Gamification for Teaching Sustainability to Engineering Students

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***Abstract*— This innovative practice full paper describes sustainability teaching through game-based activities in engineering classrooms for potentially enhancing student interest in Science, Technology, Engineering and Mathematics (STEM) fields. Meta-analytic research indeed supports that gamification enhances student learning by increasing engagement and motivation, promoting goal setting behaviors and supporting the need for recognition. While there is a high scope for utilizing game-based tools to help students connect with global sustainability challenges, literature reflects a scarcity of such innovative pedagogical tools in engineering education. To tackle this challenge, we introduced interactive game-based modules to teach sustainability within two different education cultural contexts – one in the U.S. as a part of a Honours course at a large public university, and one in India, as a part of the first year engineering curriculum at a small private university.**

To broaden the outlook of engineering students towards sustainability, our game-based activity learning outcomes for students were to: 1) contextualize sustainability and its importance in contemporary global issues 2) recognize how Sustainable Development Goals (SDGs) could be interrelated, 3) explain how change in entropy and our actions can affect sustainability. To facilitate these broad learning outcomes, we developed two interactive gamified activities and implemented them online (due to COVID-based shift to instruction) in two different engineering institutions. This innovation article reports the design of two gamified activities used to teach sustainability, and studies its impact on student learning outcomes through SDT framework of motivation and thematic analysis of student reflections. We used surveys and minute paper to record student perceptions which were analyzed thematically. Results indicated that students enjoyed these games, saw value in peer learning, and simultaneously developed a deeper, more contextual understanding of sustainability by perceiving the interconnections between SDGs and ways in which entropy through their everyday actions influence sustainability.

Keywords—gamification, game-based learning, sustainability, SDGs, engineering education

I. INTRODUCTION

Global institutions like the United Nations have long voiced the critical role engineers play in solving the world's sustainability challenges. This requires universities to re-define the connotation attached to "becoming an engineer". One opportunity to do so is by introducing sustainability education in engineering early on where students realise their individual roles as engineers in preserving life on our planet and are empowered to actively solve associated socio-technical challenges [1]. Traditionally, engineering universities have integrated sustainability in their curriculum by introducing new courses/lecture series on sustainability, including sustainability topics in existing courses or adding an optional specialisation in sustainable development. However, these approaches have been criticised for integrating sustainability in a non-holistic, piecemeal fashion [2] and creating only a surface level understanding of sustainability in students [3].

To help solve grand challenges of our society as engineers, it is important to develop a deeper understanding of what constitutes the sustainable world. For this, we need new evidence-based pedagogical tools to teach sustainability in engineering classrooms. Research shows successful use of experiential learning activities to effectively teach sustainability concepts e.g., from Model United Nations, at several universities [4]. Active, constructive and community-oriented learning strategies can thus lead to better cognitive learning outcomes in students [5]. These strategies focus on both the comprehension and the retention aspect of learning as opposed to traditional learning which mostly focuses on the comprehension part of student learning [6]. Despite benefits to deep learning, the application of active learning in teaching sustainability to engineering students is limited by several barriers. These include rigid curriculum/course structures with limited space to intervene, difficulty in developing teaching tools for sustainability due to abstract, complex, and value-laden nature of the concept, sparse empirical evidence on effective integration tools for teaching sustainability, and insufficient resources for implementation [7] – [9]. This brings us to the question: **How do we apply active learning strategies to effectively teach sustainability to engineering students?**

One popularly known learning strategy to integrate sustainability in a flexible manner in education is gamification. There is growing evidence on how game-based learning tools can help expand engineering student perspectives on complex concepts like sustainability through critical reflection facilitated by interpersonal communication [10]. Empirically tested tools include board games, roleplays, and virtual/online games that have been applied in niche fields like manufacturing, construction, agriculture, and water to cover a few of the known sustainability challenges [11] – [14]. Meta-analytic research also supports that gamification leads to improved learning outcomes in students in an enjoyable manner by increasing students' engagement and motivation, promoting goal setting behaviours in them and supporting their need for recognition [15]. While there is a high scope for utilising game-based tools to help engineering students connect with global sustainability challenges, literature

reflects a scarcity of such innovative pedagogical tools applied in engineering education.

This paper discusses the development and implementation of two specific games used to teach sustainability in engineering courses at two different universities in the world. Both games were designed with following intent: 1) students' awareness of sustainability issues in the world should be enhanced, 2) complex STEM concepts like entropy should be also unfolded through the lens of sustainability; 3) student learning should include recognition of the impact of their everyday actions on sustainability.

