IEEE TRANSACTIONS ON EDUCATION

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

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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

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 the National Science Foundation under Award 1830741 and Supplement 1905680. (Faisal Aqlan and Richard Zhao contributed equally to this work.) (Corresponding author: Faisal Aqlan.)

This work involved human subjects or animals in its research. Approval of all ethical and experimental procedures and protocols was granted by IRP.

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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 nontechnical skills that are usually not part of the curricula. These nontechnical 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 and 2) students utilize different skills and improve their group

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effectiveness skills when they work on solving problems collaboratively.

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]-[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 [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

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	Enterprise	Lego Aircraft	
Simulation			
Lean Product Development	Product	K'nex Product	
Simulation	Development		
5S Mini-Factory Simulation	Manufacturing	Tabletop Mini Factories	
Furniture Factory Simulation	Manufacturing	Wooden Furniture	
Ship Repair Design Process	Design	Container Ship	
Simulation	Process		
Value Stream Mapping	Manufacturing	Board Game	
Board Game			
Lean Lego Simulation	Manufacturing	Lego Cars	

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.

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: 1) lack of stress on soft or professional skills; 2) a mistaken focus on "linear lean," 3) misunderstanding of the key role of the facilitator; and 4) 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 [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. de Vin et al. [23] 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 a 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





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

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 handson simulation activities to design and produce car toys according to specific customer requirements. Fig. 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 sections 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 Fig. 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 four tasks (design, sourcing, assembly, and test) and students worked in groups where each task was performed by a student.

TABLE II CHARACTERISTICS 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
Secretary.	2x10	2.8	\$0.25	64
6	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
80	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
(6)	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

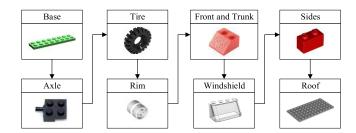


Fig. 2. Main steps for the car toy assembly process.

TABLE III SAMPLE CUSTOMER REQUIREMENTS

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

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 min 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.

The simulation also involved a customer and a supplier (see Fig. 3). The descriptions of the six jobs were as follows: 1) the



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

customer who will buy the car; 2) the design engineer; 3) 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: 1) design; 2) sourcing; 3) manufacturing; and 4) inspection.

- 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.
- 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.
- Manufacturing: Identify and design the manufacturing processes for producing the product based the design. Assemble the car toy from the parts provided by sourcing.
- 4) 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.

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) *Nontechnical 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; and 8) *Production Parameters:* High quantity versus low variety.

The simulation game in this study was designed so that students worked in groups on the assembly of car toys according to prespecified customer requirements. Every group of

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.

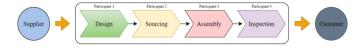


Fig. 4. Layout of the mass production simulation activity.





Fig. 5. Sample assembled cars.

maximum four had to assemble toy cars together. Table IV includes some key concepts considered in the manufacturing games.

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 2 h. Participants must collaborate in order to complete the tasks since each person was responsible for a portion of the total task (Fig. 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. Fig. 5 shows the 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

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	Measured using a pre and post survey of
Knowledge	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)

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	1.66 (0.57)	0.77	2 minutes	≤ 2 minutes
Cycle Time	minutes	minutes		
Total Cost of	\$43.09	\$6.18	\$114.66	=
Parts	(47.06)			
Total	\$80.04	\$27.99	\$129.66	-
Production	(41.70)			
Cost				
Total price	\$84.01	\$5.29	\$155.59	-
	(52.27)			
Profit	\$18.87	\$-11.24	\$79.94	> \$0
	(26.96)			

skills are measured using the task analyzer questionnaire (TAQ) and the collaboration is measured through 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.

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

TABLE VII
CONCEPTUAL KNOWLEDGE QUESTIONS

The busine	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 manuf	facturing system used in Mass Production is:				
a)	Dedicated manufacturing system				
b)	Flexible manufacturing system				
c)	Advanced manufacturing				
d)	General purpose machines				
The produ	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				

TABLE VIII
RESULTS OF CONCEPTUAL KNOWLEDGE

Personalized products made with advanced technology

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

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 5% 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.

