Assessment of Collaborative Problem Solving in Engineering Students Through Hands-On Simulations

Faisal Aqlan and Richard Zhao

Abstract*—*Contribution: **This article discusses the use of manufacturing simulation games to study collaborative problem-solving skills in engineering students. The simulation represents the mass production paradigm in which large quantities of identical products are produced. Empirical data is collected from the simulation to evaluate the skills engineering students used in solving the problem and their group effectiveness.**

Background: **The use of simulation games to teach problem solving in design and manufacturing is an effective approach to convey concepts to students. Simulation games engage students in experiential and collaborative learning with fun elements.**

Research Questions: **How does hands-on simulation engage students in collaborative problem solving? How does participation in collaborative problem solving affect group effectiveness?**

Methodology: **This work presents a study of 37 university-level engineering students in the United States. Participants worked in groups completing the simulation game and responded to surveys on their various skills used.**

Findings: **Participants utilized analytical, metacognitive, and thinking skills in their engagement, reported that the simulation games enhanced their understanding of manufacturing concepts and active collaboration improved problem-solving effectiveness.**

***Index Terms*—** **Collaborative problem solving, educational games, manufacturing systems, product design, simulation games.**

I. Introduction

PROBLEM solving is the process of defining and analyzing problems and finding viable solutions for these problems [1]. Successful problem solving requires both analytical and creative skills in collaboration with others. This is referred to as collaborative problem solving (CPS). In CPS, two or more individuals work together on solving the problem by sharing effort and understanding in order to develop a solution for the problem [2]. Problem-solving in design and manufacturing focuses on optimizing the product design and/or improving the production process.

Problem solving is an iterative process that requires brainstorming, analysis of the problem, development, and test of solutions. It relies on the understanding of what is known and what is unknown about the problem space. A person's knowledge of the knowns and unknowns is termed metacognition [3]. According to Peñalvo [4], new engineers must understand their own metacognition as well as other group members' metacognition in order to derive the best solution for engineering problems given different constraints.

Today there is a sizeable skills gap in manufacturing, and it is expected that this will result in failure to fill two million manufacturing jobs in the next decade [5]. The major factors that contribute to this gap include baby-boomer retirements, economic expansion, lack of skilled workers, and a gradual decline in technical education [6]. The current Coronavirus Disease 2019 (COVID-19) pandemic will also increase this skills gap as many people are losing their jobs.

Problem-solving skills are among those needed by today's manufacturing. Such skills include creativity and innovation, critical thinking, metacognitive awareness, collaboration, and teamwork. Engineering professions require both technical skills (e.g., design and manufacturing skills) that are incorporated in academic curricula and non-technical skills that are usually not part of the curricula. These non-technical skills include CPS, creative thinking, design thinking, and metacognitive awareness.

According to Griffin et al., [7], CPS is considered as one of the core competencies of the 21st century. In manufacturing, CPS is crucial to maintaining or improving business processes, and opportunities for improvement often exist in any manufacturing environment. Structured problem-solving strategies in manufacturing usually consist of the following steps: 1) defining the problem, 2) understanding the process, 3) identifying root causes, 4) developing solutions, and 5) sustaining the improvement.

This study aims to answer the following research questions: (1) how does hands-on simulation engage students in collaborative problem solving? and (2) how does participation in CPS affect group effectiveness? The research questions are based on the following hypotheses: (1) using the proposed manufacturing simulations, students learn more about manufacturing and engage in collaborative problem-solving activities, (2) students utilize different skills and improve their group effectiveness skills when they work on solving problems collaboratively.

Manuscript received July 27, 2020; revised January 11, 2021, April 12, 2021 and April 28, 2021; accepted May 3, 2021. This work was supported by National Science Foundation under Award 1830741 and Supplement 1905680. The authors contributed equally to this work.

Faisal Aqlan is with Industrial Engineering in the School of Engineering, The Behrend College, The Pennsylvania State University, Erie, PA, 16563, USA (e-mail: aqlan@psu.edu).

Richard Zhao is with the Department of Computer Science, University of Calgary, Calgary, AB, T2N 1N4, Canada (e-mail: richard.zhao1@ucalgary.ca).

II. Relevant Literature

In recent years, research has been conducted to assess how simulation games can be used in the education of engineers across different disciplines of engineering [8, 9, 10]. This line of research has been spurred by earlier studies that showed evidence of using computerized simulation games in education to increase retention more than traditional learning methods [11]. Couple this with the fact that there is a skills gap in manufacturing; it becomes imperative to improve engineering education to enhance problem-solving skills, metacognition and increase retention of engineering skills and concepts. This experiment also uses games as a teaching method, which is another research field. Using games, such as the current experiment of building plastic bricks into cars, as a teaching tool has been found to be successful in terms of improving attitudes and learning in engineering students. Despite this positive outlook, more research is needed to improve validated approaches in this field of research [12].