In the first instance, we fostered interactive learning via the "SDGs-Newspaper Mapping" game where students worked in teams to match various given pre-selected newspaper-headlines with suitable SDG(s). The objective was to identify correct SDGs and explain how they are relevant to topics covered in recent newspaper headlines. This game was implemented at Plaksha university in India, in a course named "Innovation Lab and Grand Challenges Studio" taught to 90 freshmen engineering students. In the second instance, we developed a strategy board game "Halma" through which students explored the concept of entropy, its relation to sustainability and how their actions can influence sustainable practices in the real world using the context of entropy. The Halma game was taught to 17 students at University of California, Davis in the US, as a part of an unique Honors course jointly taught by Arts and Engineering faculty.

Through this study, we demonstrate how interactive pedagogy such as gamification can enhance student interest in understanding sustainability. We contribute to the gamification in engineering education literature by disseminating two new gamified tools (templates provided in appendix for use) that can help universities, faculty, and researchers utilise and evaluate novel ways of integrating sustainability in their engineering courses. In turn, we hope that the socio-emotional learning experiences provided by our activities can specifically help recruit and retain women and the underrepresented groups by broadening their outlook towards engineering as a socio-technical field.

II. Example 1 – SDGs Newspaper Mapping Game

SDGs Newspaper Mapping game was played with first-year engineering students as a part of a project-based course named Innovation Lab and Grand Challenges Studio (ILGC) at Plaksha university in India. In this section, we elaborate on the motivation for introducing the game in the course and describe the course and associated game in detail. In the end, we discuss assessments used to measure student learning outcomes and analyse its findings.

A. Course Introduction and Motivation

ILGC is a new 2 credit course designed to take engineering students through the process of breaking down complex Engineering grand challenges and Sustainable Development Goals (SDGs), turning ideas into actionable solutions and carving solutions with an entrepreneurial mindset. The course is integrated across the 4 years (8 semesters) of undergraduate engineering curriculum at this university. The first semester ILGC is composed of two projects. The first project (Week 1 – 7) introduces students to problem framing of an existing daily-use object using a whole system mapping, prioritizing an intervention objective and scope using life cycle analysis, brainstorming for solutions using biomimicry, and finally using metrics to evaluate ideas and choose winning idea for sustainable redesign/ innovation. The second project (Week 8 – 13) gave students an opportunity to implement sustainability design skills and mindsets that they learned in first half of the semester to a local problem of their choice. Projects were implemented in 21 interdisciplinary teams of about 3-4 students each. Course assessment involved project-work done in team (60% of course grade), as well as individual reflection (30%) and class participation (10%).

B. Inspiration for Gamifying Activity

Since the course involved addressing sustainability challenges and engineering students taking this course were fresh high school graduates new to the concept of sustainability, we introduced the SDG-Newspaper game early on in the course (Week 2). The game was used as a means for students to explore prevalent sustainability issues and associated SDGs in India and realize how these are affected by their everyday actions. It was designed to seed the notion that SDGs could be achieved by engineers too, and not just by policymakers, government officers alone. We further to inculcate a healthy discussion around the deeper meanings and consequences of SDGs on their lives. The game was designed in a manner such that the game flow supports scenarios where each situation involves multiple solutions (e.g. multi choice multi correct answers) and where the primary objective is collaborative discussion within a team on the chosen question or theme. Numerous games with this game mechanic were studied and the board game Taboo was chosen to be our prime source of inspiration. Through team discussions during the game and debrief afterwards, we aimed for students to analyse multiple perspectives attached to different SDGs to better unpack the complexity of sustainability concept.

C. Learning Outcomes

In the first week of ILGC course, students were introduced to the concept of sustainable design after which they learnt about various SDGs through a group of short interactive lectures, videos and a quiz testing their knowledge on SDGs. We introduced SDGs Newspaper headlines matching game in the 2nd week of the 15-week semester. ILGC class length is 50 mins of lecture followed by 2 hours of lab / activities. The game was positioned after the 1st hour of lecture on sustainability and timed for 40 minutes after explaining the rules for 10 minutes (total game activity time = 50 minutes). Debrief and discussion following game was 50 minutes.

At the end of this game, students will be able to:

- Describe interpretation of each SDG in their own words
- Describe the interrelationship between various SDGs
- Realize how SDGs are connected to global, real-world issues
- Realize how sustainability could be achieved through engineering domains

Through these learning outcomes, we hoped that the students go beyond the surface level meaning of SDGs and gain a deep understanding of them by analysing ways in which SDGs are interrelated and linked to their surroundings and real-world issues. Students learn how to work and communicate in teams and ways to strategize and articulate their findings in order to get the best outcome in game. They

appreciate ways in which different teammates perceive SDGs and ways in which they can create an impact.

