A Framework for Teaching Manufacturing Paradigms Using Simulation

Scott McCurdy
Cochranton Junior-Senior High School
Cochranton, PA 16314, USA
scott.mccurdy@craw.org

John Namey
Jefferson Area Junior-Senior High School
Jefferson, OH 44047, USA
john.namey@jalsd.org

Faisal Aqlan
Industrial Engineering Department
Penn State Behrend
Erie, PA 16563, USA
FUA11@psu.edu

Abstract

This study presents a learning framework for manufacturing paradigms utilizing both physical and computer simulations. The objective of this study is to attract more people to manufacturing and address the problem of lacking young talents in the field. First, physical simulations of the five manufacturing paradigms (*i.e.*, craft production, mass production, Lean production, mass customization, and personalized production) are developed in order to understand the past, present and future of manufacturing and identify the associated skill sets. Then computer simulations are developed to imitate the physical experiments. The developed simulation will be used to teach high school students the basics of manufacturing and how simulation can be used to perform analysis of manufacturing systems. Preliminary results are discussed and suggestions for future work are presented.

Keywords
Manufacturing education, manufacturing paradigms, physical simulation, computer simulation.

1. Background

Effective educators understand and employ techniques that promote student engagement. Engaging learning experiences are those that have clear applications to the real world and use differentiated instructional strategies such a hands-on activities, multimedia events, creative thinking, and cooperative learning to name a few. Specific to Science, Technology, Engineering, and Math (STEM) education, engaging activities can readily align to real-life applications associated with manufacturing and industrial processes. STEM education continues to expand which affords more opportunities to expose students to manufacturing processes. The use of computer simulation to study and analyze manufacturing systems have been discussed by many authors in the literature. Simulation provides an easy method to run experiments on the system model and make changes on it that may be very costly if performed on the real system (Al-Hawari et al., 2010). Studies also showed many manufacturing improvement possibilities based on simulation of various production control strategies in production systems (Kosturiak and Gregor, 1998). Several studies have used simulation for different applications in manufacturing systems such as capacity analysis (Gujarathi et al., 2004), production line consolidation (Aqlan et al., 2014), study of design changes (Zhiwei and Yongxian, 2008), and evaluation of design alternatives (Owens and Levary, 2002).

This study considers three manufacturing paradigms, namely craft, mass, and lean production. The first paradigm, craft production, is characterized by skilled craftsmen individually producing goods without the use of automation or assembly lines. It is considered the original form of production models that produces a relatively low volume of highly varied products, analogous to woodworkers and pottery artisans. The latter exemplar outlines production of a large number of similar products efficiently. Mass production is typically described as system that uses mechanization, such as an assembly line, to achieve accurate organization of material and work flow. The two paradigms fall on different sides of the push-pull production strategy, where craft production follows the “pull” action by waiting for customer requests and special arrangements, and mass production exhibits the “push” approach by making projections on demand which then determines what enters the production process. Lean production is a philosophy that promotes increase in efficiency and productivity for production by removing wastes and reducing lead time.

The developed simulations discussed in this study will be used to teach the principles of manufacturing paradigms to high school students. We first developed physical simulations of manufacturing paradigms which is conducted by high school teachers, most of them have years of experiences working in manufacturing industry. Then we collected data from the physical simulation hands-on activities and developed computer simulations that mimic the physical simulations. Computer simulations will allow for studying the behavior of the systems and performing different what-if scenarios. A unit plan is developed so that STEM subject teachers can use in high school classrooms that will expose students to manufacturing systems while aligning to state and national learning standards. The unit plan includes differentiated instructional strategies and teems with real-world applications. The classroom becomes a manufacturing facility, production includes building Lego cars, and students physically perform the various roles in the process. Students also use computer simulation software (e.g., Arena®, Simio®, Plant Simulation®, FlexSim®, Simcad®, AnyLogic®) to represent the process visually and conduct verification and validation analysis.

2. Research Methodology

Shown in Figure 1, the proposed research methodology focuses on developing simulations for manufacturing paradigms that will be used to teach high school students the principles of manufacturing systems as well as the use of computer simulation to study and analyze manufacturing systems and processes. First, the goals of the research study were defined which include developing simulations for manufacturing systems and associated lesson plans. Then the researchers identified the configuration of the manufacturing system to be studied and how the system will be modeled. The physical simulation activities are then developed. While running the physical simulation activities, data were collected and analyze to be used in the computer simulations. The physical simulations use Lego® blocks and are conducted by groups of high school teachers. Computer simulations are developed in Simio® and Arena® simulation software (www.simio.com; www.arenasimulation.com). Data collected from the physical simulation include process times, number of products produced, and defect rates. Computer simulation models are fine-tuned through verification and validation processes to make sure the model is a correct representation of the original system. Once the simulation model is verified and validated, it can then be used to conduct what-if analysis and study the impact of different variables on system performance. Lesson plans can be developed to be used in a high-school classroom setting. Examples of lesson plans to be developed: (1) basics of computer simulation and statistical analysis, (2) the use of computer simulation to study and analyze manufacturing systems, (3) effect of variability on manufacturing system performance.