Simulation games have grown in use as a training and education tool over the last fifty years. Simulation games and hands-on activities provide a means to engage students in classrooms, which allows students to become more active and interested in the topic [13]. Moreover, hands-on simulations can improve student attendance by 50% [14]. According to Kumar and Labib [15], the most popular of the early games was "Top Management Decision Simulation," which is a board game developed by the American Management Association in 1956. Different types of simulation games are available today including physical games, computer-assisted games, computerized games, and virtual reality games. Physical games, also known as manual games, are conducted manually with a group of players and a facilitator who runs the games and guides the players. In manufacturing education, simulation games and hand-on activities can be an effective method for teaching students the principles of manufacturing systems and processes. Several studies in the literature have developed physical simulations for manufacturing systems and processes. For example, Simpson [16] developed hands-on activities to compare and contrast craft production and mass production in the classroom. A paper airplane activity was used to demonstrate the benefits and drawbacks of craft and mass production. In a similar study, Ozelkan and Galambosi [17] developed a simulation game that can be used to educate students and industry professionals on lean manufacturing principles. Aqlan and Walters [18] also discussed the use of simulation games to teach lean manufacturing principles. Table I shows a list of the simulation games that are widely used in manufacturing, along with their individual focus and the goal of each game. The table was extracted from a long table provided in Badurdeen et al. [19] that summarized lean manufacturing simulation and games.

Simulation games are effective tools for teaching design and manufacturing development techniques that have been historically practiced. The educational purpose of manufacturing simulation is helping students to learn different methods of the manufacturing process and familiarize them with the actual practice in the real world. Allowing students to explore unknowns is a major key factor in entrepreneurship. The simulation motivates students to focus on critical thinking, problem solving and finding alternative solutions and techniques for producing a better product.

TABLE I
EXAMPLES OF MANUFACTURING SIMULATIONS

Name of Simulation/Game	Focus	Product
UK Paper Clip Simulation	Manufacturing	Paper Folders
Buckingham Lean Game	Supply Chain	NA
Lean Enterprise Value Simulation	Enterprise	Lego Aircraft
Lean Product Development Simulation	Product Development	K'nex Product
5S Mini-Factory Simulation	Manufacturing	Tabletop Mini Factories
Furniture Factory Simulation	Manufacturing	Wooden Furniture
Ship Repair Design Process Simulation	Design Process	Container Ship
Value Stream Mapping Board Game	Manufacturing	Board Game
Lean Lego Simulation	Manufacturing	Lego Cars

Badurdeen et al. [19] presented a survey and future research direction for teaching lean manufacturing using simulation games. The study indicated that there are four gaps in existing simulation games: lack of stress on soft or professional skills, a mistaken focus on "linear lean," misunderstanding of the key role of the facilitator, and lack of realism. Hauge and Riedel [20] evaluated two simulation games for teaching engineering and manufacturing, which were: a new product development simulation game, and a risk management simulation game. The study noted that serious games such as these deliver positive learning outcomes. However, there are some drawbacks to their use that need to be considered, principally the high cost of development and the need for expert facilitators for running game sessions. The impact of gaming experience on the learning process of a manufacturing operation using the virtual simulation was presented in Ordaz et al. [21]. The study discussed a serious game that simulated manufacturing environments in order to train operators to perform manual tasks. Blöchl and Schneider [22] developed a new simulation game with the learning focus on internal material flow, intelligently combined with Industry 4.0 components. In de Vin et al. [23], they reported experiences from using both desktop simulation games and a full-scale simulator for lean production. The study found that for both students and industrial workers, training effects and immersion tend to be higher when using a full-scale simulator.

While previous work has examined problem solving using simulations, this research expands on previous work by examining collaborative problem solving, which is problem solving in a group environment. The research presents a study using simulation games for teaching manufacturing concepts to undergraduate engineering students and evaluating their problem-solving skills. The simulations utilized plastic blocks and students worked in groups to produce car toys. As a game, each participant can be considered as a "player." A point system was created to measure how well a participant performed in the tasks. The customer requirements became challenges for the participants to overcome in the game. The rules were explicitly stated at the start of the game. Groupmates collaborated to complete their tasks together by having discussions with each other. They completed the tasks without a teacher's guidance. Conceptual knowledge and various skills were measured through surveys.

III. Methodology

A. Participants

In this data set, there were 32 men and 5 women recruited from a university in the United States. The average age of participants was 19.19 years old with a standard deviation of 1.07 years. They were in an engineering major where 22 were first-year, 7 were second-year, 2 were third-year, and 6 were fourth-year or above. They had taken an average of 30 credit hours with a standard deviation of 32.8 credit hours. All participants stated that they would prefer to be an engineer over other professions. For this research, they were randomly divided into groups of maximum four participants and ten groups were formed.

B. Simulation Description

In this research, engineering students participated in hands-on simulation activities to design and produce car toys according to specific customer requirements. Figure 1 shows the simulation kits and workstation layout used for the activities. Car manufacturing is a typical industry that allows for the simulation of the different types of manufacturing paradigms (i.e., craft production, mass production, lean manufacturing, mass customization, and personalized production) as well as different product designs. The simulation kit includes a set of plastic bricks. Table II shows the characteristics of the plastic bricks including size, weight, price, and available quantity in one simulation kit.

This research focuses on simulating one manufacturing paradigm, namely mass production. Students worked in groups on the car toy assembly in the mass production activity. The following subsections describe the simulation activity in detail.

In order to have a standard evaluation process for the problem-solving skills, a sequence of steps for the car assembly was developed and all the student groups followed the same sequence. The steps for the toy car assembly are shown in Figure 2. The simulation games included product design, sourcing, product assembly, and inspection and test as well as a supplier and a customer. In the activity, there were the four tasks (design, sourcing, assembly, and test) and students worked in groups where each task was performed by a student.