D. Game Description

Students were required to map 12 recent news articles to relevant SDG(s). These articles were randomly selected from various newspapers, from various sections such as current world affairs, geopolitics, sports, and cinema. The articles were filtered to ensure that age-inappropriate content or content leading to tangential discussions were dropped. The final game contained 12 news articles where each team of 3 students were expected to map any 8 articles with one or more associated SDGs. The 12 questions were provided via a single google form per team with each question defined as the headline of each news article (link to the full article was hyperlinked in each question). Each question/headline was provided with a drop-down list of all SDGs to choose from. Each correct mapping carried 1 point while each incorrect mapping resulted in loss of 0.25 points. Scores were allocated for every team's final answers and not for individual answers. Every team member could select only one of the many associated SDGs and were expected to discuss and collaborate with the team to strategize to score better. They were also informed in advance that they would be asked to explain their rationale for certain answers post the game session. Total 21 teams (maximum of 3 students each) participated in the game.

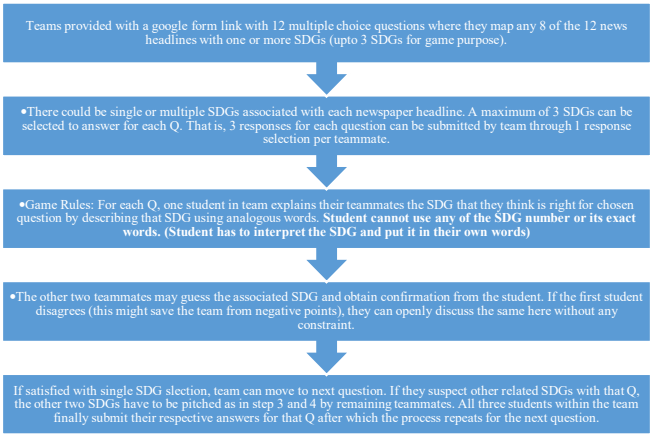

Fig. 1. Flow of the SDGs Newspaper Game

The game scores were shared with students in the third week of the ILGC class.

E. SDT-based Analysis of Game Elements

Self-determination theory (SDT) shows that motivation in learning can be enhanced by meeting three innate psychological needs of competence, relatedness, and autonomy [16]. We tried to design our game to meet each of the three needs of SDT. For example, autonomy need was met by allowing each student within the team to select the SDG of their choice after discussion with the team and by allowing teams to answer any 8 out of 12. The relatedness factor in SDT was addressed in three ways by connecting sustainability to everyday actions and happenings (content relatedness); peer relatedness was addressed through teaming up to discuss SDGs choices; and the instructor to student relatedness was met by offering a prelude to game discussing the intent of the game, facilitating healthy discussing during the game, and then debriefing the game outcome and discussing incurred challenges. Competence was incorporated by allowing application of knowledge about learned SDGs. The table below shows how different elements of the game incorporate the three SDT needs for enhancing player motivation for work towards meeting SDGs.

TABLE I. GAME ELEMENTS CLASSIFIED BY DIFFERENT SDT NEEDS

SDT Need	Game Elements
Autonomy	• Flexible scoring scheme where teams have the freedom to choose any number of solutions (up to 3 max.) • Any 8 of the 12 questions can be answered. • Players work in a separate team setup with where they independently explore ways of finding and discussing correct SDGs for each news headline within their team.
Relatedness	• Players are provided news headlines from their surrounding communities so that they can see the relevance of SDGs in their local context. This also allows them to see the impact of their everyday actions on these SDGs (content relatedness) • Teaming up to discuss choices of SDGs (peer relatedness) • Instructors discussing the intent of the game, facilitating the game, debriefing the game outcome, and discussing the challenges incurred with students (instructor connectedness)
Competence	• Provided scoring scheme for winning the game • Need for communication and team skills for team discussions and gaining consensus in order to proceed the game effectively as a team

F. Assessment Method

To assess whether the game influenced student attitudes towards sustainability, students were asked to fill a Qualtrics survey before and after they played the game. The survey required students to rate their level of agreement to 13 statements that gauged their attitudes towards different SDGs on a 6-point Likert scale (6 = Strong Agree; 1 = Strongly Disagree). These statements were taken from the attitudes subsection (α = 0.933) of a published survey instrument measuring the awareness level towards SDGs in university students by finding significant relationships between student knowledge, attitudes, and practices towards SDGs [17].

Additionally, to record student reflections post the game, we asked students:

- After thoughts on the activity: What effect did this activity have on you?
- What do you think was the expected outcome of this activity?
- Do you have suggestions to improvise this activity?

G. Results and Discussion

a) Quantitative Analysis: Due to COVID-19 pandemic forcing the instruction to be online, the game was played in Zoom breakout rooms. Total 62 first-year engineering students (20 females, 42 males) participated in the game. The maximum score a student can get on the sustainability attitudes survey is 78. The mean and standard deviation

scores of students who took the survey pre and post the game are given in table II.