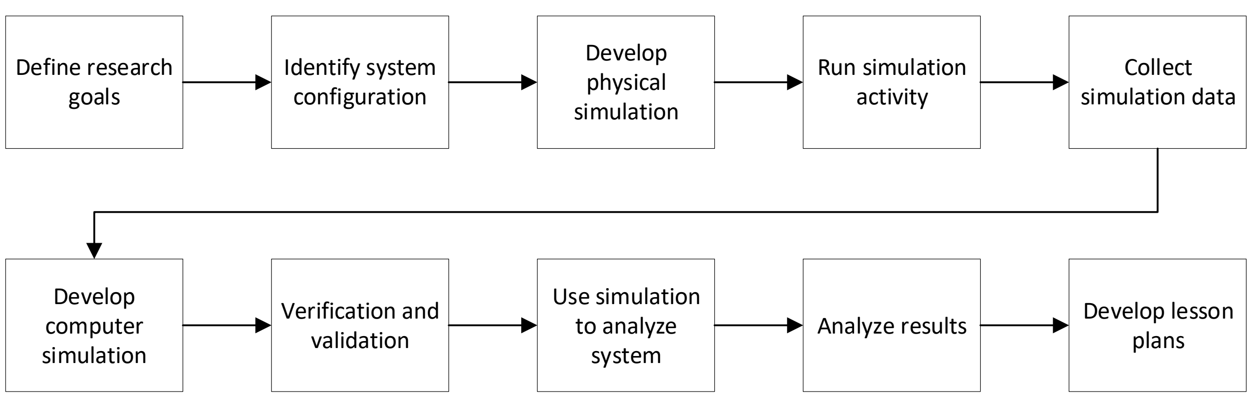


Figure 1. Research framework

3. Case Study

In this Section, we present simulations of three manufacturing paradigms, craft, mass, and lean production. Through the perspective of a high school classroom context, we developed a series of activities that will become lesson plans for high school students. By working through these activities, students will gain a deeper understanding of the characteristics of craft production and mass production paradigms and the lean philosophies that can be applied. We planned five different learning activities to engage students and foster understanding of the two manufacturing paradigms: (1) create process flow charts, (2) perform physical simulation activity, (3) organize data acquisition and analyze collected data, (4) develop computer simulation models, (5) conduct verification and validation analysis.

3.1. Process Flow Charts

The purpose of the flow chart is to simplify the production process into a visual aid with certain shapes indicating a particular type of step, as shown in Table 1.

Table 1. Flow chart symbols and their meaning

Symbol	Name	Description
○	Circle	Process start/stop
⇨	Arrow	Connectors, direction of flow
▭	Rectangle	Work station, action process
◇	Diamond	Decision point
▱	Parallelogram	Input/output data

For craft production, we elected to represent production of Lego cars with two processes: (1) Ordering Process, (2) Building Process. The ordering process highlights the steps involved in craft production from the customer-builder perspective and is represented in Figure 2.

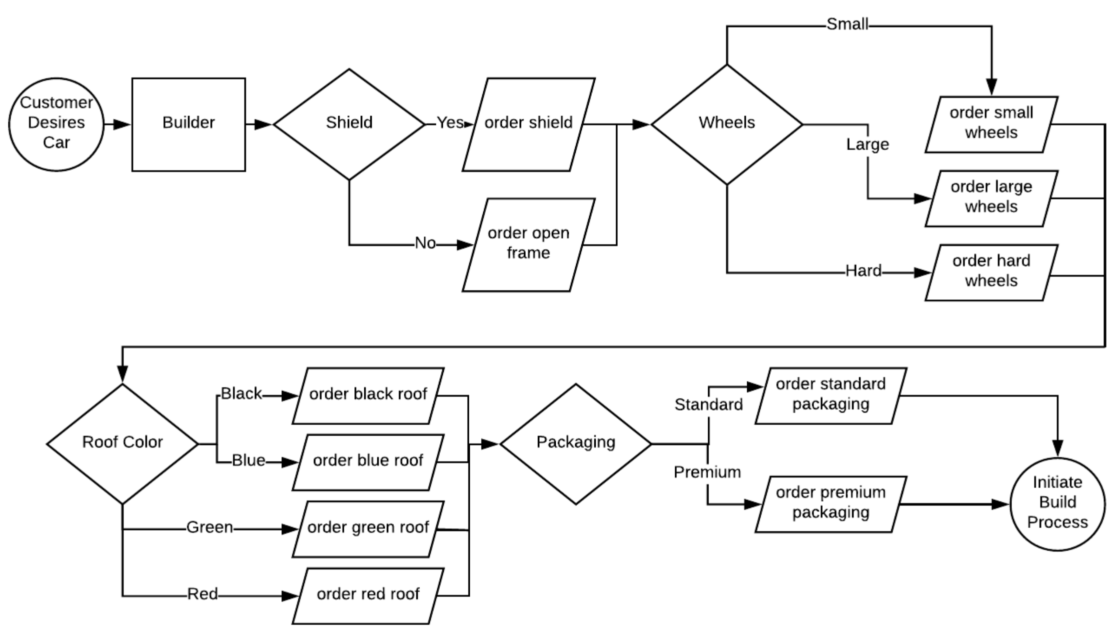


Figure 2. Ordering process flow chart for craft production simulation

The building process highlights the steps involved in craft production from the builder's perspective. Steps include supply acquisition and assembly, quality control and packaging, as shown in Figure 3.

