k: total\ volume\ of\ car\ k$
$v_{ij}: volume\ of\ part\ i\ with\ size\ j$
$N_k: minimum\ number\ of\ different\ colors\ for\ car\ k$

The objective function maximizes the total profit which is calculated as the difference between the selling price (i.e., revenue) of the order and the total cost of producing a specific order.

$$Profit = Revenue - Cost$$

The model constraints are set as:

| | |
|---|---|
| Material cost constraint | $Z_k \sum_{i=1}^{I} \sum_{j=1}^{J(i)} \sum_{r=1}^{R} c_{ij}\, X_{ijrk} \leq p_k, \forall k \in K$ |
| Weight constraint | $W_{min} \leq Z_k \sum_{i=1}^{I} \sum_{j=1}^{J(i)} \sum_{r=1}^{R} w_{ij}\, X_{ijrk} \leq W_{max}\ , \forall k \in K$ |
| Volume constraint | $Z_k \sum_{i=1}^{I} \sum_{j=1}^{J(i)} \sum_{r=1}^{R} v_{ij}\, X_{ijrk} \leq V_k, \forall k \in K$ |
| Wind shield constraint | $Z_k \sum_{j=1}^{2} X_{6j4k} = 1\,, \forall k \in K$ |
| Roof constraint | $Z_k \sum_{j=1}^{J(2)} \sum_{r=1}^{R} X_{22rk}\ \geq 1, \forall k \in K$ |
| Steering constraint | $Z_k X_{515k} = 1, \quad \forall k \in K$ |

Tires and rims constraint

$$Z_k \sum_{j=1}^{J(7)} \sum_{r=1}^{R} X_{7jrk} = Z_k \sum_{j=1}^{J(8)} \sum_{r=1}^{R} X_{8jrk} = 4 , \forall k \in K$$

Color constraint

$$Z_k \sum_{r=1}^{R} min\left( 1, \sum_{i=1}^{I} \sum_{j=1}^{J(i)} X_{ijrk} \right) \geq N_k, \forall k \in K$$

Axles constraint

$$Z_k \sum_{j=1}^{J(4)} \sum_{r=1}^{R} X_{4jrk} = \{2,4\} , \forall k \in K$$

The optimization model was tested with a small number of orders. We ran the model for 9 different orders using Excel Solver. Figures 11 the optimization model results; the profit and the total cost of each order. The model also provides the best combination of components for each order that meet the customer and manufacturing requirements with the least possible total cost. Table 5 shows the optimization results for the best combination of components for order 4. Using this approach, students can learn how to formulate basic optimization models for real-world problems and see the results improve the production performance.

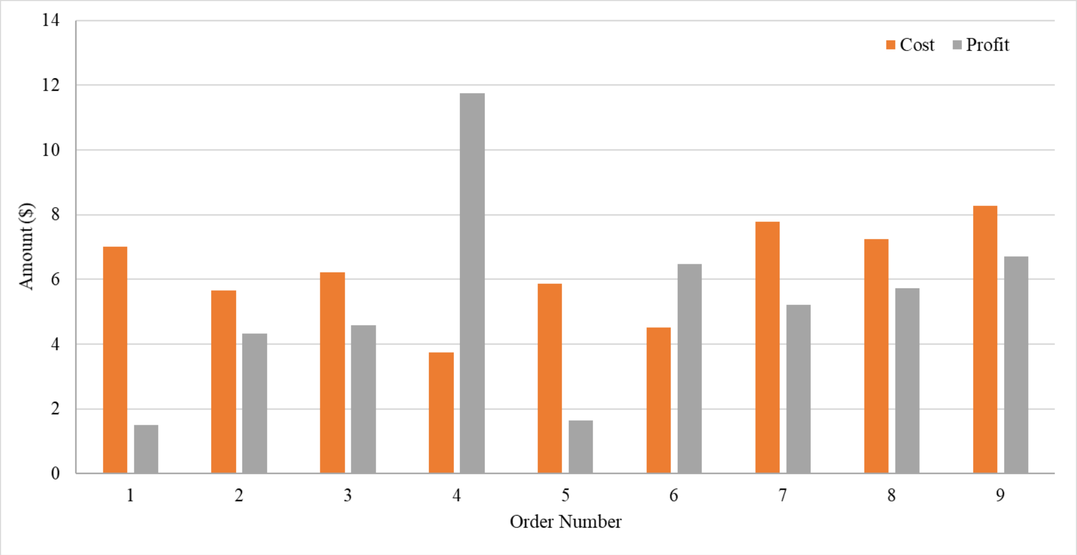


Figure 11. Optimization results for nine orders.