To assess the problem-solving skills during the simulation activities, individual's ability to adhere to requirements was recorded. Sample customer requirements were divided into two main categories shown in Table III. The simulation activity also required that (1) simulation time was 20 minutes, and (2) all the tasks were performed by a maximum of four students in a group. The selling price for the car toys was $5 for small car toy, $10 for medium car toy, and $15 for large car toy. The goal was to minimize the total cost of producing the car toy while satisfying the requirements of the customer.

Fig. 1. Simulation kit (left) and workstation layout (right)

TABLE II
CHARECTERISTICS OF PLASTIC BRICKS

Type	Size	Weight	Price	Quantity
Brick	1x1	0.45	$0.07	140
	1x2	0.8	$0.11	70
	1x3	1.15	$0.12	50
	1x4	1.5	$0.15	50
	2x2	1.15	$0.14	70
Plate	2x2	0.6	$0.11	80
	2x6	1.7	$0.19	6
	2x8	2.25	$0.25	38
	2x10	2.8	$0.25	64
	4x6	3.35	$0.43	2
	4x10	5.4	$0.54	4
Slope	1x2 (closed)	0.65	$0.11	40
	1x2 (open)	0.7	$0.11	40
	2x2	1.05	$0.14	40
Tire	Large	5.45	$0.61	16
	Medium Soft	2.6	$0.29	20
	Medium Hard	1.3	$0.29	40
	Small	0.65	$0.15	30
Rim	Large	1.55	$0.30	16
	Medium	0.7	$0.25	40
	Small	0.25	$0.20	30
Axle	One-size	0.7	$0.15	20
Steering wheel	One-size	0.6	$0.29	20
Windshield	One-size	2.5	$0.38	4

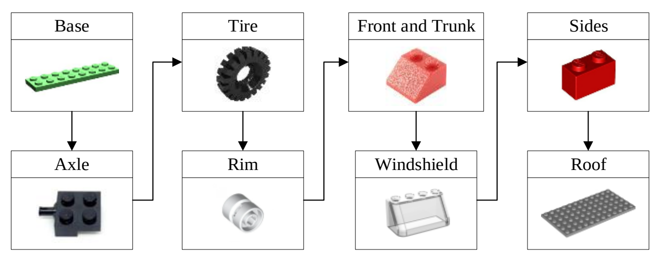

Fig. 2. Main steps for the car toy assembly process

TABLE III
SAMPLE CUSTOMER REQUIREMENTS

Vehicle Requirements	Functional Requirements
(a) vehicle weight between 20 and 40 grams (b) material cost <= $10 (c) vehicle must fit completely within the design footprint "parking space" (d) number of different colors for plastic blocks >= 5 (excluding driver and wind shield) (e) vehicle must have four tires (with axles), wind shield, driver, steering wheel, and roof	(a) driver must be able to get in and out of the vehicle and see where he is going while traveling (b) vehicle must be able to travel over ramp conditions, stay on ramp, and cross the finish line fully intact (c) vehicle must remain intact following a drop test

The simulation also involved a customer and a supplier (see Figure 3). The descriptions of the six jobs were as follows: (1) the customer who will buy the car, (2) the design engineer, (2) the sourcing engineer, (4) the manufacturing engineer, (5) the quality engineer, and (6) the supplier who provides the car toy components. Hence, there were four main functions for the car toy production: design, sourcing, manufacturing, and inspection.

a. *Design:* translate customer requirements into specifications and design the product based on the customer needs. Create a drawing for the product design to be used by sourcing and manufacturing.

b. *Sourcing:* plan and purchase the raw materials (plastic bricks) that will be used to produce the car toy. Provide manufacturing with a bill of materials along with the costs of the parts.

c. *Manufacturing:* identify and design the manufacturing processes for producing the product based the design. Assemble the car toy from the parts provided by sourcing.

d. *Inspection:* develop a system to ensure the products are designed and produced to meet customer requirements. Test and inspect the final products to determine if the customer requirements are met.

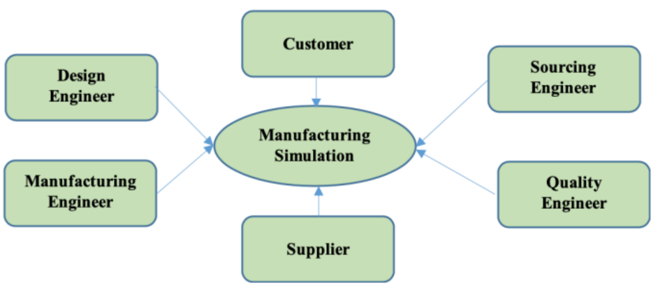

Fig. 3. Roles of the participants in the simulation game

C. Materials

Mass production is generally linked with the invention of the automobile industry's assembly line that was introduced by Henry Ford in 1913. In the mass production paradigm, high production volumes are produced to reduce the manufacturing cost. Relatively unskilled workers assemble the products on a moving assembly line.

The main characteristics of the mass production paradigm are: 1) Principle: based on the principles of specialization and division of labor as first described by Adam Smith, 2) Technical Skills: moderate technical skills required, 3) Non-technical Skills: communication, teamwork, 4) Business Model: design → make → sell, 5) Product Design: products are initially designed by the Original Equipment Manufacturer (OEM) and are constructed with the hope that there always are enough customers to buy them, 6) Manufacturing Processes: assembly, casting, machining, grinding, polishing, injection molding, etc., 7) Production Type: batch production, and production line, 8) Production Parameters: high quantity vs. low variety.

The simulation game in this study was designed so that students worked in groups on the assembly of car toys according to pre-specified customer requirements. Every group of maximum four had to assemble toy cars together. Table IV includes some key concepts considered in the manufacturing games.