TABLE II. DESCRIPTIVE STATISTICS BEFORE AND AFTER SDT-NEWSPAPER MAPPING GAME

SDG Newspaper Mapping Game	Mean	SD
Before Game	62.60	4.901
After Game	63.15	4.486

A paired-samples t-test was conducted to compare means for student attitudes towards SDGs before and after playing the SDG-Newspaper Mapping game. No significant difference was found between pre-game (M=62.60, SD=4.901) and post-game means (M=63.15, SD=4.486) for student attitudes towards SDGs; $t(61) = 1.3338$; $p = 0.187$. We speculate four potential reasons for this finding:

- Student attitudes towards SDGs were already found to be positive in the pregame survey perhaps because students were already aware about sustainability and were also exposed to content related to sustainability through lectures in week 1 and 2, which could have piqued their awareness and interest in sustainability before playing the game
- Another reason for high baseline could be social desirability bias where students would want to present a pro-sustainability image for their instructor and therefore, rate themselves more positively
- There was a need for a stronger and more continuous nudge for seeing a visible shift in student attitudes towards SDGs. In this case, the game was of a comparatively shorter duration and was played once by students.
- Attitudes about social sustainability are difficult to shift because it requires a significant conceptual departure from students' deep-seated preconceptions [18]

To delve deeper, we also performed pre- and post-game statement-wise comparisons for each of the 13 statements used in sustainability attitudes survey. We found a significant paired t-test result for the statement "environmental problems are a matter of my concern"; $t(61) = 2.0016$; $p = 0.049$. This finding indicated how the game could have enhanced students' individual relatedness with SDG issues and perhaps also shifted the onus of responsibility of environmental care from others to self. Such an attitude shift about environmental sustainability only and not about other aspects of sustainability did not surprise us as other scholars have previously shown how the environmental sustainability is easier to incorporate in engineering curricula than other aspects of sustainability, such as social sustainability [18].

b) Qualitative Analysis: To gain a more holistic understanding of the impact that our game had on student learning, we performed an exploratory thematic analysis on student reflections that we collected post the game. The analysis involved identifying prevalent themes around how the game contributed to student understanding of sustainability. The thematic map below illustrates the three themes revealed from the analysis.

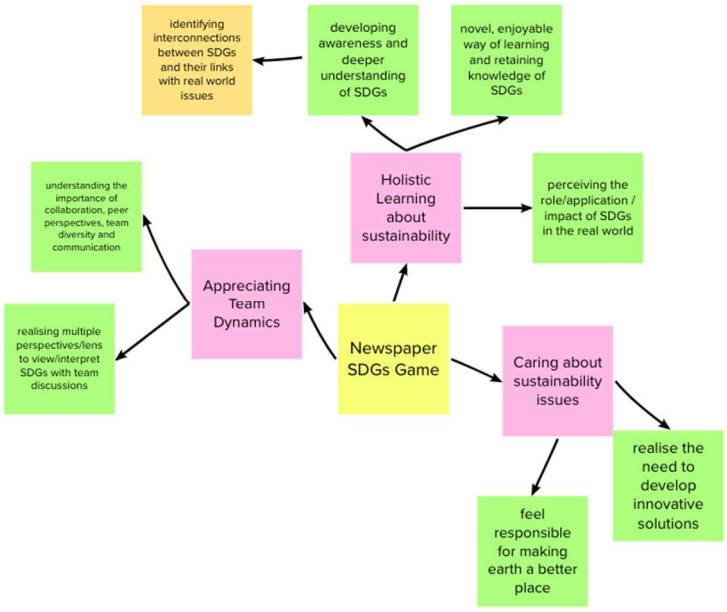

Fig. 2. Thematic Map visualising the Impact of SDG-Newspaper Mapping Game on Student Learning Outcomes

Below, we elaborate on identified themes by discussing its sub-themes and analyse ways in which they address the learning outcomes of the game.

- Holistic Learning about Sustainability

The game helped students widen their perceptions about sustainability as revealed through their statements such as "[The game] *Widened my horizon pertaining to sustainability and helped me grasp a better understanding of the concept.*" Game demonstrated ways in which various SDGs are interconnected (supported by student statements such as "*really interesting to see how so many SGDs are interconnected*") and how they play out in the real world issues ("*This activity helped me better understand the SDG's and their application in everyday happenings around the world.*", "*Made me think of how one little article can affect so many aspects of our lives*").

Students became more aware about different kinds of SDGs and how they interconnected with each other. (e.g. students said: "*I have been able to think of all 17 sdgs and am more aware of the sdgs and their real world impacts*", "*To develop an understanding of how complex problems can be and how there is never only one area worth focusing on.*").

Students found gamification very enjoyable to learn and retain SDGs ("*I think that this was supposed to be a fun way to make us remember and engage with the SDG's instead of forcing us to memorise them*").

- Caring about Sustainability Issues

As students understood the relevance of SDGs in their everyday actions, they felt more individually responsible for the sustainability of the earth ("*We need to be more responsible as an individual in protecting our planet.*"). With more responsibility, there arose a need to solve the sustainability problems identified during the game ("*These circumstances in articles provide a lot of fuel for problem solving and coming up with innovative solutions.*").