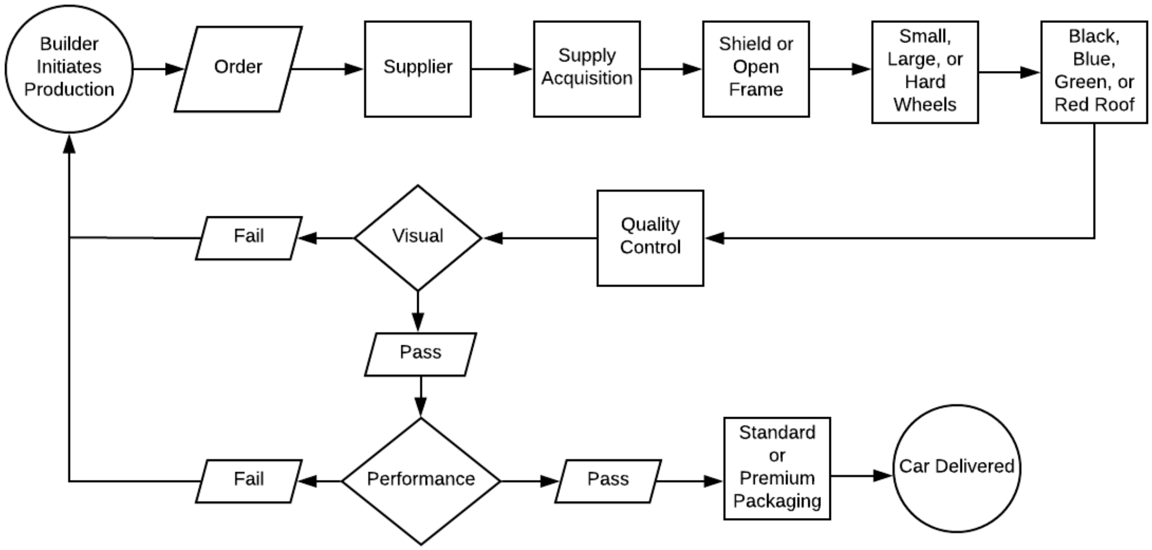


Figure 3. Building process flow chart for craft production simulation

Mass production begins with the company pushing the industry based on high volume and profit. The customer does not play a role until the point of purchase. The flow chart in Figure 4 highlights the steps involved in mass production, including steps in an assembly line, inspection checkpoints, performance testing, and packaging. Figure 5 shows the flow chart for Lean production

