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# Mapping Learning and Game Mechanics for Serious Games Analysis in Engineering Education

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**Abstract**—In a world where students are increasing digitally tethered to powerful, 'always on' mobile devices, new models of engagement and approaches to teaching and learning are required from educators. Serious Games (SG) have proved to have instructional potential but there is still a lack of methodologies and tools not only for their design but also to support game analysis and assessment. This paper explores the use of SG to increase student engagement and retention. The development phase of the Circuit Warz game is presented to demonstrate how electronic engineering education can be radically reimagined to create immersive, highly engaging learning experiences that are problem-centered and pedagogically sound. The Learning Mechanics–Game Mechanics (LM-GM) framework for SG game analysis is introduced and its practical use in an educational game design scenario is shown as a case study.

Index Terms—Engineering Education; Learning Mechanics–Game Mechanics (LM-GM) model; Game based learning.

## I. Introduction

As evidence-based planning, practice and quality enhancement develop across the educational sector, universities require increasingly sophisticated ways of both engaging students and of quantifying levels of student engagement. This undertaking has been made more difficult in recent years by the increase in ways students can access and consume content through a diverse range of powerful hardware devices with new modes of interactions. Gamification is a term used to describe the application of video game mechanics to non-game processes to improve user engagement. Game based learning is increasingly being used in educational settings and is widely predicted to become mainstream in the next 3-5 years [1-3].

Serious Games have proved to have instructional potential due to their ability to present realistic simulations of real-life situations [4]. However educational games need to be designed properly to find the correct balance between gameplay and learning objectives and the integration of education and game design principles [5-6]. One possible approach to this problem is the use of the Learning Mechanics-Game Mechanics (LM-GM) framework which supports SG analysis and design by allowing reflection on the various pedagogical and game elements involved [7]. This paper provides a practical example and case study of using the (LM-GM) framework for game design for teaching electrical and electronic engineering. It demonstrates how a commercial game engine (Unity3D) can be used to rapidly prototype simulations to teach advanced electronic/electrical circuit theory where students must use and apply their knowledge and understanding of circuit theory to bias a series of electronic circuits successfully to complete the game. The game is designed to ensure a high level of user engagement and replayability with a competitive leaderboard element and analytics to measure student retention.

Section II of this paper discusses the practical use of game based learning in electronic and electrical engineering. Section III introduces the Sand Box Serious Game approach and Learning Mechanics-Game Mechanics (LM-GM) framework and demonstrates their use in the design of the Circuit Warz game for teaching electronic and electrical engineering. Sections IV and V presents a practical example of a mobile game designed using these approaches and looks at the practicalities of assessment, analytics and game validation in this context. Section VI presents the conclusion and future work in this area.

## II. Game Based Learning in Engineering

The Serious Games & Virtual Worlds research team at Ulster University focus on the potential of video games technologies for undergraduate teaching of electronic and electrical engineering related subjects. The Circuit Warz project was conceived with the overall aim to investigate if creating a compelling, engaging, immersive and competitive environment to teach electronic circuit theory and principles would increase student engagement [8]. To achieve this objective it was first necessary to investigate how to create a game related to the biasing of electronic and electrical circuits. The core loop of the original game was based on calculating/selecting the correct value(s) of individual circuit components e.g. resistors/capacitors, to generate a given circuit output/response based on a known value of input/stimulus and formula provided (Figure 1).

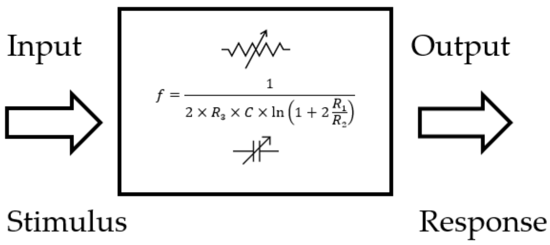


Figure 1 Core game loop for Circuit Warz project

To determine the validity of the approach a game prototype was created based on the principles of positive feedback in operational amplifier oscillators and was modelled in Excel to fine tune core gameplay (Figure 2). Oscillators are astable devices that produce an alternating or pulsing output voltage which is primarily dependent on the values of resistor/capacitor combinations chosen. The game design approach was to present the students with randomly generated output values/responses from the