Another interesting aspect was innovation mindset evolving through a need to effectively solve complex issues around sustainability ("*I think the world requires numerous innovative ideas to counter the dilemmas & problems of each individual on this earth faces. And, I think this activity has pumped me a lot and aided me to develop a unconventional perspective towards problems & the path towards the solutions.*").

- Appreciating Team Dynamics

Since the game involved a significant amount of team collaboration to achieve intended outcomes, students realised the importance of teamwork in expanding their capacity to think critically about sustainability issues ("*This activity helped me think about the world problems, in critical thinking and helped me realise the importance of teamwork.*").

Students also saw value in peer learning and diversity as they were exposed to multiple perspectives to SDGs while working in diverse teams ("*After doing this activity I got to know how my teammates interpret about the same article. It helped me learning different approaches to the same problem due to varied diversity.*"). They even saw the team diversity as a crucial learning element in the game ("*The expected outcome of this activity was to enable one to know about different viewpoints and thought processes of people and how interlinked and widely spread these issues are*").

Finally, there was an increased appreciation of effective communication as students were not allowed to use the name of SDGs to indicate their answer to their teammates during the game. This constrained communication element led to the heightened need to understand peer perspectives on SDGs to gain a more holistic view. ("*The outcome was to help us understand effective communication and view the different perspectives of our peers. This indeed helps in having a better view of Sustainable Development Goals*.").

Overall, insights from the thematic analysis support our intended learning outcomes of game. The game helped develop a holistic learning experience for students by making them aware of a spectrum of SDGs and highlighting their relevance to everyday issues. Through analysing peer perspectives during team discussions, students were able to see sustainability as a multifaceted concept that required deeper exploration and felt responsible for solving sustainability challenges through innovation. Finally, they also appreciated game elements that required effective teamwork and communication in order to navigate through various sustainability issues.

III. Example 2 – Entropy and Sustainability Game

A. Course Introduction and Outline

An honors course on Entropy and Sustainability of Earth was offered in the Spring 2022 quarter (January-March) at University of California, Davis in the United States. This course taken by 17 undergraduate students consisting of mix of engineering (5) and non-engineering majors (12). Due to Omicron/COVID-19 conditions, the 11 week-long course was hybrid, with a portion of the classes being remote. The greater part of the classes, notwithstanding, occurred in person.

The course had following student learning outcomes:

- Have a profound understanding of entropy and human role in accelerating and slowing down entropy
- Develop using all senses including focusing on the collective movement of a group of people in understanding, engaging, and working in and through entropy
- Develop analytical reading and writing skills
- Interpret the principle of maximum entropy production (MEP) and its application to a range of Earth system processes
- Learn about how entropy is increasing due to human actions and natural forces at work

The course was exceptional in that it was group instructed by faculty working in areas of Asian American Studies, Performing Arts, and Biomedical Engineering Education. The course blended lectures, discussions, active learning, and making and playing out a score (notations showing sequences of movement composition and simple choreographic tools). The course provided students with short reading assignments on different subjects connecting with entropy seen from the perspectives of art and science in each class. They were requested to come ready by finishing the appointed reading, presenting a discussion post on LMS, and practicing any relegated dance exercises and performances. There were no prerequisites for the course. Students need not have an engineering, art, history, or dance major or have had experience in dancing, making art, or coding a game.

B. Inspiration for Gamifying Activity

To define entropy via game, the game board should depict the increase in entropy of game parts with time. Progression of energy expenditure was expected to drive the quantum of entropy increment. After preliminary exploration, Chinese Checkers was picked as game inspiration since these were driven by permutations and combinations of players' activities, and each resulting activity was reliant upon the history of activities (and therefore energy expended in the past action). The replacement of coins of one playing party by another could be a good motive for a game as well as a springboard for students to think about energy expended at each step and entropy resulting from each step. This inspiration led us to a game called Halma. Halma is a strategy board game invented in 1885 by George Howard Monks in Massachusetts [19]. Our game is dissimilar to Halma in that it triggers collaborative thought process on entropy and sustainability, whereas other games explored are highly competitive and without learning outcomes related to sustainability/energy.

C. Learning Outcomes of the Game

- Understanding the concept of entropy through game dynamics
- Explaining how an open system moves towards Maximum Entropy Production
- Discussing how choice of our actions contribute to entropy production
- Exploring the need for sustainable practices in real world scenarios using the context of entropy

D. Game Description

The game is played by two or four players seated at opposing corners of the board. The game is won by being first to transfer all of one's pieces from one's camp into the opponent's camp. A player moves a single piece to an

adjacent open square on each turn or jumps over one or more pieces in sequence. A sample of game flow is provided in Fig. 3.

In the present model, instead of competition among players of same team, there is cooperation encouraged to reach the opposition camp by minimizing the number of moves and time required to do so compared to other teams. The game players are also expected at the end to pair up and answer reflection questions together.

