FOSTERING ENGINEERING THINKING WITH CURRICULUM INTERGRATED STEM GAME

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ABSTRACT

This paper shares the experience of implementation of STEM-based learning in the first year of engineering undergraduate programs for Metallurgy Engineering, Heat Engineering and Welding Engineering. STEM-based gaming competition “Engineering Cluster” is implemented under the scope of networking collaboration between Siberian Federal University and Moscow Polytechnic University in the first semester of 2016-17. The paper substantiates role and importance of STEM gaming activities at the stage of adaptation to learning process in university. Major issues concerning partial gamification of learning content are described. The results of “Engineering Cluster” competition showed that significant point is made in students’ abilities for self-study and solving interdisciplinary problems. Moreover, the game put attention to practical importance of natural sciences for understanding engineering problems. Overall, the proposed learning model could be a ground for change of mindset of both faculty and students on how traditional disciplines can be taught and learned.

KEYWORDS

STEM, Gamification, Introduction to Engineering, Engineering Thinking, Standards 3, 4, 7

INTRODUCTION

To educate engineers able to successfully perform professional tasks in a rapidly changing world, the education itself should evolve in the very context of engineering problems and challenges the society and technology are facing now (Jeschke, 2016). Worldwide CDIO Initiative propose a practice-oriented approach based on a concept of learning by designing real engineering products (Crawley et al., 2007). The CDIO approach could be adopted by the means of basal revision of traditional understanding of “education” turning then to active and project-based learning as a systemic basis for curriculum design.

At the stage of designing the CDIO-based curriculum, one will inevitably encounter a challenge of overcoming the traditional, historically accepted paradigms of learning and common attitudes of students and teachers concerning education. The most probable systemic conflict emerges at the point of rethinking natural sciences – math, physics and chemistry. These disciplines dwell at the very fount of any technical education, being the stem for every engineering programme. However, due to complexity and ever decreasing formalizability of engineering problems, the conceptual knowledge of natural sciences alone is no more sufficient for modern engineer (Kamp, 2016). Thus, in most cases, the traditional theoretical mode of math, physics and chemistry is a subject to change for modern engineering education.

Aiming to increase learning effectiveness, education system is shifting from passive knowledge transition towards experiential knowledge acquisition through various learning activities (Standard 8). Gaming activities are the form of active learning methods, based on principle that students acquire experiential knowledge through acting simulated gaming patterns. Games are best known for high learning efficiency caused by participants' emotional immersion while reaching game goals and perceiving situations of success (Hamari et al., 2014). Implementation of gaming principles in non-gaming area, referred as gamification (Herger, 2014) became widespread phenomena in marketing, management, education etc.

The concept of STEM (Science, Technology, Engineering, Math) was created to answer both needs: to improve education quality in natural sciences and develop modern methodologic apparatus for these disciplines, as well as bring engineering context in learning process (Gonzalez & Kuenzi, 2012). Including both conceptual basics of natural sciences and modern gaming methods, STEM technologies can bridge the gap between theory and practice at earlier stages of engineering curricula. Despite the criticism of gamification phenomena (Fuchs et al., 2014), implementation of STEM games in learning process can be viewed as a stage of students' acquaintance with problems of engineering professions at the beginning of their studies in university (Standard 4). The engineering context of STEM games put attention to significance and demand for integrative application of natural sciences to solve engineering problems.

Due to diversity of application area, gamification phenomenon focuses mainly on using IT. Considering both technologic potential and gradual digital gaming principles development, computer games, existing for a few decades, became one of the most influential media industries today. As long as IT, media and computer games remain significant part of youth culture, they can be successfully adopted to learning, increasing overall interest and motivation of students as well as learning efficiency. This phenomenon relates to the specific way of information perception by today's young people, and was described in numerous studies.

In general, digitalization of content allows students to bring learning to more comfortable environment than a classroom – to their own devices. In the framework of basic disciplines of the first year of undergraduate programme, bringing content to youth-native digital environment using gaming context could facilitate students' interest and change the mindset of studying natural sciences.

"Engineering Cluster" – A STEM GAME CONCEPT

Aiming to change the learning process by gamification of content and digitalization of environment, Moscow Polytechnic University developed a STEM game "Engineering Cluster" for 1st and 2nd year students. The game represents an online market simulator, where student teams become competitive companies developing high-tech engineering products. From educational point of view, "Engineering Cluster" utilize the content of physics, chemistry and math at the level of the first year undergraduate programme, bringing atop of that engineering and economical contexts implemented through project-based approach. The game plot suggests that students' companies must compete at the product market by means of developed products quality and business strategy.