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circuit i.e. peak to peak voltage (Vpp) and period of the waveform and the formulas to calculate these values. The student would then have to select the individual component values from an existing bank of resistors and capacitors to create the correct combination of components to provide this target output/response. To do this successfully the student would need to have a clear understanding of both the underlying circuit theory and its application. The subsequent score achieved was based on how close the value of actual output of the circuit (frequency and Vpp) was to the target output of the circuit and expressed as a percentage (Figure 3).

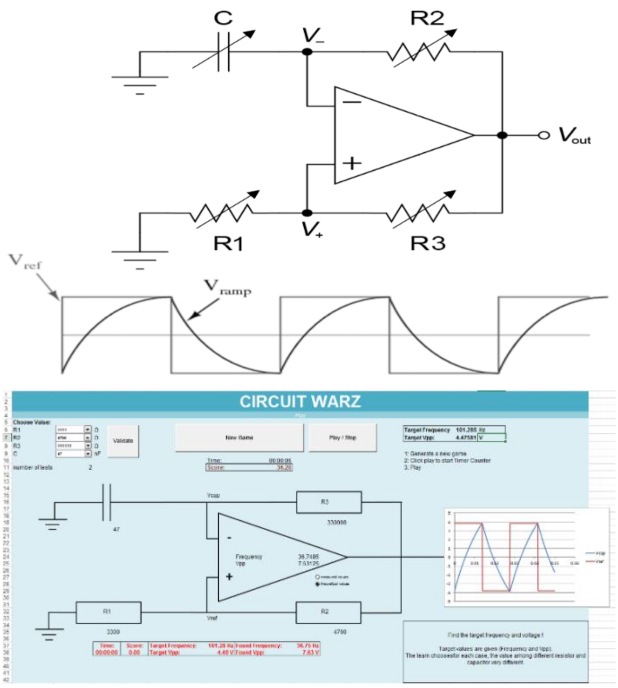


Figure 2 Solve for R1, R2, R3, C to achieve target frequency and Vpp

A weighting coefficient α of 0.7 was added to the score calculation to allow more emphasis on the accuracy of the frequency calculated. The scoring mechanism provides feedback to the student on their level of understanding of the circuit theory as there is a direct correlation between the percentage value received and accuracy of the result.

$$Vpp = Vsupply \times \frac{R_1}{R_1+R_2} \qquad freq = \frac{1}{2\times R_3\times C\times \ln(1+2\times\frac{R_1}{R_2})}$$

$$Freq\ \% = \frac{Min(Target\ freq,\ Actual\ freq)}{Max(Target\ freq,\ Actual\ freq)}$$

$$Vpp\ \% = \frac{Min(Target\ Vpp,\ Actual\ Vpp)}{Max(Target\ Vpp,\ Actual\ Vpp)}$$

$$\text{Score} = 100\times (\alpha\times freq\ \%.+(1-\alpha)\times Vpp\ \%)$$

Figure 3 Calculation of student score from Oscillator game

The first iteration of the project was created using the OpenSim virtual world simulator. The evaluation process focused on user acceptance of the environment as a teaching tool. A number of shortcomings were identified related to practical usability and the OpenSim platform [9].

## III. SAND BOX SERIOUS GAMES/LM-GM APPROACH

To address the previous shortcomings the project was redesigned and repurposed for deployment using Unity3D [10], a cross-platform game engine used to develop video games for web browsers, consoles and mobile devices.