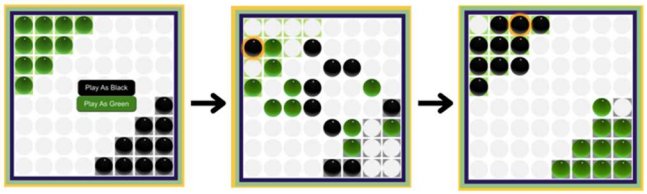

Fig. 3. Game Flow of Halma (from left to right)

E. Game Rules and Setup

- The board consists of an 8×8 squares grid.
- Each player's camp (delineated) consists of a cluster of adjacent squares in one corner of the board.
- Each player's camp is a cluster of 10 squares for two-player games. The camps are on opposite corners.
- Each player has a set of pieces in a distinct color of the same number as squares in each camp.
- The game starts with each player's camp filled with pieces of their color.
- Players determine who will move first.
- Pieces can move in eight possible directions (orthogonally and diagonally).
- Each player's turn consists of moving a single piece of one's own colour in the following ways (Fig. 4)

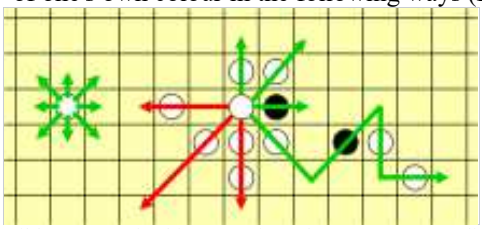

Fig. 4. Possible Moves of White Pawn in Halma (Green are Valid and Red are Invalid)

    - One move to an empty square
        - Place the piece in an empty adjacent square.
    - One or more jumps over adjacent pieces:
        - An adjacent piece of any color can be jumped if an adjacent empty square is on the opposite side of that piece.
        - Place the piece in the empty square on the opposite side of the jumped piece.
        - The piece that was jumped over is unaffected and remains on the board.
        - After any jump, one may make further jumps using the same piece or end the play.
- Once a piece has reached the opposing camp, a play cannot result in that piece leaving the camp.
- The game ends if the current play has every square of the opposing camp occupied by one's pieces by both players. Otherwise, play proceeds clockwise around the board.

F. Game Timeline and Dynamics

The game was introduced in week 2 of the of the 11-week course instruction. Each week, two classes of 90 mins each were offered. In week 1, students were introduced to various concepts such as the three pillars sustainability (economic, social, environmental), SDGs, Entropy, Thermodynamic equilibrium and disequilibrium, Earth as a thermodynamic disequilibrium, and the Maximum Entropy Production (MEP) Principle. Before coming to the class, they had schemed through the topics of the Cosmic Context of MDGs [20], the thermodynamic basis of Earth [21], The Entropy Law; Cosmology and the Second Law; Time, Metaphysics and Entropy; Life and The Second Law; and Exosomatic instruments and Energy [22].

TABLE III. GAME DYNAMICS AND TIMELINE FOR EACH ACTVITY

Game Activity	Time Taken
Game Rules and Team Formation	10 minutes
Let's Play Halma	15 minutes
Think – Individual Reflection	2 minutes
Pair – Team Reflection	3 minutes
Share Reflections with Class	5 minutes
Debrief	10 minutes
Google Form based Minute Paper	5 minutes
Total	50 minutes

G. SDT Application

The game associated complex and abstract engineering concepts such as entropy with sustainability to demonstrate students how they as future engineers can play a direct role in influencing sustainability through their daily actions. Within the SDT framework, student autonomy was supported by game features like choice in coin selection and deciding the direction and movement of coin, open ended student reflections at the end. Student competence was supported by the multiple moves required to win and multiple times the game could be played. The need for relatedness was supported in three ways: entropy change recognition through game moves (content connectedness), team collaboration for answering reflection questions (peer connectedness), and discussion with instructor upon reflected answers in class (instructor connectedness). By meeting the three SDT needs through the game, we hoped to increase student motivation for working towards sustainability challenges.

H. Assessment Method

To record student reflections post the game, we utilized two methods:

1. In-class Think-Pair-Share Activity

Students were required to reflect both individually and in pairs to see connections between entropy and sustainability. After reflection, they shared their insights with the class. Following prompts were provided.

Individual Reflection (Think):

- Do the two starting positions/two colors (Black and Green) embody anything from the real world to you? Think in the

context of real-world challenges around Energy, Entropy, Sustainability.

- If each action/turn is associated with energy loss, what do you think would have happened if players competed instead of collaboration?

Team Reflection (Pair):

- Imagine that the player with black coins represents the role of the "Industrialist" and the player with green coins represents the role of "environmentalist"
- What was the initial strategy set by your team? Do you think the strategy would have changed in the above context of Industrialist and Environmentalist?
- What does this conversation between the two sides represent in the real world for you? What does this mean for environmental sustainability?