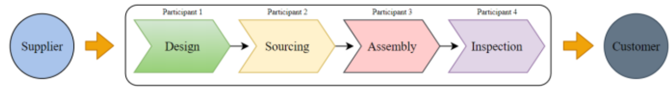

Fig. 4. Layout of the mass production simulation activity

TABLE IV
EXAMPLE KEY MANUFACTURING CONCEPTS

Concept	Definition
Mass Production	Production of large quantities of identical products.
Lead Time	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 demand.
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.

D. Procedure

Participants signed up for the study approved by the Research Ethics Office Institutional Review Board. They were each assigned to a group for the study. The study was performed in one setting of two hours. Participants must collaborate in order to complete the tasks since each person was responsible for a portion of the total task (Figure 4). Participants were not taught by a teacher before or during the activities. They received scores based on how well they completed the customer requirements as well as time to complete the tasks. Figure 5 shows sample completed car toys.

In addition to the simulation activity, participants completed a conceptual knowledge survey before the activity, and the following surveys after the activity: analytical skill assessment, conceptual knowledge measure, measures of metacognition and measure of collaborative group effectiveness.

Table V is a summary of the assessments that were used to measure students' various skills. The analytical skills and conceptual knowledge are important for successful problem solving. Metacognition is an important dimension of problem solving because the problem solvers should be aware of their thinking and be able to monitor and regulate their cognitive processes. The flow state is the mental state in which the problem solver is fully immersed in a feeling of involvement, focus, and enjoyment in the simulation activity. The thinking skills are measured using the Task Analyzer Questionnaire and the collaboration is measured through Group Style Inventory.

Fig. 5. Sample assembled cars.

TABLE V
SUMMARY OF ASSESSMENT MEASURES

Student Skills	Assessment Measure
Analytical Skills	Measured by calculating how students achieved against the given constraints on weights, costs, etc.
Conceptual Knowledge	Measured using a pre and post survey of manufacturing questions.
Metacognitive Skills	Measured using Process Improvement Practice (PIP) Scale
Feelings of Flow	Flow State Scale (FSS)
Thinking Skills	Measured by the Task Analyzer Questionnaire (TAQ).
Collaboration	Group Style Inventory (GSI)

IV. Results and Analysis

A. Analytical Skills

In the simulation, participants were asked to calculate the profit and other measures of the group's success including cost, time, car weight, and price. Not all groups met the target on all requirements. Table VI shows a summary of the results. The "Mean (SD)" column is the average of all participants with the standard deviation in the bracket. The "Minimum" column is the smallest result from the participants. The "Maximum" column is the largest result from the participants. The "Target" column is what the participants were told to try to achieve.

The total production cost is calculated as: cost of parts + simulation time in minutes * $0.25 * 4 workers. The profit is calculated as: total production cost - sales price of the car toys.

The results show that a majority of participant groups were able to effectively utilize analytical skills, given constraints of the problem, and work out their solutions.

TABLE VI
RESULTS OF ANALYTICS SKILLS

Item	Mean (SD)	Minimum	Maximum	Target
Car Weight	25.14 (3.58)g	17.85g	29.90g	Between 20g and 40g
Car Toy Cost	$4.49 (0.67)	$3.12	$5.25	≤ $10
Average Cycle Time	1.66 (0.57) minutes	0.77 minutes	2 minutes	≤ 2 minutes
Total Cost of Parts	$43.09 (47.06)	$6.18	$114.66	-
Total Production Cost	$80.04 (41.70)	$27.99	$129.66	-
Total price	$84.01 (52.27)	$5.29	$155.59	-
Profit	$18.87 (26.96)	$-11.24	$79.94	> $0

B. Conceptual Knowledge

To assess the students' learning, students were asked to answer questions about the simulation before and after they completed the simulation game. This was their conceptual knowledge. The conceptual knowledge questions are shown in Table VII. The participants' scores would be expected to increase after the simulation activity. Here the "test" refers to the simulation. Table VIII shows that the post-test score increased for many participants, with the mean increased by five percentage points. However, a t-test statistical analysis showed that this increase is not statistically significant (p-value is 0.6409 with 95% confidence level). A larger data set may reveal a significant increase in students' scores.

C. Metacognitive Skills

The Process Improvement Practice (PIP) metacognitive scale [24] measures five metacognitive constructs on a seven-point Likert scale. In reference to the PIP, metacognitive experience is described as how the participant relies on previous cognitions when creating strategies to solve the problems at hand. Metacognitive monitoring is described as the use of feedback to re-evaluate and manage the strategies used to address the problem. The means and standard deviations are shown in Table IX. A Cronbach's alpha value of 0.83 demonstrates the reliability of the results. The results show that the students were able to utilize metacognitive skills by participating in the simulation activities.