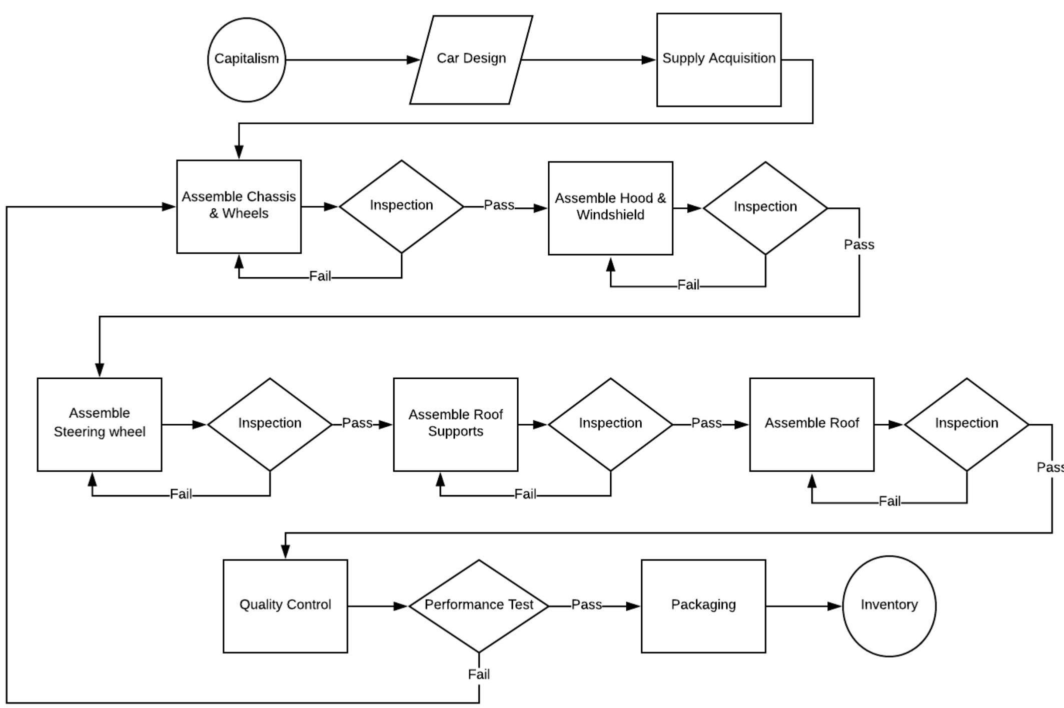


Figure 4. Process flow chart for mass production simulation

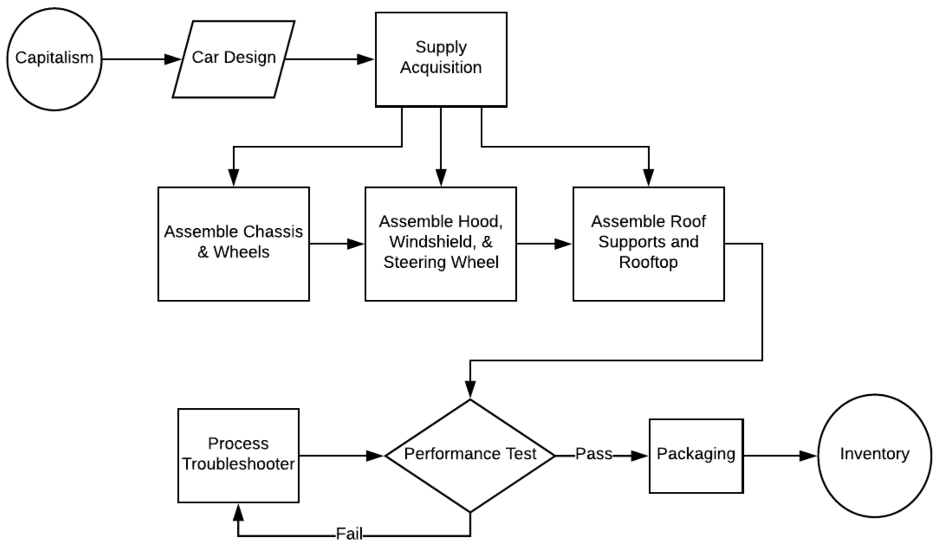


Figure 5. Process flow chart for lean production simulation

3.2. Physical Simulation Event

The physical simulation can be performed by approximately 14 members divided into two groups of to perform roles associated with craft production paradigm: five builders, one supplier, and one person collecting data and also serves as the customer. We used dice rolls to produce random customer orders. Figure 6 represents the basic classroom setup for one group. This layout is for the craft production paradigm and other layout can also be developed for the other types of manufacturing paradigms.

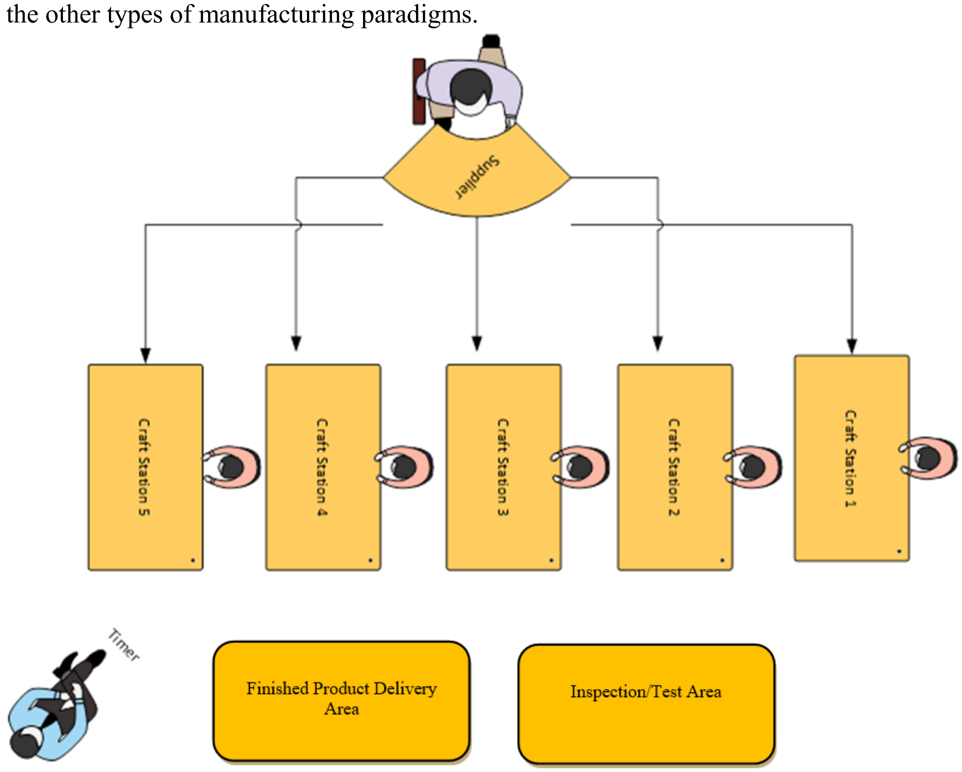


Figure 6. Group layout for craft production hands-on activity

The physical simulation of mass production involved 14 members divided into two groups of seven to perform roles associated with mass production paradigm: five assembly stations, one inspector traveling to each station, and one person doing performance testing and packaging. Each assembly worker recorded time data as they completed their step. Inspector then signs off on completion and car moves to next step. Customers were represented by dice roll at the end of production run time, randomizing purchase volume. Figure 7 represents the basic classroom setup for one group for the mass production activity.