Table 5. The best combination of components for order 4.

| Component | Size | Color | Quantity |
|---|---|---|---|
| Brick | 1x1 | Yellow | 1 |
| Brick | 1x3 | Green | 1 |
| Plate | 2x6 | White | 1 |
| Steering Wheel | 1x2 | Black and White | 1 |
| Wind Shield | 3x6 | colorless | 1 |
| Tires | Small size | Black | 4 |
| Axle | Small One Side | Black | 4 |
| Rim | Small | White | 4 |

## 4. Adaptation of the Physical Simulation to a Multiplayer VR Serious Game

**Rationale:** with the rapid spread of the 2019 Corona Virus Disease (COVID-19), many schools and universities around the world are changing the basic way of course delivery. The outbreak of COVID-19 has forced these institutions to move to online learning. However, many educators are facing challenges to keep student engaged because these educators do not have prior experience with online teaching and the transition happened rapidly. One effective way to keep students engaged and improve their learning is by using serious games. Even when the COVID-19 crisis is over, online learning will be given more attention and many educators will consider it in their courses. In addition, most students will have computers and Internet access and educators are going to adopt online tools to support their classes. Hence, the development of virtual reality games that can be integrated into online courses will have a great impact on engaging students in hands-on activities and improving their learning experience. Multiplayer VR games provides an opportunity for transforming todays education. For example, the game developed in this research is accessible from anywhere in the world. The instructor and students can join the game at the same time and perform the simulation tasks together. Instructor provides guidance to the students and assigns the tasks to them in the virtual environment. This can be helpful for hands-on labs that require students to work together on experimental work.

### 4.1 VR Game Design

The physical simulation involves four people working with each other. In a VR game, this means four users working on four computers, each paired with a VR headset. The four computers can be located physically in the same room, or they can be located apart from each other across vast distances. Each computer runs the game and all four computers must share their information with each other, in real time, over the Internet.

To build the infrastructure allowing for four users to collaborate, we chose a client-server architecture where the first computer starting the game acted as the hosting server, and the subsequent computers acted as clients connecting to the first computer using a room number as an identifier (Figure 12). Clients communicated with the hosting server over a regular network connection. Since the server was created as needed from the first computer that ran the game, this vastly reduced the cost compared to running and maintaining a constantly-running server machine. We used the Unity game engine. In Unity, a widely accepted and used development framework called Photon Unity Networking was able to handle this connection. In terms of programming the multiplayer system, the Photon framework did much of the heavy-lifting and the programmers only had to think about one type of programming framework for both the server and the client. Every object in the game that must be seen or interacted with had to contain a network identity which told all clients and server who had ownership over the object. Every time a user interacted with an object Unity would ask the network identity of that object for ownership over the object. This was all provided through the Photon framework and had been documented in an easy-to-use way. Photon handled the creation of rooms and the hosting of a list of all rooms using its internal application programming interface (API). In order for each client to correctly display all the characters inside the virtual environment, the location and the rotation of each user's head and heads were synchronized through the server. Each client then interpreted the synchronized head and heads data to display the entire character. Photon also had built-in support for voice chat over the network, though it was not used in our game.

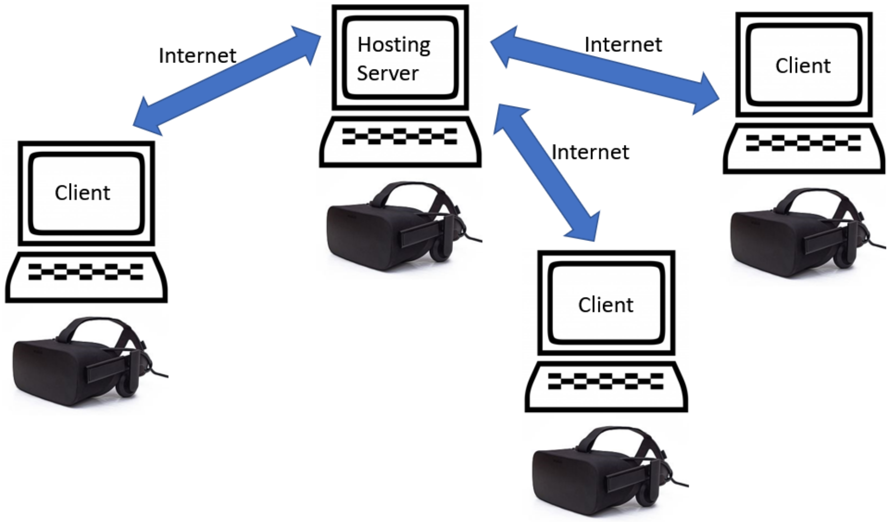


Figure 12. A client-server architecture showing how four users can work together in VR.