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

TABLE IX RESULTS OF PIP SCALE

Constructs	Survey Items	Mean (SD)
Goal	We often define goals for ourselves	5.48 (1.33)
Orientation	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)
	We ask ourselves if we have considered all the options when solving a problem.	4.91 (1.54)
Metacognitive	We re-evaluate our assumptions when we get confused.	5.73 (1.12)
Strategy	We ask ourselves if we have learned as much as we could have when we finished the task.	4.73 (1.75)
	We stop and go back over information that is not clear.	5.91 (1.06)
Metacognitive	We find ourselves analyzing the usefulness of a given strategy while engaged in a given task	5.41 (1.37)
Monitoring	We find ourselves pausing regularly to check our comprehension of the problem or situation at hand.	5.50 (1.82)

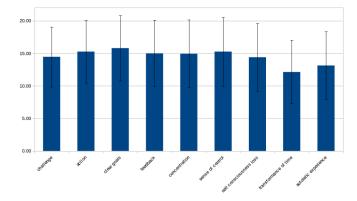


Fig. 6. Results of FSS scale.

constructed of 9 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, and challenge.

It is thought that these feelings indicate that a person is in a problem-solving state. The results are shown in Fig. 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

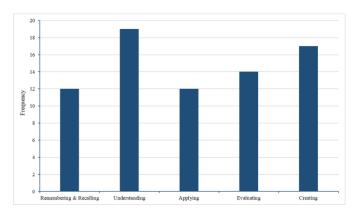


Fig. 7. Results of thinking skills.

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.

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 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 (Fig. 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 Fig. 7 represent the frequency of each skills mentioned by the students.

F. Group Effectiveness

To assess the collaboration in students, the 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: 1) constructive; 2) passive/defensive;

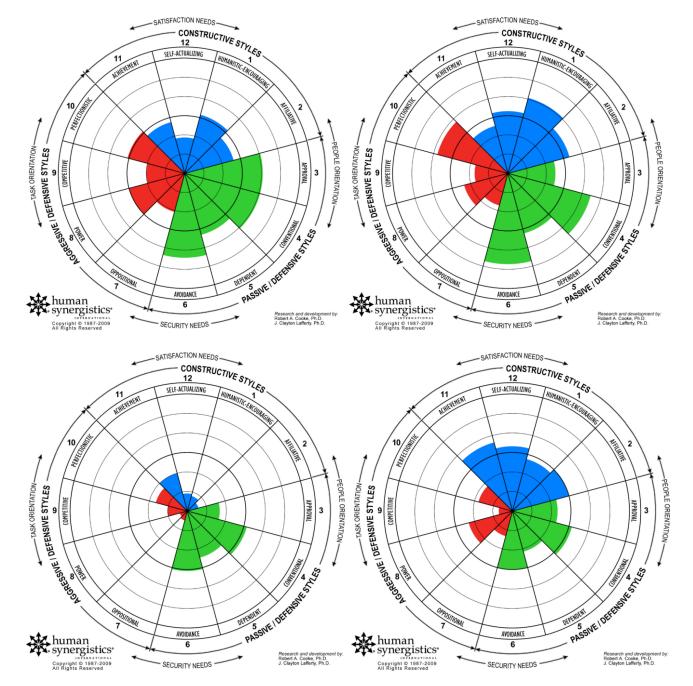


Fig. 8. GSI for individual (top row) and group (bottom row) activities for two groups. Participants of group 1 are shown on the left column. Participants of group 2 are shown on the right column.

and 3) 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. Fig. 8 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 CPS. 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 CPS in design and manufacturing. The proposed simulations presented in this study were used to assess CPS 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 FSS. 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