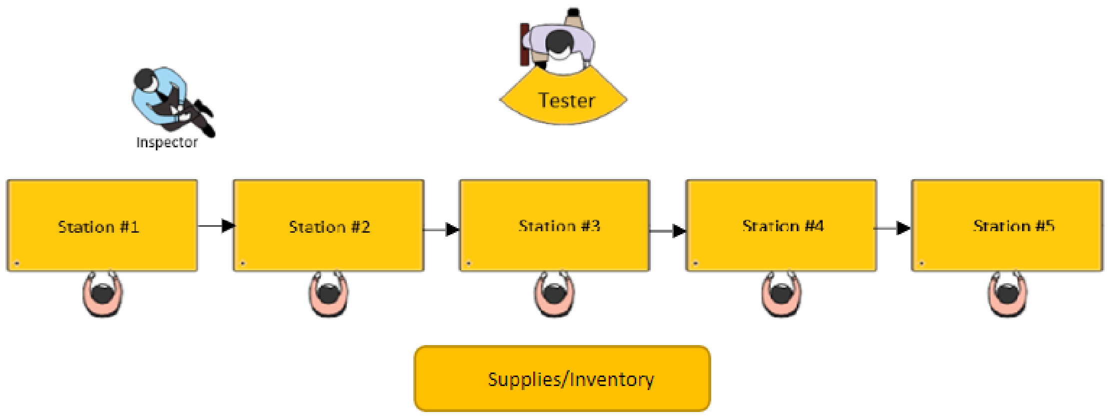


Figure 7. Group layout for mass production hands-on activity

The physical simulation for lean production (shown in Figure 8) included a floating worker called a process troubleshooter, three assembly stations, and a performance testing station. Inspection was part of each assembler's responsibility. The process troubleshooter kept the parts supply flowing as well as reworked any cars that failed performance testing so that assembly production flow was never interrupted. Figure 9 shows some pictures of the physical simulation activities for the manufacturing paradigms.

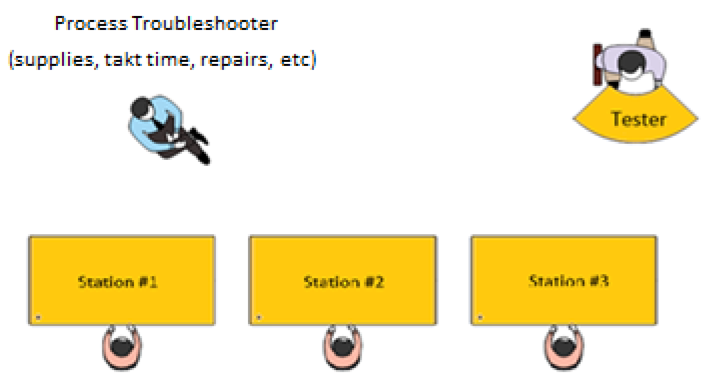
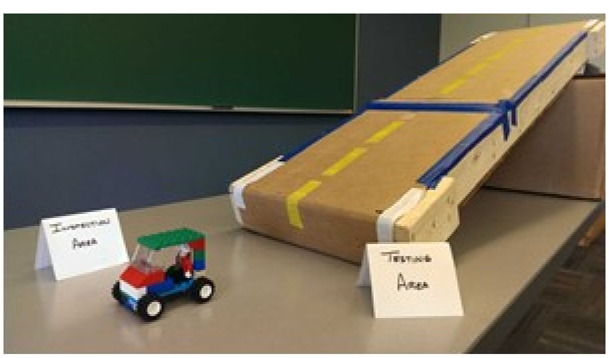


Figure 8. Group layout for lean production hands-on activity



Inspection and Test

Finished Product

Figure 9. Physical simulation activity

3.3. Data Collection

Data collection focused on timing the production steps, quality control pass/fail rates, and production quantities. This data is used later as input for the simulation software that represents the process. An example of the data collected for process time (in minutes) for the craft production activity is shown below. This data was then fitted into proper statistical distribution (see Figure 8) to be used as input for the computer simulation model. Other data collected include failure rates, order arrivals, and throughput.

4.87, 4.34, 3.08, 5.89, 4.85, 4.2, 5.00, 6.25, 4.85, 3.95, 7.00, 5.44, 5.44, 3.69, 4.64, 6.73, 1.43, 6.60, 4.94, 4.12, 4.48, 6.49, 2.44, 7.03, 4.96, 6.35, 8.14, 4.41, 5.23, 4.05