## 4.2 VR Game Description

We designed the VR simulation to mirror the physical simulation of the four-member team production process. The VR simulation was built in the Unity game engine in the 2018 Long Term Support release. The simulation worked both with the HTC Vive VR headset and the Oculus Rift S headset, the two most popular virtual reality platforms. For this section, we use "user" to refer to a student or a participant using the VR simulation. The simulation was designed for the simultaneous participation of four users, although two to three users would be able to participate with some adaptation. Each user wore either an HTC Vive headset or an Oculus Rift S headset. The headsets could be mixed. Through the headset, each user was presented with a shared virtual environment of a factory with a series of workstations. They were able to interact with the environment using the controllers on each hand (Figure 13).

Inside the VR simulation, there was a large factory room with a row of workstations, as shown in Figure 14. A user wearing a VR headset was able to see the virtual environment and other users in the virtual environment. Figure 15 shows what a user saw as the other three users were working. Every user was shown in the simulation with body and hand tracking, meaning that a user could see where the other users were and what the other users were doing with their hands. While inside the simulation every user was represented with a male virtual character in a black body suit, in the future we are planning to create a diverse set of characters, and the ability for each user to choose their own character in VR.

Once all four users entered the simulation, the assembly process could begin. Each user moved to one of the stations in VR to complete their own tasks. Moving around in VR was done using the controllers on their hands as shown in Figure 13. A user did not need to physically walk around, since the physical space around the user could be limited. Walking around physically while wearing a VR headset (thus seeing only the virtual environment) was not advisable. By using the controllers, a user could teleport (moving instantly) to any location in the room.

Figure 13. Four users using the VR simulation to complete the production process. Three users were wearing Oculus Rift S and one user was wearing HTC Vive Pro.

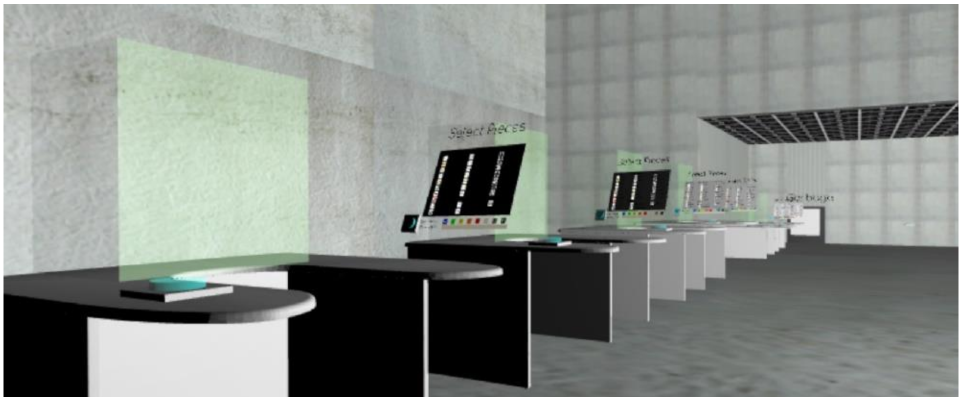


Figure 14. The VR environment built in the Unity game engine, showing workstations in a row.

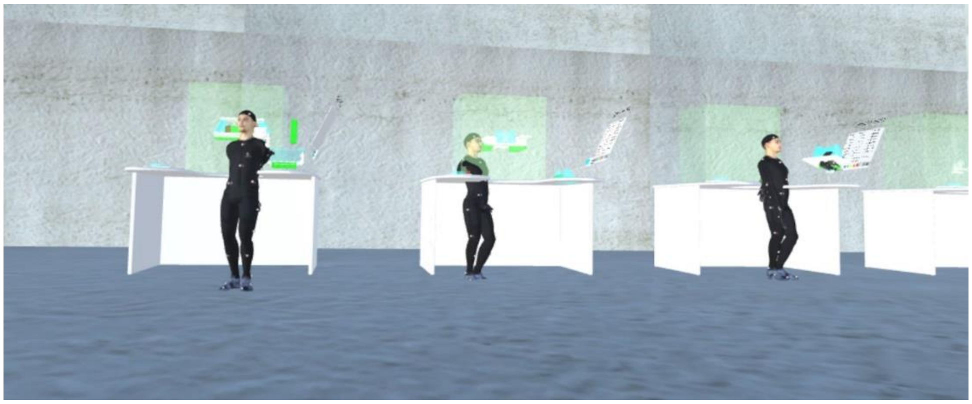


Figure 15. An in-VR view of three users working, from the perspective of the fourth user.