The game focus and scope was extended to include seven increasingly difficult levels for the student to complete, based around fundamental electronic and electrical circuits typically found on first year undergraduate engineering courses. Individual levels in the game provide landmarks to support orientation and integrate the game elements and learning objectives in pedagogically meaningful ways by embodying units of knowledge with concrete, focused activities involving a sequence of small tasks to develop skills, each of which has a specific instructional target or learning outcome [11-13]. A Sand Box Serious Game (SBSG) approach was used as the sequential, task/mission based nature of the Circuit Warz's game design lends itself well to this experiential and exploratory learning format [14]. The Learning Mechanics-Game Mechanics (LM-GM) framework for supporting serious games analysis was employed to map the pedagogical elements/learning outcomes of Circuit Warz to game mechanics (Figure 4). Table 1 provides a description of each game level, circuit type, player objectives, related circuit theory, learning outcomes and initial mapping to game mechanics. Table 2 extends the LM-GM-based analysis.

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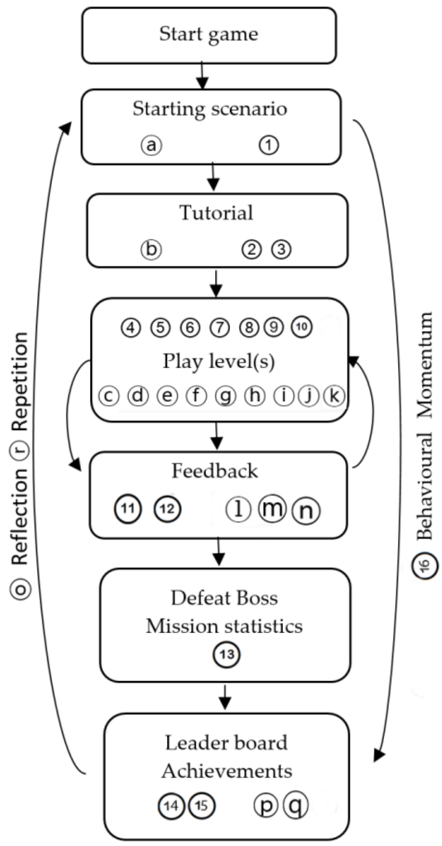


| Learning mechanics | | Game mechanics | |
|---|---|---|---|
| a) Instructional | j) Modelling | 1) Cut scene/Story | 9) Planning |
| b) Tutorial | k) Simulation | 2) Tutorials | 10) Levels |
| c) Observation | l) Feedback | 3) Cascading info. | 11) Feedback |
| d) Experiment | m) Motivation | 4) Simulate/Response | 12) Assessment |
| e) Modelling | n) Assessment | 5) Movement | 13) Meta-game |
| f) Hypothesis | o) Reflection | 6) Time pressure | 14) Competition |
| g) Analyse | p) Competition | 7) Capture/elimination | 15) Rewards |
| h) Action/task | q) Incentive | 8) Strategy | 16) Behavioural Momentum |
| i) Explore | r) Repetition | | |

Figure 4. Circuit Warz game map using LM-GM-based analysis

Table 1. Game stages/levels with player objectives, theory, learning outcomes and associated game mechanics

| Stage/level | Objective/circuit | Theory | Learning outcomes/role | Game mechanic |
|---|---|---|---|---|
| Introduction | Backstory, rationale | N/A | Set game context and player role | Cut scene, tutorial |
| Level 1 Series/parallel | Solve for R1 given Vi,R2,R3 to get value Vo | $V_o = \frac{R_{eq} \times V_{in}}{R_{eq} + R_1}$ | Parallel and series circuits. Equivalent resistance. Circuits and current flow. | Cascading information, simulate, response, movement, time pressure, capture, elimination, strategy, planning, levels, feedback, behavioural momentum, rewards, competition meta-game |
| Level 2 RC filter | Solve for R1, C to get target cut off $f_c$ | $f_c = \frac{1}{2\pi RC}$ | RC circuits and cut off frequencies Low/high pass filters. | |
| Level 3 Graetz Bridge | Align diodes. Solve for C given Vpp, R, f to get target output V | $C = \frac{Vpp}{2 \times R \times f \times V_{smooth}}$ | Convert AC to DC. Ripple reduction using capacitors. Diodes in rectification. | |
| Level 4 Wheatstone | Solve for Rx given R1, R2, R3 and Vpp. Balance bridge Vg=0 | $V_g = V_{pp} \times \left(\frac{R_2}{R_1 + R_2} - \frac{R_X}{R_3 + R_X}\right)$ | Components/operation of bridge. Find unknown resistance value using circuit. | |
| Level 5 Summing amplifier | Solve for R0 given R1,R2,R3 to achieve target Vout | $V_{out} = -R_0\left(\frac{Ve_1}{R_1} + \frac{Ve_2}{R_2} + \frac{Ve_3}{R_3}\right)$ | Op amps in summing amplifiers Relationship input/output Voltage Role of feedback resistor (R0) | |
| Level 6 Transistor switch | Solve for R*in* and R*l* given Vpp, Vin to achieve target IC. | $I_C = \frac{V_{pp} - V_{CEsat}}{R_l}$ | Understand saturation/cut-off in transistor as switches. Relationship between RC and IC | |
| Level 7 Oscillator | Solve for R2, R3 and C to achieve target frequency and V*pp* | $f = \frac{1}{2 \times R_3 \times C \times \ln\left(1 + 2\frac{R_1}{R_2}\right)}$ | Convert DC source to (AC). Compute oscillation frequency from components. | |
| Generator | Fire laser to save planet | N/A | Impact of players actions | Assessment |