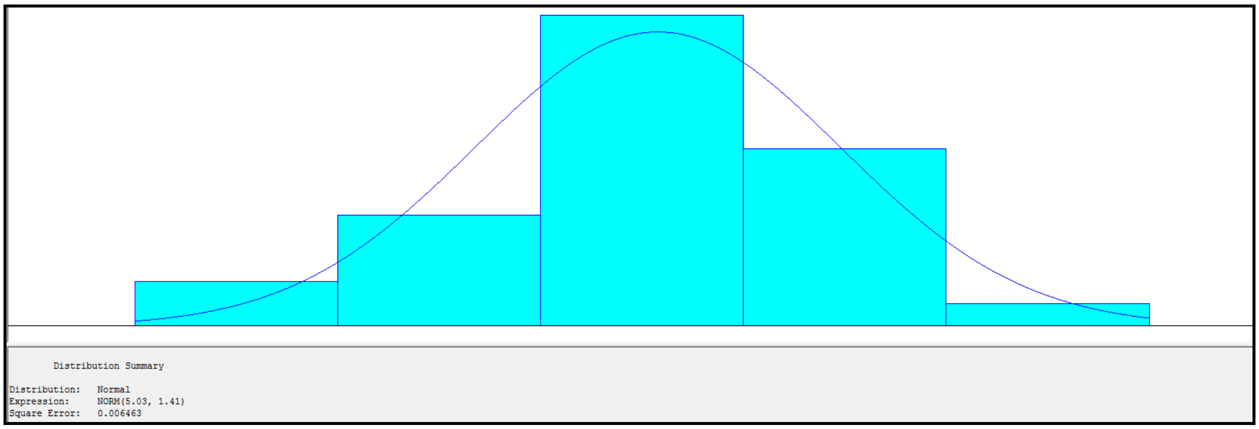


Figure 10. An example of fitting process time data into statistical distribution

Similar to the craft production case study, data collection focused on timing the production steps, quality control pass/fail rates, and production quantities. This data is used later as input for computer simulation. An example of the data collected for process time (in minutes) for one of the assembly stations is shown below. The data was fitted into statistical distribution as shown in Figure 9.

0.67	0.29	2.06	4.58	0.95	0.74	0.74	0.96	0.69	0.3
0.32	0.94	2.19	4.16	1.13	0.32	1.04	0.16	0.65	0.2
0.65	0.9	2.73	3.33	0.9	0.36	0.14	0.26	0.68	0.91
0.73	0.24	2.8	0.6	0.78	0.14	1.76	0.36	1.12	0.62
0.67	0.56	2.38	0.8	0.15	0.14	2.92	0.64	0.38	0.64
0.17	2.06	3.71	0.77	0.22	0.33	1.78	0.64	0.37	

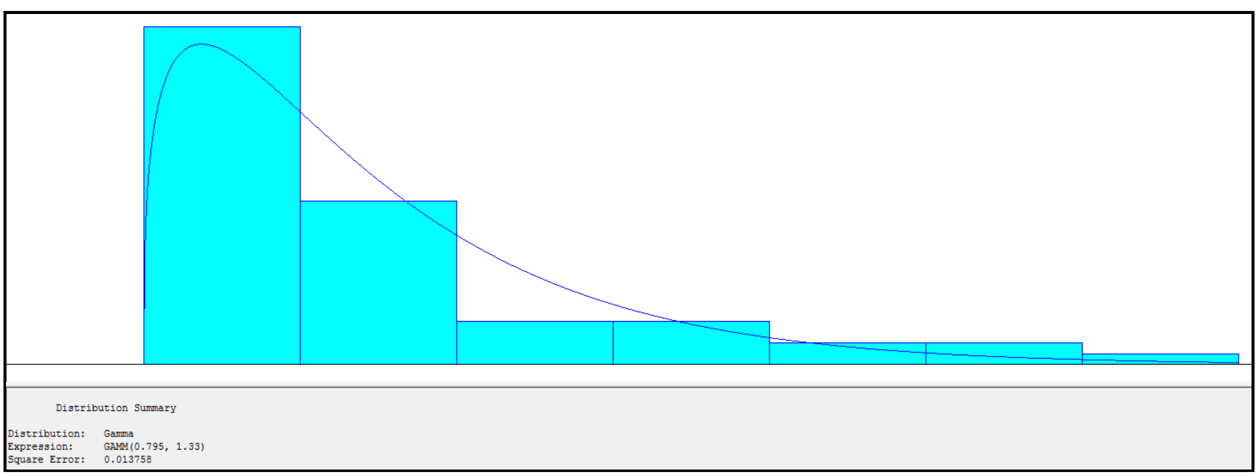


Figure 11. An example of fitting assembly station process time data into statistical distribution

Tables 2 and 3 show the statistical distributions for the mass production and Lean production process timers, respectively. The p-values of > 0.5 indicate that the fitting of the distributions is good.

Table 2. Statistical distributions for mass production process times

Process	Distribution	P-value
Station 1	WEIB(0.972, 2.51)	0.087
Station 2	LOGN(0.748, 0.659)	0.195
Station 3	EXPO(0.365)	0.527
Station 4	2.24 * BETA(1.04, 2.93)	0.150
Station 5	2.39 * BETA(1.17, 3.08)	0.150
Station 6 - 1	0.24 + 1.76 * BETA(1.68, 0.896)	0.150
Station 6 - 2	LOGN(0.394, 0.421)	0.121

Table 3. Statistical distributions for Lean production process times

Process	Distribution	P-value
Station 1	0.17 + 0.93 * BETA(0.909, 0.839)	0.642
Station 2	0.01 + 0.99 * BETA(1.1, 1.18)	0.061
Station 3	LOGN(0.298, 0.268)	0.050
Station 4	1.36 * BETA(1.36, 1.68	0.144
Station 5	0.02 + EXPO(0.206)	0.201

3.4. Developing Computer Simulations

In order to develop the computer simulation models, we first developed the conceptual models (shown in Figures 2, 3 and 4). Then Simio® and Arena® software were used to build the models. Figure 12 shows a high level example of the computer model in Simio.