TABLE VII
CONCEPTUAL KNOWLEDGE QUESTONS

The business model used in the Mass Production paradigms is: a) Sell-Design-Make b) Design-Sell-Make c) **Design-Make-Sell** d) All of the above
Workforce in the Mass Production paradigm is: a) Highly skilled b) Moderately skilled c) **Relatively unskilled** d) None of the above
The manufacturing system used in Mass Production is: a) **Dedicated manufacturing system** b) Flexible manufacturing system c) Advanced manufacturing d) General purpose machines
The production volume in Mass Production (as compared to other manufacturing paradigms) is: a) Low b) **High** c) Medium d) None of the above
Which of the following statements best describe the Mass Production paradigm: a) Options of customized standard products b) Market of one c) **Standard products** d) Personalized products made with advanced technology

TABLE VIII
RESULTS OF CONCEPTUAL KNOWLEDGE

	pre-test score	post-test score
Min	0%	0%
Max	63%	88%
Mean	33% (*SD* = 19%)	38% (*SD* = 24%)

D. Feelings of Flow

Flow is a state of deep cognition that is closely related to metacognitive skills. The Flow State Scale (FSS) [25] is constructed of nine constructs which are rated on a 5-point scale. This scale measures nine aspects associated with feelings of flow in the simulation activity during problem solving. These measures are defined as Autotelic Experience, Transformation of Time, Self-conscious Loss, Sense of Control, Concentration, Feedback, Clear goals, Action, Challenge.

TABLE IX
RESULTS OF PIP SCALE

Constructs	Survey Items	Mean (*SD*)
Goal Orientation	We often define goals for ourselves	5.48 (1.33)
	We set specific goals before we begin a task	5.27 (1.64)
Metacognitive Knowledge	We think of several ways to solve a problem and choose the best one.	5.50 (1.26)
	We try to use strategies that have worked in the past.	5.77 (1.31)
Metacognitive Experience	We know what kind of information is most important to consider when faced with a problem.	5.14 (1.49)
	We consciously focus our attention on important business information.	4.55 (1.60)
Metacognitive Strategy	We ask ourselves if we have considered all the options when solving a problem.	4.91 (1.54)
	We re-evaluate our assumptions when we get confused.	5.73 (1.12)
	We ask ourselves if we have learned as much as we could have when we finished the task.	4.73 (1.75)
Metacognitive Monitoring	We stop and go back over information that is not clear.	5.91 (1.06)
	We find ourselves analyzing the usefulness of a given strategy while engaged in a given task	5.41 (1.37)
	We find ourselves pausing regularly to check our comprehension of the problem or situation at hand.	5.50 (1.82)

It is thought that these feelings indicate that a person is in a problem-solving state. The results are shown in Figure 6. Cronbach's alpha is 0.93, demonstrating the reliability of the results. The results indicate that the students developed a feeling of flow in the simulation activity.

According to the FSS, the feelings of flow can be divided into these nine constructs; the Autotelic subscale measures intrinsic motivation, or the ability for the activity to provide reward within the activity itself. The FSS Challenge subscale measures the balance between the difficult aspects of the activity and the participants' skills. The FSS Feedback subscale measures the ability of the simulation to provide automatic feedback on how well the participant is performing according to the goals of the simulation. The FSS Action subscale measures how automatic the participants actions are in response to the feedback or how immersed the participant feels in terms of automatically knowing what to do next in the simulation. The FSS Loss of Self-conscious subscale measures how the participant feels that he/she needs to represent themselves during the simulation. A loss of self-consciousness indicates that they feel so immersed in the simulation that they forget things such as their shoes are too tight or loose or what others may think about their appearance or performance.

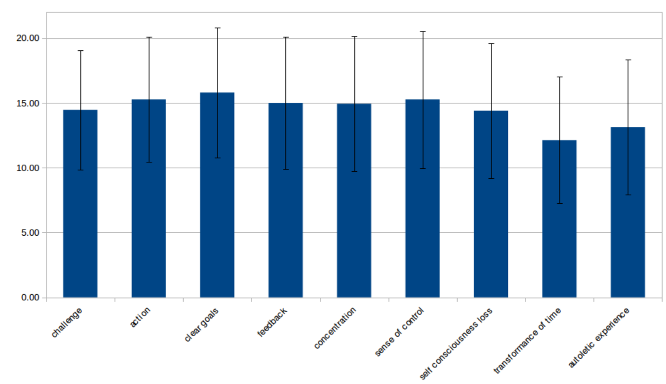

Fig. 6. Results of FSS scale.

E. Thinking Skills

In the 1950s, Benjamin Bloom developed a classification of thinking skills (also known as Bloom's taxonomy) [26]. These skills are remembering and recalling, understanding, applying, analyzing, evaluation, and creating. A study discussed the potential of using Bloom's taxonomy as a labeling tool to support active cognitive processing in collaborative groups [27]. In this research, data was collected from the study participants using the Task Analyzer Questionnaire (TAQ) [28], which asked the participants to self-report their use of the different thinking skills. The data collected showed that the students were utilizing all the skills (Figure 7) during the collaborative problem-solving activity. Students were asked to answer the following question: what kind(s) of thinking (remembering, understanding, applying, evaluating, creating) did you use in solving this problem? The results in Figure 7 represent the frequency of each skills mentioned by the students.

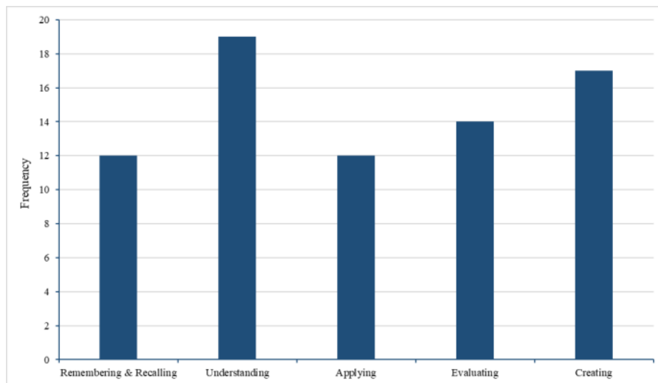

Fig. 7. Results of thinking skills.