Table 2. Circuit Warz extended LM-GM-based analysis

| Game mechanic | Implementation | Learning mechanic | Description |
|---|---|---|---|
| Cut scene/Story | Pre-rendered videos explain the game objectives, mechanics and outcomes through storytelling | Instructional | Backstory sets game scenario. Planet is under imminent threat of invasion. Player must fix the giant laser to defeat the invaders |
| Tutorials Cascading information | Tutorials at start guide user through basics mechanics of movement etc. | Guidance/Tutorial | Player is guided through the initial stages of game by informative graphics and cut scenes. |
| Simulate/Response | Player must select correct value of component(s) in circuit to achieve required output values/response. | Observation, Analyse Experimentation Modelling, Hypothesis | Game play tasks such as correctly biasing circuits provide the player with a sense of empowerment. |

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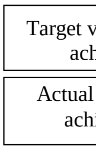
| | | | |
|---|---|---|---|
| Movement | Navigate player quickly in levels using first person shooter approach | Action/Task | Performing interactive tasks successfully and completing levels/destroying sentinels provides a sense of progress, player satisfaction and game mastery. |
| Time pressure Capture/elimination | Time constraints on level. Add tension, pressure/urgency with sentinel attacks | | |
| Strategy/planning | Flexible design of level layout and circuit puzzles to allow different game completion strategies to emerge. | Explore, modelling | Explore level layout and complete in timely manner. Deeper understanding of circuit theory/analysis through modelling/heuristics |
| Levels, Feedback Assessment Meta-game | Advance to next level. Score shows time taken, stage, accuracy and level of understanding of task completed | Feedback Motivation Assessment, Reflect | Level score reinforces sense of understanding and progress to maintain motivation. Provides benchmark for reflection process |
| Competition Rewards | Game leader board and achievements | Competition Motivation, Incentive | Public leader board/achievement allows student to compare their score/performance. |
| Behavioural Momentum | Game play repeats itself through multiple levels to cause a shift in player behaviour. | Repetition | Repetitive gameplay reinforces behaviour change. Score improvement using multiple strategies |