Share: A team representative is invited to share with class the key takeaways from the team reflection.

Due to online mode, we were only able to conduct the individual reflections part of the activity using zoom chat. The responses from this chat are summarized in the section below.

2. Post-class Minute Paper

Students were asked to fill a minute paper (called 3-2-1) online via google form to answer the questions mentioned below.

- Three things I learned in class today:
- Two ways I contributed to class today:
- One question I still have is:

We received total 17 student responses (5 males, 11 females, 1 non-binary) from this activity which were then used to do a thematic analysis to identify broad student learnings from the game.

I. Results and Discussion

1) In-class Think-Pair-Share Activity Results

Students reflections demonstrated they successfully connected the movement of coins in the game to energy loss caused by human activities. They realized how each step in the game led to an increase in entropy which involved moving from an orderly towards a disorderly state. The game required shifting this disorderly state back to an orderly state which caused further energy loss. Students compared moving towards the end of the game as reaching equilibrium.

For some students, green coins represented green energy and black coins represented fossil fuels. For these students, humans shift towards green energy from fossil fuels also requires spending energy and contributes to increasing entropy. Others saw the interplay between green and black coins as an effort towards balancing environmental and economic sustainability in the world.

Students also recognized the importance of strategizing with their game partner to coordinate each other's coin moves in a way that leads to minimum energy loss and maximum progress. Other felt the need to pre-plan their moves so that they can finish the game in least number of turns and save energy.

2) Qualitative Analysis of Minute Paper Responses

We received 17 responses from students via the 3-2-1 minute paper activity. Thematic analysis revealed four major themes (in blue) as illustrated in the map below.

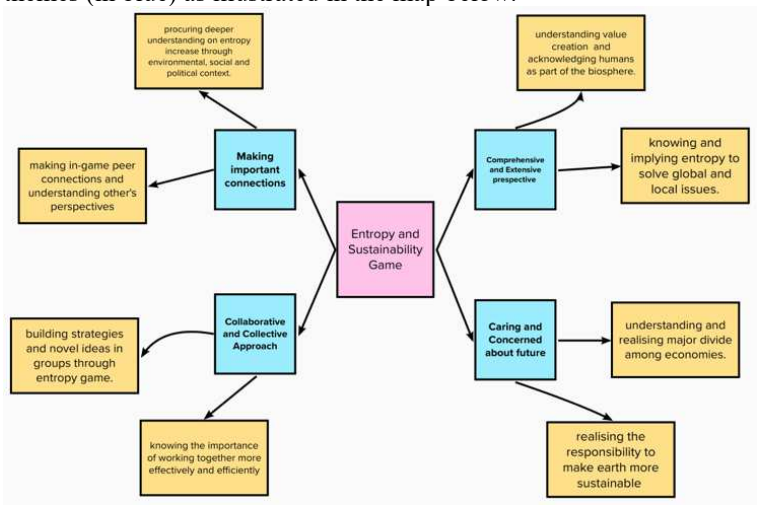

Fig. 5. Thematic Map revealing the Impact of Halma Game on Student Learning

We elaborate on recognized themes and how they meet student learning outcomes below.

- Making Important Connections

During the game, students made interdisciplinary connections to get a deeper perspective on how entropy is linked with sustainability in influencing real world issues ("*we began making connections between entropy and real life scenarios, best use of entropy, efficient use and conversion of energy through Halma Game*"). They further analysed sustainability problems using multiple lenses ("*With the entropy and sustainability game we began understanding sustainability in environmental, social and economic aspects, and reasons for increase in entropy*").

- Comprehensive and Extensive perspective

Students talked about take-aways that impact large communities. They utilised diverse ways to holistically understand the link between entropy and sustainability ("*through the game we understood the importance and inevitability of entropy, interacting with complex and open ended content. Also, analysing historical data to know contemporary issues around sustainability with broad and open-minded outlook*"). Consequently, students realized the impact of their actions on sustainability ("*In process of playing the game I started acknowledging sustainability, understanding that every action has certain reaction on environment*").

- Collaborative and Collective Approach

Students appreciated the importance of team dynamics through collaborative working on game and collectively executing critical tasks ("*it* [the game and reflection]*provided an engaging way to learn the concept through our mutual, co-operative and collaborative approach on actual actions and keeping team member and dynamics as the priority for efficient way to sustainability and issue of increasing entropy*"). Students remembered teamwork as a critical component of the game. ("*I will remember quite a good deal about entropy because this game is memorable, includes team contributions and peer need for each other at every step*").

- Caring and Concerned about Future

By understanding the implications of their actions on sustainability, students realised their responsibility in making earth more sustainable. ("*during in-game activities, we made connection(s) between Halma game and energy production, exhalations and varied human behavior. Understanding different perspectives and their implications on environment and our lives.*"). With greater responsibility, there emerged a need to take care of the sustainability issues recognized during the game.