At each station, the user was presented with a screen of different brick pieces to choose from (Figure 16), and the selection was done by pointing at a piece with the virtual controller, which moved with the actual hand of the user. Once the user selected the necessary parts, the parts appeared in VR on the desk in the station allowing the user to assemble them as needed.

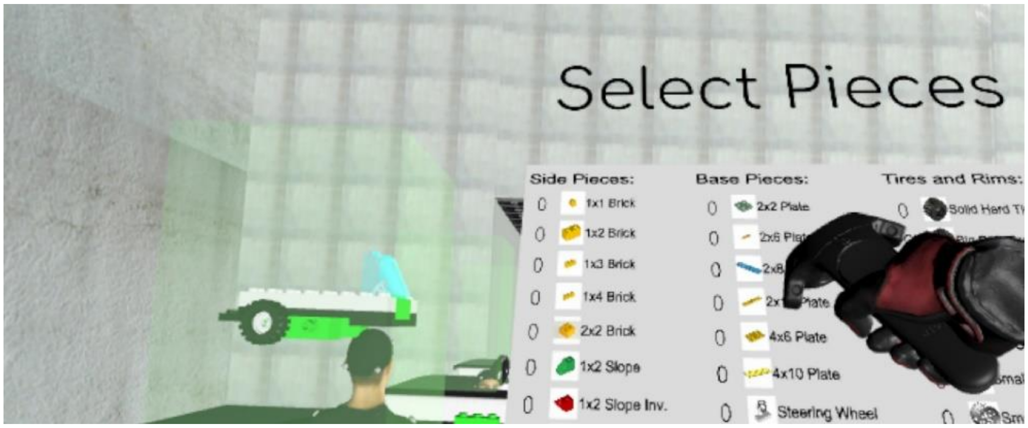


Figure 16. In-VR view of a user, where the user selected the appropriate parts in the Pieces Selection Screen to assemble the toy car. Another user is shown in the next station assembling a part of a car toy.

At each station a user was tasked with assembling a different part of the car before passing it off to the next station. At the first station a user was tasked with assembling the base of the car. At the second station a user was tasked with assembling the sides of the card. At the third station a user was tasked with putting the windshield, roof, and steering wheel on. Finally, the last station was tasked with putting on the axels and wheels for the car before moving it to the finished pile.

The VR headset was fitted with eye-tracking capabilities. As a user worked through the simulation, the system tracked the user's eye movements, including fixation points, latencies, and saccades. The Unity game engine also provided us with an exact timeline of which brick pieces the user had looked at any given time in the simulation process. We used this eye tracking data to model attention and provide a better understanding of metacognitive process. Eye-tracking can be used to analyze decision making for machine learning within the game.

## 4.3 Pilot Testing the VR Game

One research question we wanted to ask is whether the multiplayer VR simulation could be used as an alternative to physical simulations. We asked our four undergraduate research assistants (three men and one woman) to pilot test the multiplayer VR simulation and had them fill out a NASA Task Load Index (TLX) survey. The NASA TLX survey [11] is a subjective workload assessment tool that was developed to allow users to assess subjective workload assessments on various human-machine interface systems. The NASA TLX survey tracks six factors: mental demand, physical demand, temporal demand, performance, effort, and frustration. A participant provided a rating for each of the six factors. The factor of Performance was rated on a scale of "good" to "poor" while the other five factors were rated on a scale of "low" to "high." The survey also asked participants to make a series of binary choices between two of the six factors to set the weights for each of the scales, such as "Effort or Performance." In this case a participant should pick the one more important to his/her own experience. We chose this survey to measure the viability of our VR simulation as an alternative to physical simulations.

In a previous similar study, ten undergraduate student participants filled out a NASA TLX survey after completing a similar physical simulation using physical plastic bricks. Figure 17 shows the average adjusted score for each of the six factors, based on user post-participation responses. For VR, frustration was the heaviest scored factor in workload, signaling that the VR user interface had areas to improve to reduce users' level of frustration. This was not surprising as the VR interface was still in early prototype stage. Performance received the least score among the factors suggesting that the users were generally satisfied with their performance in the required tasks – low performance ratings indicate "good" performance.