The approach to mapping learning objectives/outcomes to game mechanics was to first set the game context through a backstory which then defined the player's objectives and rationale for subsequent actions. This was achieved using cut scenes. Next the player was introduced to the core mechanics through a tutorial becoming familiar with the user interface and main controls. The core loop of the game was to solve increasingly difficult circuit problems in seven stages, where the player explores each level (behavioural momentum), tries to understand its purpose (cascading information) and how to efficiently solve the problem (strategy) using a simulate/response approach to observe, experiment and analyse circuit behaviour under time constraints. The end of each level provides feedback to the player on their progress (score achieved), possible rewards (achievements) and competition (leader boards). The final level/generator room provides an overall score (assessment) and completes the story arc. To ensure the game has replay value and offers new (educational) challenges each time the game is played, elements of the problems to solve are different each time a level is attempted. This was facilitated by dynamically changing the value(s) of the target output responses of the circuit. The number of possible permutations of component values to choose from on later levels and the non-linear relationship between component values (e.g. selecting a capacitor value in Nano farads (nF) or microfarads (μF)) makes solving circuits more difficult. This approach ensures that students have to learn, fully understand and practically apply the underlying circuit theory to successfully complete each level at each attempt. The physical layout of the levels and the design of the game puzzles allow the students to make strategic decisions about how to complete the game. Overall score obtained is based on accuracy and time taken to complete each level. The student can decide to take more time to accurately calculate the values of the individual components to obtain the required target output or save time by using a "rule of thumb" or heuristic approach. Both strategies would increase the depth of the student's knowledge and understanding about theoretical/practical circuit operation.

The game backstory, physical environment, setting, initial challenge, characters, puzzles, feedback and resolution was created using the heuristic framework for educational games where the game is considered as a narrative [15] and provides a structured and systematic approach to the integration of the story with the learning outcomes (Table 3). The game is set in the near future when the Earth is under imminent threat of alien invasion. As the alien ship approaches it passes our last line of defense, a laser facility on the Moon. The laser is sabotaged and malfunctions. The player/engineer has to solve a series of increasingly difficult puzzles through the practical application of circuit theory under severe time constraints, while been attacked by the compromised moon base security system (sentinels), to fix the generator and fire the laser and save the planet from destruction.

Table 3. Heuristic approach Circuit Warz (Dickey 2006)

| Heuristic approach | Circuit Warz |
|---|---|
| Present initial challenge Identify potential obstacles and develop puzzles, minor challenges and resources | Fix laser/call to action. Apply practical electronic circuit theory to complete puzzles. Destroy sentinels |
| Identify and establish roles | Play role of engineer |
| Establish the physical, temporal and environmental dimensions of environment | Game setting is moon defense base. Severe time constraints to complete tasks |
| Create backstory. Develop cut scenes to support development of narrative storyline | Imminent threat of alien invasion. Save planet. Use cut scenes for plot hooks. |




## IV. Implementation

Given the near ubiquity of smart phones and tablets the game was redesigned and optimized for deployment on mobile devices with touch capabilities using a first person perspective and viewpoint. A first person shooter approach was chosen as the overall experience was intended to be a competitive, fast paced action game which is appropriate for the sequential, level based layout of Circuit Warz. The first-person perspective allows the student to experience the action through the eyes of the protagonist and provides greater immersion into the game. This perspective choice meant that game implementation did not require the additional overhead of designing a full third person character and negated the need for complex camera control systems. The inclusion of the sentinels and the gun were added to increase the intensity and pressure of the game, reinforcing the idea of an imminent alien invasion and possible base infiltration, adding a sense of urgency and reinforcing the backstory and overarching narrative.

The game is intended to be used as part of a blended learning approach and as a supplementary resource to complement/augment existing teaching resources. The

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physical layout of individual circuits on each level was accurately recreated. This is important as the circuit layout and physical operation have to accurately reflect the constraints of their real world counterparts (Figure 5) Orientation and overall cognitive load are important considerations in the game design. Timely and meaningful feedback in a game, particularly related to progress and rewards, is essential in educational products as it motivates students [16]. There are two main feedback/progress mechanisms to provide orientation and status information in Circuit Warz, the head-up display (HUD) and the generator status board. The HUD (Figure 6) is accessible to the student at any time and gives context/location related information on current location, objectives and task(s) to complete, component values and current status, target value(s) to achieve or achieved and score on level.