F. Group Effectiveness

To assess the collaboration in students, the Group Style Inventory (GSI) survey was used to measure group effectiveness. Group effectiveness is defined as "the group's productivity in relation to the needs of the organization" [29]. Effectiveness in this context is measured in terms of the group' synergy, performance objectives, skills, use of resources, and innovation [30]. In this research, these variables are measured using a questionnaire designed to combine the measurements of internal dynamics and external group outputs that facilitate the group's self-assessment. GSI is a research-based tool that provides a valid and reliable measure of how people in groups interact with each other and work as a group to solve problems [31]. The GSI Circumplex shows three types of group styles: constructive, passive/defensive, and aggressive/defensive. Effective groups should have higher score – ideally exceeding the bolded middle ring – in constructive style (blue) and lower scores in both passive/defensive (green) and aggressive/defensive styles (red). For this survey, two groups of students were asked to conduct the simulation activity both individually and in groups. When the activity was done individually, students were not allowed to discuss and collaborate with each other. When the activity was done in group, students were actively encouraged to collaborate to complete their tasks together by discussing the tasks. Figure 8

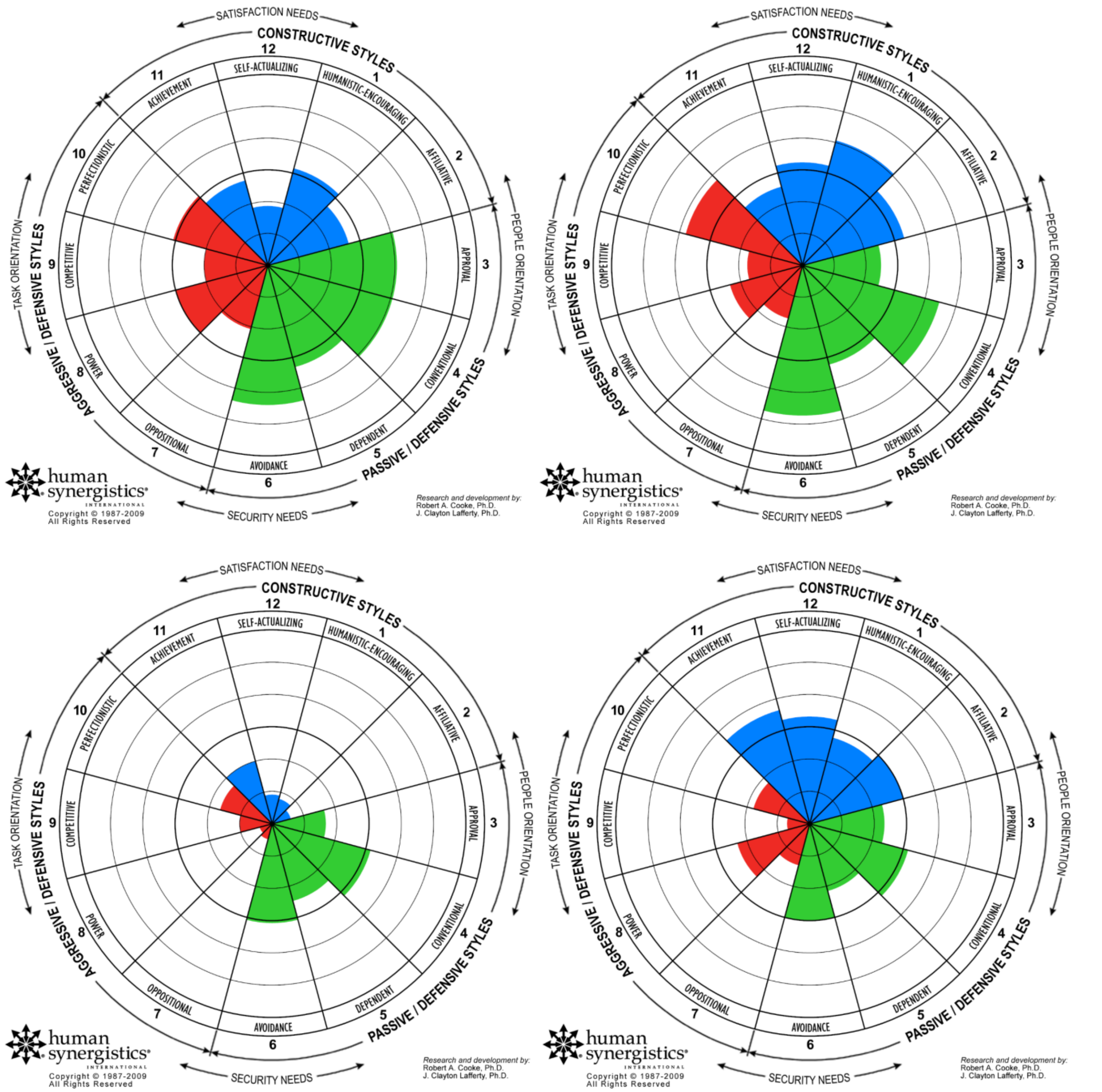

Fig. 8. GSI for individual (top row) and group (bottom row) activities for two groups. Participants of group 1 are shown on the left column. Participants of group 2 are shown on the right column.

shows the GSI results for the two groups, measured after completing the simulation activities. The results show that the group effectiveness scores in almost all the measures were improved when students worked on the simulation activities in groups.