Overall, insights from the thematic analysis supported game objectives by fostering an all-encompassing learning experience for students, making them mindful of multiple ways in which entropy affects sustainability and how their daily actions contribute to global issues involving faster rise in entropy. Through dissecting peer viewpoints during team conversations, students saw sustainability as a multifaceted idea that expected further exploration and felt liable for addressing sustainability challenges.

3) Aftermath of the Game

As class homework, students could design a new game that captured and simulated the learning objectives of the Halma game. This led to the creation of two new games by class students that taught sustainability in different ways. By playing Halma game in the class, students did not only learn about sustainability and entropy but also saw value in using gamification as a tool to teach such concepts. Below, are descriptions of games crafted by two course students.

One student created a choice-based game called "Tiny Planet Adventure" that requires players as "Gods" to flourish their "kingdoms" by investing money in different causes supporting population, technological and sustainability growth of their kingdom. The game allows players to travel to different time-zones where they encounter different kingdom issues (e.g., energy, agriculture, environment) and can invest accordingly. They can make a maximum of 3 investments within each time zone and receive kingdom and environmental points according to how much and where they invest. Based on player's investments, the game proceeds into a situation where they must maintain both environmental and kingdom points to ensure the survival of their kingdom and continue the game. The game ends when the in-game year reaches 150 or when environmental score falls to or below 0.

Another student developed a dice game inspired from "Snakes and Ladders" where players move towards the end-goal by rolling the 6-sided dice and encounter different colored-blocks on the way that can affect the level of entropy their moves create or change player's path of movement affecting their level of pace for reaching the end goal. The idea is to analyse how every move that players make impact entropy and how they can strategize to minimise that to support sustainability and reach their destination.

The above two examples demonstrate how using gamification in class can also lead to creativity in students and accelerate the development of new game-based tools for teaching sustainability that can help solve the problem of scarcity of engineering education tools in the gamification literature.

IV. Conclusion and Future Implications

Games are an effective and fun way to introduce engineering students to sustainability issues as they support active learning through promoting continuous interaction and collaboration between students. Engineering universities can leverage this method to diversify their curriculum by integrating sustainability without requiring extensive external resources. Often, the responsibility to inculcate sustainability learning in students lies on the shoulders of the faculty who may not have concrete tools in hand to integrate sustainability in their courses [5]. The two games discussed in this paper are an effort towards expanding the faculty's teaching toolbox for this purpose.

This study used both qualitative and quantitative measures to evaluate the impact of these games on student learning outcomes. Though we did not find a significant effect of the first game in influencing sustainability attitudes of students, we did find a significant shift in student attitudes towards environmental sustainability such that students felt a personal responsibility towards solving environmental issues. Thematic analysis findings from both games found that students developed a deeper, more contextual awareness of different sustainability issues, understood the multifaceted and interlinked nature of SDGs through peer perspectives, and analyzed how engineering concepts like entropy affect world sustainability through their everyday actions.

Diversity and inclusion literature in engineering has repeatedly highlighted the underrepresentation of women in STEM and engineering. Despite the high demand for engineering skills, low participation of women in engineering is seen due to narrowed perceptions of engineering as a male-dominated, technical field [23]. Now, more than ever, we need to broaden the way engineering is perceived so that it attracts diverse students who can see their personal relevance in engineering and consider it as a potential career route. To broaden the concept of engineering, universities need to start diversifying their engineering curriculum by including elements of contemporary relevance such as sustainability development. The two games discussed in this paper can be used by instructors and universities aiming to diversify their curriculum by integrating sustainability education. However, some limitations should be noted. Given the diverse student backgrounds, institutional, cultural, and educational settings across the world, the study needs testing in different contexts to assess the reliability of these games. Since work was performed at a single institution in both India and the U.S, so the findings should not be generalized directly. The sample size in this study was limited to 62 students each for in-person and online instruction. The game activities in this study were conducted in online instruction mode, and in-person application although straightforward, needs to be tested.

Finally, like how Halma game led some students to develop new games in sustainability, we hope that this paper motivates other educators and researchers to develop more research-based gamified tools that connects other engineering topics with sustainability. Over time, these efforts will broaden the understanding of engineering as a concept which in turn will help engineering institutes attract more diverse student populations and prepare well-rounded engineering graduates who are impelled to solve diverse global sustainability challenges.

APPENDIX

SDGs-Newspaper Mapping Game Template:
https://docs.google.com/document/d/1BkuzMqD1jYqomnSLFwuHgEkRImx1jJI8KmUVcz5Qp-8/edit?usp=sharing
Halma Game Template:
https://docs.google.com/document/d/1v7MFWnZPjivrafYk0szEf7HHz3nisikl87-P-6VKAv8/edit?usp=sharing

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