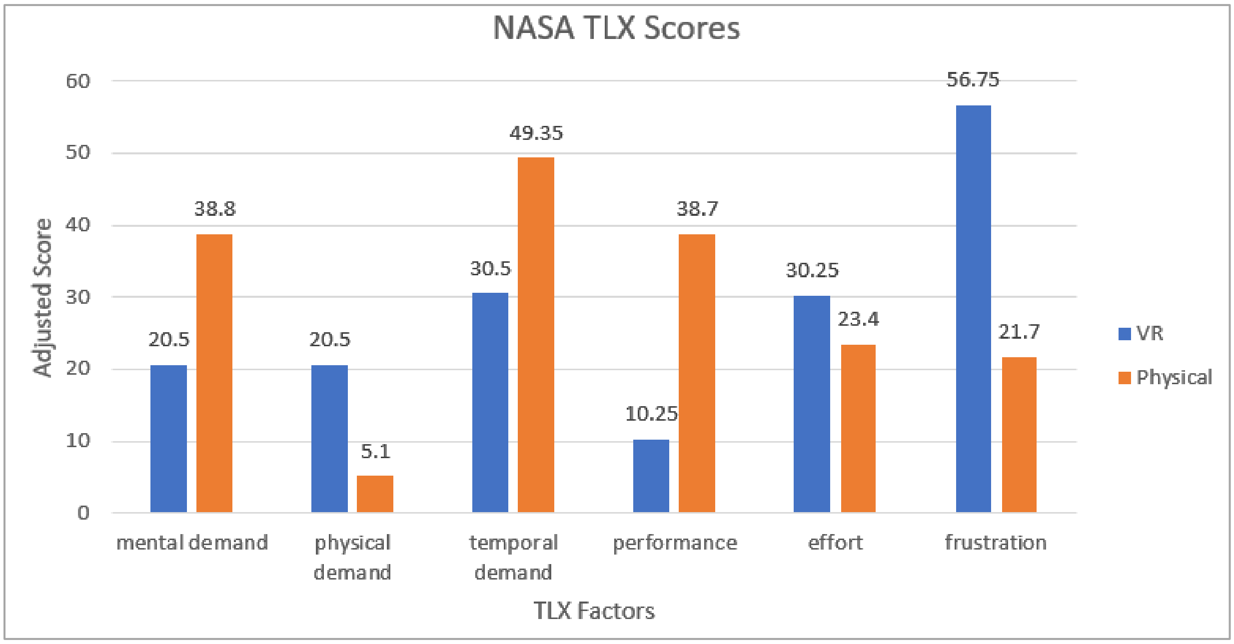


Figure 17. NASA TLX Scores for the six factors. For each factor, a lower score is desired.

The proposed simulation game is portable, and students and instructors can perform the simulation activities from anywhere in the world given that they have access to the required hardware and software. The hardware needed to run the simulations includes simulation kit (costs about $50), VR headsets (e.g., Oculus Quest which costs about $400), gaming computer (costs about $1000), and simulation instructions (Figure 18). Required software include Unity and Oculus.

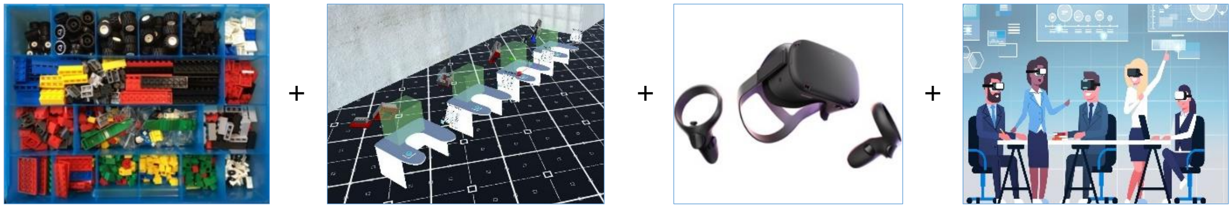


Figure 18. Portable VR multiplayer simulation game

## 5. Conclusions and Future Work

This paper proposed the use of VR technology to replace physical simulations of manufacturing processes with VR simulations, allowing for multiple users from different physical locations to work together in a VR simulation. We addressed the technical challenges in enabling multiple users in the same virtual environment. We built a VR simulation environment using rapidly developing gaming technology in order to provide a learning ground for teamwork and Lean philosophy. The pilot study was limited, but it helped us to understand how the simulation needed to be improved for future studies. Future work will focus on improving the simulation and conducting simulation activities to study knowledge assessment, problem solving, and metacognition in engineering students.

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