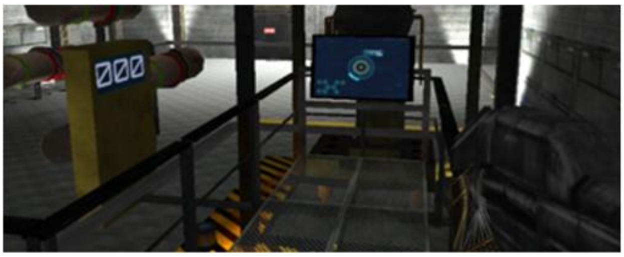


Figure 5 Level 6 Physical layout of Summing Amplifier

The generator status board (Figure 7) provides progress and status information about the current state of the game i.e. overall score in the game and the remaining tasks to complete. This board is available outside of each game level with a final board with the total score and time taken to complete the game on the final reactor/laser level.

Figure 6. HUD layout



Figure 7. HUD layout and generator status board for player feedback

## V. Assessment, Analytics and Validation

Assessment of learning in SG relates to the process of using data to demonstrate that the stated learning objectives are actually being met by a learner and involves interlacing game mechanics oriented to facilitate building new knowledge with mechanics oriented to assess the new knowledge acquired [17]. Circuit Warz uses a summative and formative approach to assessment (Table 4).

Table 4 Assessment dataset and related achievements

| Data point | Description |
|---|---|
| Global score (completion) | Total score when completing game. Displayed on final level. |
| Global time (completion) | Total time taken to complete game. Displayed on final level. |
| Time per level | Time per level. Shown at level end. |
| Score per level | Level scores. Shown at level end. |
| HUD activated | Indicator attempts taken on level. |
| Connect components | Indicator attempts on each level. |

| Level/award | | Achievement |
|---|---|---|
| 1 | Series sensei | Scored 100% in under 30 secs. |
| 2 | Filter-mania | Scored 100% in under 40 secs. |
| 3 | Bridge builder | Scored 100% in under 40 secs. |
| 4 | Wheatstone ace | Scored 100% in under 15 secs. |
| 5 | Sum-sensation | Scored 100% in under 40 secs. |
| 6 | Transistor-tastic | Scored 100% in under 50 secs. |
| 7 | Oscillator ninja | Scored 100% in under 45 secs. |
| | Circuit Master | Score 100% all levels under 260 secs. |

Formative assessment is stealth based/implicit and carried out throughout the game, continuously monitoring student progress and providing feedback through the HUD and Generator status boards. This approach has a number of advantages as it can be carried out in real time without interrupting the user’s flow [18]. Elements of formative assessment include the time taken to complete level(s) and score achieved per level (Table 4). Summative assessment is carried out at the end of the game with an overall total accumulated score and awarding of in-game achievements e.g. achieving a score of 100% within a constrained time period. In-game achievements have a dual role i.e. awarding progress and increasing engagement/retention. Some game levels are more difficult to complete successfully due to their inherent complexity and high number of possible component permutations. The time constraints related to earning achievements on these levels are deliberately demanding to encourage the students to try different approaches to solving the circuits. A global leader board adds a competitive element allowing the student to benchmark their performance against others.

Recent advances in game and learning analytics have allowed developers and educators to gain new insights into how users interact with their games by simplifying the collection of large amounts of data. Serrano-Laguna et al., proposed a two-step generic approach to using learning analytics in educational games [19] where in-game measures/generic traces are gathered from gameplay (Table 5) and then queried using specific assessment rules aligned with the games educational objectives. Game analytics [20] offer similar functionality in the form of core and custom metrics. Core analytics measure standard metrics e.g. general game usage, daily and monthly active users, time of day and length of sessions. Custom metrics can record game specific actions or traces of interest decided on during the game design process e.g. level completion or score which can be cross referenced and analyzed further using cohorts and funnels [20]. Circuit Warz uses a combination of core and custom analytics to track user activities. Table 5 maps in-game measures to game analytics and their subsequent use in the game.