V. Discussion and Recommendations

The results provided by the analytical skills assessment, PIP, FSS, TAQ helped to answer the research question on student engagement. The analytical skills results show that based on the target given to the participants, most groups were able to satisfy the targeted requirements, implying that they were effectively engaging the tasks with analytical skills. The results of the PIP metacognitive skills show consistently high values in the 12 survey items. A high Cronbach's alpha value implies internal consistency of the results. These together with similar results from FSS demonstrate that participants were effectively using metacognition in their collaborative problem solving. Finally, student engaged in different thinking skills when completing the tasks. “Understanding” was used the most while “Remembering and Recalling” and “Applying” were used the least.

The research question on group effectiveness is answered by the GSI results. Active collaboration in problem solving provided a positive effect on almost all the GSI measures. These results provide evidence for educators to actively encourage their students to collaborate in a group-based problem-solving tasks.

VI. Conclusion

This research discussed the use of simulation games to study collaborative problem solving in design and manufacturing. The proposed simulations presented in this study were used to assess collaborative problem solving in engineering students. Based on the analysis of the conceptual knowledge of the students who participated in the study, the students' scores increased as a result of participating in the simulation. The study examined the skills engineering students engage in when problem solving. Participants also felt that they were experiencing a flow state that is associated with problem solving as measured by the Flow State Scale. The results showed improved learning outcomes in terms of increased knowledge, increased feelings of metacognition and problem solving. The simulation activities can be a useful tool for teaching manufacturing problem solving. Through the measurements of GSI group effectiveness scores, the results showed that the scores for the students improved when the students actively collaborated on working to solve the problems.

Future work of this research will focus on conducting further activities and collecting more data to answer other research questions such as: does any of the process-level scales predict success on the activity (analytical skills)? Collecting more data will allow for developing regression models to answer this question. Future research can also focus on developing new simulation games for the other manufacturing paradigms, i.e., lean manufacturing, mass customization, and personalized production. Virtual reality simulation games will also be developed for the manufacturing paradigms and the results of both physical simulations and virtual reality simulations will be compared. Since the measures used in this research were independent of the activities, the study can also be expanded to other contexts that require collaboration of a group of problem solvers.

Acknowledgment

Any opinions, findings, or conclusions found in this article are those of the authors and do not necessarily reflect the views of the sponsor. The authors would like to thank the anonymous reviewers for their valuable comments.

References

[1] K. Duncker, and L. S. Lees, "On problem-solving," *Psychological Monographs*, vol. 58, no. 5, 1945.

[2] C.J. Chang, M.H. Chang, C.C. Liu, B.C. Chiu, S.H. Fan Chiang, C.T. Wen, F.K. Hwang, Y.L. Chao, C.S. Chai, "An analysis of collaborative problem-solving activities mediated by individual-based and collaborative computer simulations," *Journal of Computer Assisted Learning*, vol. 33, no. 6, pp. 649–662, 2017.

[3] S. Sengul, and Y. Katranci, "Meta-cognitive aspects of solving indefinite integral problems," *Procedia-Social and Behavioral Sciences*, vol. 197, pp. 622-629, 2015.

[4] F. J. García Peñalvo, "Entrepreneurial and problem-solving skills in software engineers," *Journal of Information Technology Research*, vol. 8, no. 3, pp. 1-4, 2015.

[5] Deloitte and The Manufacturing Institute, "The skills gap in U.S. manufacturing: 2015 and beyond," 2015.

[6] K. Levesque, J. Laird, E. Hensley, S. P. Choy, E. F. Cataldi, and L. Hudson, "Career and technical education in the United States: 1990 to 2005," Statistical Analysis Report, National Center for Education Statistics, 2008.

[7] P. Griffin, B. McGaw, and E. Care, "Assessment and teaching of 21st century skills: Methods and Approach," New York, NY: Springer, 2012.

[8] G. Chung, T. Harmon, and E. Baker, "The impact of a simulation-based learning design project on student learning," *IEEE Transactions on Education*, vol. 44, no. 4, pp. 390–398, 2001. doi: 10.1109/13.965789

[9] A. A. Deshpande, and S. H. Huang, "Simulation games in engineering education: A state-of-the-art review," *Computer Applications in Engineering Education*, vol. 19, no. 3, pp. 399–410, 2009. doi: 10.1002/cae.20323

[10] D. Johnson, and R. Singh, "Utilizing Simtronics, a chemical engineering process simulation software, in chemical engineering coursework to reduce the skills gap," *Computer Applications in Engineering Education*, vol. 27, no. 2, pp. 519–525, 2018. doi: 10.1002/cae.22079

[11] J. M. Randel, B. A. Morris, C. D. Wetzel, and B. T. Whitehill, "The effectiveness of games for educational purposes: A review of recent research," *Simulation Gaming*, vol. 23, pp. 261-276, 1992.

[12] C. A. Bodnar, D. Anastasio, J. A. Enszer, and D. D. Burkey, "Engineers at Play: Games as Teaching Tools for Undergraduate Engineering Students," *Journal of Engineering Education*, vol. 105, no. 1, pp. 147–200, 2015. doi: 10.1002/jee.20106

[13] S.H. Ammar, and R.H. Wright, "Introduction to operations management: The MBA in-class experience," *Decision Lines*, vol. 29, no. 5, pp. 3-6, 1998.

[14] S.M. Kresta, "Hands-on demonstrations: An alternative to full scale lab experiments," Journal of Engineering Education, 87(1), pp.7-9. 1998.