- K. Duncker and L. S. Lees, "On problem-solving," in *Psychological Monographs*, vol. 58. Washington, DC, USA: Amer. Psychol. Assoc., 1945
- [2] C.-J. Chang et al., "An analysis of collaborative problem-solving activities mediated by individual-based and collaborative computer simulations," J. Comput. Assist. Learn., vol. 33, no. 6, pp. 649–662, 2017.
- [3] S. Sengul and Y. Katranci, "Meta-cognitive aspects of solving indefinite integral problems," *Procedia Soc. Behav. Sci.*, vol. 197, pp. 622–629, Jul. 2015.
- [4] F. J. G. Peñalvo, "Entrepreneurial and problem-solving skills in software engineers," J. Inf. Technol. Res., vol. 8, no. 3, pp. 1–4, 2015.
- [5] The Skills Gap in U.S. Manufacturing: 2015 and Beyond, Deloitte Manuf. Inst., New York, NY, USA, 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," Nat. Center Educ. Stat., Washington, DC, USA, Statistical Analysis Rep. NCES 2008-035, 2008.
- [7] P. Griffin and E. Care, Eds., Assessment and Teaching of 21st Century Skills: Methods and Approach. Dordrecht, The Netherlands: Springer, 2015.
- [8] G. K. W. K. Chung, T. C. Harmon, and E. L. Baker, "The impact of a simulation-based learning design project on student learning," *IEEE Trans. Educ.*, vol. 44, no. 4, pp. 390–398, Nov. 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," *Comput. Appl. Eng. Educ.*, 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," *Comput. Appl. Eng. Educ.*, 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. V. Whitehill, "The effectiveness of games for educational purposes: A review of recent research," *Simulat. Gaming*, vol. 23, pp. 261–276, Sep. 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," *J. Eng. Educ.*, 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," *Decis. Lines*, vol. 29, no. 5, pp. 3–6, 1998.
- [14] S. M. Kresta, "Hands-on demonstrations: An alternative to full scale lab experiments," *J. Eng. Educ.*, vol. 87, no. 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," *Int. J. Eng. Educ.*, 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," *Int. J. Eng. Educ.*, vol. 19, no. 2, pp. 297–304, 2003.
- [17] E. Ozelkan and A. Galambosi, "Lampshade game for lean manufacturing," Prod. Plan. Control, vol. 20, no. 5, pp. 385–402, 2009.
- [18] F. Aqlan and E. G. Walters, "Teaching lean principles through simulations and games," in *Proc. Amer. Society Eng. Educ. (ASEE) Annu. Conf. Exposit.*, Columbus, OH, USA, 2017, pp. 1–13.
- [19] F. Badurdeen, P. Marksberry, A. Hall, and B. Gregorry, "Teaching Lean manufacturing with simulations and games: A survey and future directions," *Simulat. Gaming*, vol. 41, no. 4, pp. 465–486, 2010.
- [20] J. B. Hauge and J. C. K. H. Riedel, "Evaluation of simulation games for teaching engineering and manufacturing," *Procedia Comput. Sci.*, vol. 15, pp. 210–220, Jan. 2012.
- [21] N. Ordaz, D. Romero, D. Gorecky, and H. R. Siller, "Serious games and virtual simulator for automotive manufacturing education and training," *Procedia Comput. Sci.*, vol. 75, pp. 267–274, Jan. 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, Jan. 2016.
- [23] L. J. de Vin, L. Jacobsson, and J. Odhe, "Game-based lean production training of university students and industrial employees," *Procedia Manuf.*, vol. 25, pp. 578–585, Jan. 2018.
- [24] Y. S. Cho and K. Linderman, "Metacognition-based process improvement practices," *Int. J. Prod. Econ.*, vol. 211, pp. 132–144, May 2019.
- [25] S. A. Jackson and H. W. Marsh, "Development and validation of a scale to measure optimal experience: The flow state scale," *J. Sport Exercise*. *Psychol.*, vol. 18, no. 1, pp. 17–35, 1996.

- [26] N. E. Adams, "Bloom's taxonomy of cognitive learning objectives," J. Med. Libr. Assoc., vol. 103, no. 3, pp. 152–153, 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," *Internet Higher Educ.*, vol. 12, nos. 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," *J. Technol. Educ.*, vol. 30, no. 2, pp. 21–38, 2019.
- [29] B. Bateman, C. Wilson, and D. Bingham, "Team effectiveness development of an audit questionnaire," J. Manage. Develop., 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 *Proc. Int. ACM Conf. Support. Group Work*, Sanibel Island, FL, USA, 2007, pp. 221–224.
- [31] R. A. Cooke and J. L. Szumal, "The impact of group interaction styles on problem-solving effectiveness," *J. Appl. Behav. Sci.*, vol. 30, no. 4, pp. 415–437, 1994.

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