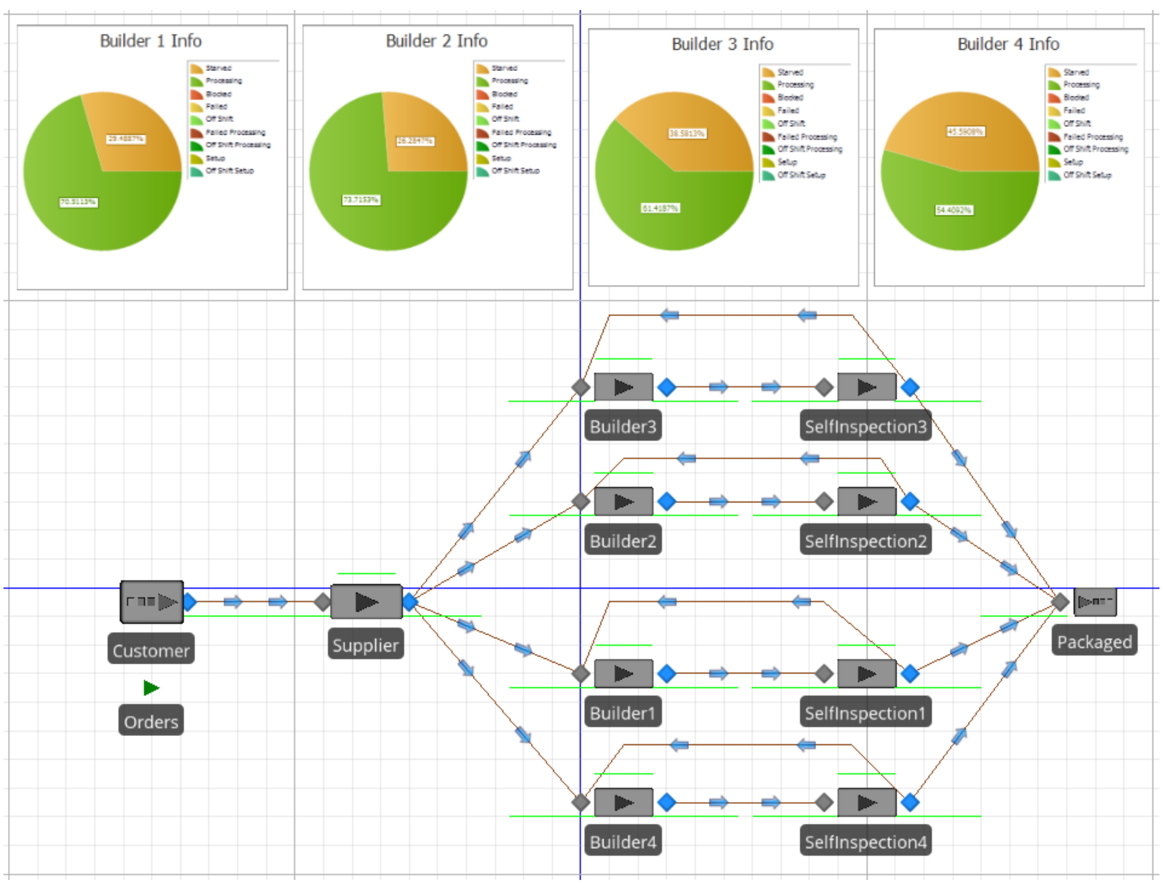


Figure 12. A simple computer simulation model for craft production using Simio

For the mass and lean production simulations, we used Arena® software. Figures 13 and 14 show examples of the simulation model in Arena for mass production and Lean production, respectively.