[15] A. Kumar, and A.W. Labib, "Applying quality function deployment for the design of a next-generation manufacturing simulation game," *International Journal of Engineering Education*, vol. 20, no. 5, pp. 787-800, 2004.

[16] T.W. Simpson, "Experiences with a hands-on activity to contrast craft production and mass production in the classroom," *International Journal of Engineering Education*, vol. 19, no. 2, pp. 297-304, 2003.

[17] E. Ozelkan, and A. Galambosi, "Lampshade game for lean manufacturing," *Production Planning and Control*, vol. 20, no. 5, pp. 385-402, 2009.

[18] F. Aqlan, and E.G. Walters, "Teaching lean principles through simulations and games," in *American Society for Engineering education (ASEE) Annual Conference and Exposition*, Columbus, OH, 2017.

[19] F. Badurdeen, P. Marksberry, A. Hall, and B. Gregorry, "Teaching Lean manufacturing with simulations and games: A survey and future directions," *Simulations and Gaming*, vol. 41, no. 4, pp. 465-486, 2010.

[20] J.B. Hauge, and J.C. Riedel, "Evaluation of simulation games for teaching engineering and manufacturing." *Procedia Computer Science*, vol. 15, pp. 210-220, 2012.

[21] N. Ordaz, D. Romero, D. Gorecky, and H.R. Siller, "Serious games and virtual simulator for automotive manufacturing education and training," *Procedia Computer Science*, vol. 75, pp. 267-274, 2015,

[22] B. J. Blöchl, and M. Schneider, "Simulation game for intelligent production logistics – The PuLL® Learning Factory," *Procedia CIRP*, vol. 54, pp. 130 – 135, 2016.

[23] L.J. de Vin, L. Jacobsson, and J. Odhe, "Game-based lean production training of university students and industrial employees," *Procedia Manufacturing*, vol. 25, pp. 578-585, 2018.

[24] Y. S. Cho, and K. Linderman, "Metacognition-based process improvement practices," *International Journal of Production Economics*, vol. 211, pp. 132-144, 2019.

[25] S. A. Jackson, and H. W. Marsh, "Development and validation of a scale to measure optimal experience: The Flow State Scale," *Journal of Sport and Exercise Psychology*, vol. 18, no. 1, pp. 17-35, 1996.

[26] N. E. Adams, "Bloom's taxonomy of cognitive learning objectives," *Journal of the Medical Library Association: JMLA*, vol. 103, no. 3, p.152, 2015.

[27] M. Valcke, B. De Wever, C. Zhu, and C. Deed, "Supporting active cognitive processing in collaborative groups: The potential of Bloom's taxonomy as a labeling tool," *The Internet and Higher Education*, vol. 12, no. 3-4, pp.165-172, 2009.
[28] O. Lawanto, A. L. Minichiello, J. Uziak, and A. Febrian, "Task Affect and Task Understanding in Engineering Problem Solving," *Journal of Technology Education*, vol. 30, no. 2, p. 21, 2019.
[29] B. Bateman, C. Wilson, and D. Bingham, "Team effectiveness development of an audit questionnaire," *Journal of Management Development*, vol. 21, no 3, pp. 215-226, 2002.
[30] A. Ounnas, D.E. Millard, and H.C. Davis, "A metrics framework for evaluating group formation," in *Proceedings of the 2007 international ACM Conference on Supporting Group Work*, Sanibel Island, FL, pp. 221-224, 2007.
[31] R.A. Cooke, and J.L. Szumal, "The impact of group interaction styles on problem-solving effectiveness," *The Journal of Applied Behavioral Science*, vol. 30, no. 4, pp.415-437, 1994.

Faisal Aqlan received his Ph.D. in industrial and systems engineering from the State University of New York at Binghamton, New York, USA, in 2013.

Dr. Aqlan is currently an associate professor of industrial engineering at Penn State Erie, The Behrend College. Prior to joining the faculty at Behrend in 2014, Dr. Aqlan was a faculty member at the University of New Haven where he taught undergraduate and graduate courses in system engineering and operations management. He has industry experience with IBM Corporation and Innovation Associates Company. His research interests include sensor-based virtual reality for manufacturing and healthcare applications, manufacturing education, and cyberlearning. He is a senior member of the Institute of Industrial and Systems Engineers (IISE) and has served as president of IISE Logistics and Supply Chain Division, co-founder of IISE Modeling and Simulation Division, director of IISE Young Professionals Group, founder and faculty advisor of IISE Behrend Chapter, faculty chair of IISE Northeast Conference, and track chair in IISE Annual Conference. He currently serves as IISE Vice President of Student Development and holds a seat on IISE Board of Trustees.

Richard Zhao received his Ph.D. in computing science from the University of Alberta, Edmonton, AB, Canada, in 2015.

From 2016 to 2020, he was an assistant professor of computer science and software engineering at Penn State Behrend where he led the game development program. Since 2020, he is an assistant professor in the Department of Computer Science at the University of Calgary. He leads the serious games research group, focusing on games for training and education where he utilizes artificial intelligence, virtual reality and eye-tracking technologies for this purpose.

Dr. Zhao has served as a program committee member on academic conferences such as the International Conference on the Foundations of Digital Games (FDG), the AAAI Conference on Artificial Intelligence and Interactive Digital Entertainment (AIIDE) and the ACM Special Interest Group on Computer Science Education (SIGCSE) Technical Symposium.