Table 5 Mapping for game measures to analytics

| In-game measures | Game analytics | Circuit Warz |
|---|---|---|
| Game traces<br>Start (id data)<br>Quit (context)<br>End (outcomes) | Metric/Core<br>Daily/monthly Active Users<br>Sessions/session length.<br>Retention/churn | Start game<br>Login<br>Quit<br>End game |
| Phase changes<br>Start<br>End (status) | Progression metric<br>Custom dimension<br>Design event<br>Start/Fail/Complete | Level(s) completed<br>No. of 100% completions |
| Meaningful variables<br>Game play events | Custom dimension<br>Design event | Level score/ time taken |
| Input traces<br>Device interaction | Custom dimension<br>Design event | Select/connect components |

Core analytics allow the measurement of student engagement/retention levels (i.e. daily/monthly active users, session times and lengths). Custom analytics track phase changes (e.g. level completions) and meaningful variables (e.g. levels scores, HUD usage and quantity of component connections /disconnections). These metrics can be cross referenced using cohorts and funnels to carry out further analysis of user activity. Funnels allow the visualization and measurement of student movements through a series of predefined events/stages and determine if game stages, elements or levels give players difficulty. Cohorts are user groups that completed specific actions within specific time periods. From an educator's perspective, the use of custom measurements, along with funnels and cohorts, inside the game analytics platform allows the exploration of the usage data to determine user retention. Custom measurements can be used to check how many levels the user completes which can then be cross referenced using funnels and cohorts e.g. how many users who completed level 1 subsequently completed level 7 within a defined time period and returned regularly to the game over a period of months. As the game design evolves in later iterations or is enhanced, the use of analytics would allow the educator to check the impact on usage and retention these changes caused e.g. changing the relative difficulty of a level and adding or removing features. Using a combination of assessment and analytics can provide educators with the tools to quantify the effectiveness of the learning activities and can serve as a starting point for validation to evaluate whether the game achieves its purpose and learning outcomes are met.

The game validation approach [21] taken in the Circuit Warz game followed a four step procedure: (1) analysis of the learning outcomes for each level and performance indicators (Table 1 and Table 4), (2) development of learning/game mechanics and detailed game scenarios (Figure 4, Tables 1 + 2), (3) careful design of the scoring mechanism (Figure 3), gameplay challenges (i.e. time constraints to complete each level and possible components permutations) and achievements (Table 4, Figure 7) to ensure that the performance indicators relate directly to the student meeting the learning outcomes i.e. high scores and achievements are only attainable through a deep understanding of the theoretical content and its practical application and (4) performance indicators are cross checked with in-game measure traces in the analytics (Table 5) i.e. the recording of a high number of component selections/connections by a student on a level would indicate that a trial and error approach was used.

## VI. Conclusion, Future Work and Discussion

This paper provides a practical case study into the use of serious games for teaching. The Circuit Warz project was introduced and the rationale, planning and implementation using a Sand Box Serious Game/heuristic approach presented. The practical use of the Learning Mechanic–Game Mechanic analysis framework in the game design process to map the pedagogical elements/learning outcomes to game elements while maintaining the balance between entertainment and learning was successfully demonstrated. The design and integration of game analytics to assess student retention and engagement levels was discussed and then mapped to learning analytics and in-game measures. A stealth approach to assessment was implemented and the game validation process discussed.

The game design and implementation phase of the Circuit Warz project is now complete and the approach taken potentially offers a new, engaging and highly interactive way to teach engineering related material. The total effort involved in creating the game was substantial and involved a large team of game designers, programmers and artists over a time period in excessive of nine months. The commercial development costs for the project would be well beyond the resources of most educators but would be necessitated by its scope and similar projects of this size would require similar effort. Generalizing the approach taken in this project to other domains or application areas would involve identifying elements that would be common in any undertaking of this type and creating a generic framework for implementation i.e. set the context and player objectives using cut scenes, introduce the player to the core mechanics and control systems using a tutorial, create the physical layout of the level(s) and design the problem(s) to solve in a flexible manner for high replay value (incentivized by achievements) allowing different strategies to emerge, include regular updates and feedback on player progression and add an element of competition to the outcomes or final assessment using leader boards. However the main challenge(s) to overcome would be repurposing the teaching material as a game experience and defining the core loop of the game i.e. what the player does over and over again, in an appropriate and compelling way to translate learning outcomes into these format/frameworks. The next stage in the project is the widespread general release of the game on the main app stores for evaluation with the target user demographic to prove the efficacy of the approach.

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