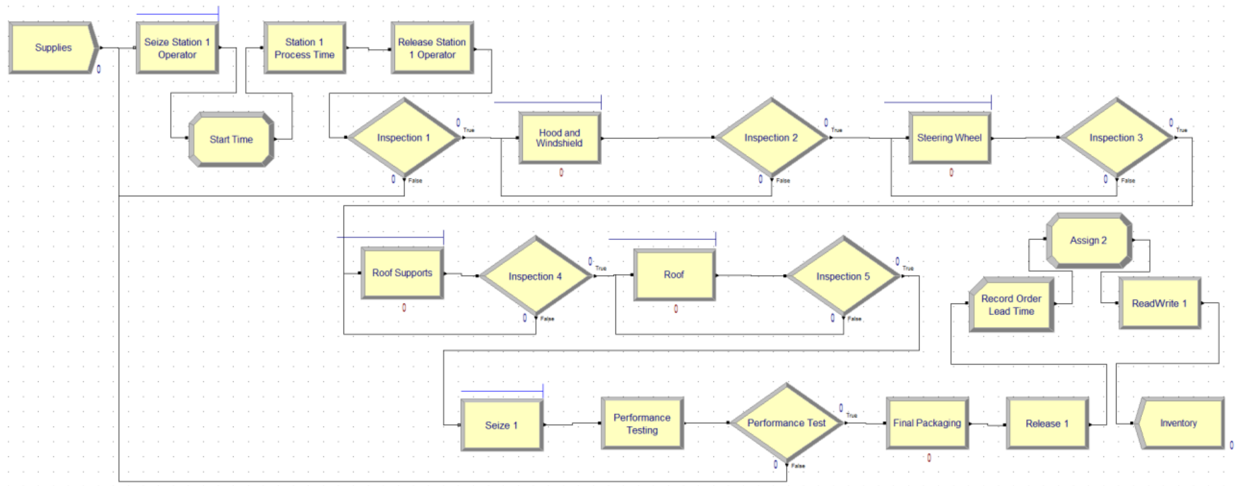


Figure 13. A computer simulation model for mass production using Arena software

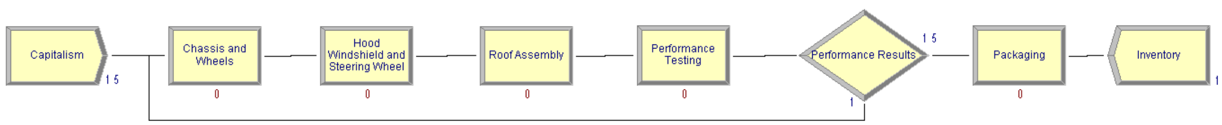


Figure 14. A computer simulation model for lean production using Arena software

3.5. Models Verification and Validation

Simulation model verification and validation are two techniques necessary to ensure the model is a good representation of the original system. Model verification, which is the process of ensuring that the model behaves in the way it was intended according to the modeling assumptions (Silva et al., 2000) is performed using animation and walkthroughs of model logic 3. Validation, however, is the process of insuring that the model behaves similar to the real system (Kelton et al., 2007). In order to check the validity of the model, the results obtained from the model are compared with the results from the real system, see Table 4. The p-values of > 0.05 indicate the validity of the simulation model which means that the simulation model is a good representation of the physical simulation. After validating the simulation models, they can now be used to study and analyze the manufacturing systems. For exampl, the number of stations in each system can be increased or decreased to study the impact on the system perofrmance. Difference scenarios acan also be generated and comapred.

Table 4. Verification and validation of mass production simulation model

	Average cycle time	Average Throughput
Physical Simulation	6.44	9
Computer Simulation	6.54	8.75
% Difference	-1.5%	2.9%
P-value	0.79	0.54

4. Conclusions

This study presented a framework for teaching manufacturing systems using simulation. Both physical and computer simulation for the manufacturing paradigms were developed by high school teachers. The developed simulations will be used to teach high school students about the principles of manufacturing systems. Results from both physical and computer simulation were obtained and compared. Future work will focus on developing simulations for the different types of manufacturing paradigms (i.e., mass production, Lean production, mass customization, and personalized production). Moreover, lesson plans and curriculum modules will be developed and aligned with educational standards. Virtual reality will be integrated with the simulations and results from physical simulation, computer simulation, and virtual reality will be analyzed and compared.

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Biographies

Scott McCurdy is in his 12th year in public education. He earned undergraduate degree and teaching certifications from Grove City College and has worked with students at all levels in the subjects of Physics, Mathematics, and General Sciences. His teaching background includes 11 years in classroom where he worked extensively on STEM-related initiatives. He connected local employers with his classroom curriculum and helped facilitate STEM professional development across the state of Maryland. He has also coached JV and Varsity sports during his career. Along the way, he earned his M.Ed. in School Administration from Liberty University and is currently the Assistant Principal and Athletic Director at Cochranton Jr/Sr High School in Pennsylvania. His most recent STEM-related ambitions focus on piloting school's first group of students to work through a newly created STEM Academy.

John Namey has been a Math teacher and and sports coach at Jefferson High School for 4 years. He obtained his BS in Mathematics from The Ohio State University. By obtaining a Resident Educator License through ODE, he has taken the mathematical theory he learned from OSU back to his hometown of Jefferson to try and get students interested in STEM. He has worked on computer programming throughout college and into his professional career.

Faisal Aqlan is currently an assistant professor of Industrial Engineering and Master of Manufacturing Management (MMM) at Penn State Behrend. He earned his Ph.D. in Industrial and Systems Engineering from the State University of New York at Binghamton in 2013. Aqlan has worked on industry projects with Innovation Associates Company and IBM Corporation. His work has resulted in both business value and intellectual property. He is a certified Lean Silver and Six Sigma Black Belt. He is a senior member of the Institute of Industrial and Systems Engineers (IISE) and currently serves as the president of IISE Logistics and Supply Chain Division, director of Young Professionals Group, and founding director of Modeling and Simulation Division. Aqlan is also a member of American Society for Quality (ASQ), Society of Manufacturing Engineers (SME), and Industrial Engineering and Operations Management (IEOM) Society. He has received numerous awards including the IBM Vice President award for innovation excellence, Penn State Behrend's School of Engineering Distinguished Award for Excellence in Research, and the Penn State Behrend's Council of Fellows Faculty Research Award. Aqlan is the Principal Investigator and Director of the NSF RET Site in Manufacturing Simulation and Automation at Penn State Behrend.