STEM game “Engineering Cluster” can be described through the following key features:

- User-friendly interface
  The game developed as a website with simple and modern graphical structure, where main elements are supported with commentaries and guides. Training missions are available for faster acquaintance with game mechanics.
- Mobility and self-organization
  The website is available 24/7 using any digital device with internet connection and browser, giving students a feeling of personalization and an opportunity for flexible planning.
- Real-life products
  All products in the game are represented by calculation models of real-life products of engineering, adopted for the first-year engineering undergraduate programme level.
- Learning content integration
  Each game product represents a problem in natural science discipline – physics, chemistry, or math.
- Diversity and difficulty
  Game products are interdependent and ranged by difficulty: high-level products include several correlated low-level products. Every product has a multitude of potentially correct solutions.
- Interdisciplinary approach
  High-level product development means parallel solving of different problems from different areas so that students can explicitly see the connection between physics, chemistry and math within a single engineering problem.
- Quality improvement cycle
  The game mechanics simulates Deming’s PDCA cycle, which represents iterative process of planning-designing-simulating-production for each product.
- Market economy
  Each team has its own economic potential influenced by quality and level of developed products. The teams undertake business transactions with each other at the game market.
- Teamwork
  Considering multitude of game sub-processes, the key to successful play is to become a sustainable team with effective role management.
- Responsibility
  Teams maintain their own game budget and make important decisions at every stage – from product requirements analysis to cooperation strategy.

The main principles of “Engineering Cluster” can be exemplified through general production cycle of one of the high-level products – Winged Rocket (Figure 1). In order to produce a Winged Rocket, the team must design its components: Rocket Engine and Accelerometer. The team will also need an appropriate Rocket Fuel in turn to produce the Engine.

Each product in the chain refers to a problem within a particular area of natural science:

- Rocket Fuel – heat of combustion calculation for selected fuel compound;
- Accelerometer – Hooke’s law application and statistical error analysis;
- Rocket Engine – calculation of heat balance for thermal system;
- Winged Rocket – flight trajectory analysis represented by saddle surface.

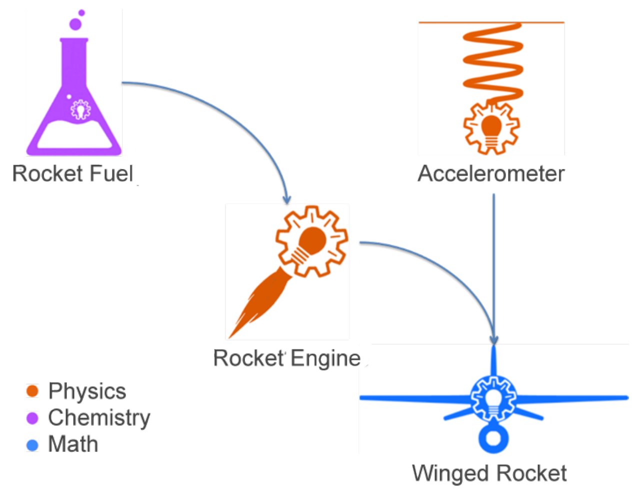


Figure 1. Winged Rocket production chain

Before undertaking a task, students must fulfil their knowledge in theory of these problems. In contrast with the traditional mode of study, students formulate the request for theoretical input at the point of encountering real-life practical problem during in-game product design. Thus, students can explicitly see the connection between natural science and engineering. Figure 2 shows a lifecycle of game product (see Appendix A for detailed stages explanation).

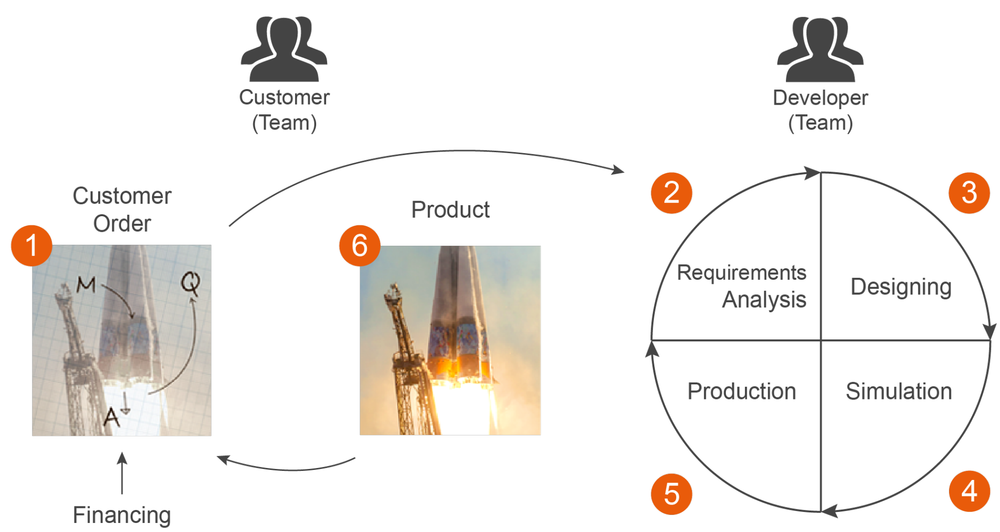


Figure 2. Game product lifecycle

STEM GAME CURRICULUM INTEGRATION: A COLLABORATIVE EXPERIENCE

“Engineering Cluster” offers salient educational potential to create an immersive practice in experiencing engineering context for first-year students. However, to maintain the salience, the complex and thorough planning are required starting from intercurricular integration of the game. This part shares the experience of collaboration between Moscow Polytechnic University (MPU) and Siberian Federal University (SibFU) for “Engineering Cluster” implementation in three CDIO-based undergraduate programs.

In compliance with CDIO Standard 5, “Engineering Cluster” was organized as a module in the Introduction to Engineering course in the 1st semester. The module workload was spread in 8 weeks including auditorium classes, special supporting events and self-study time. The timeline of the game is shown on Figure 3.

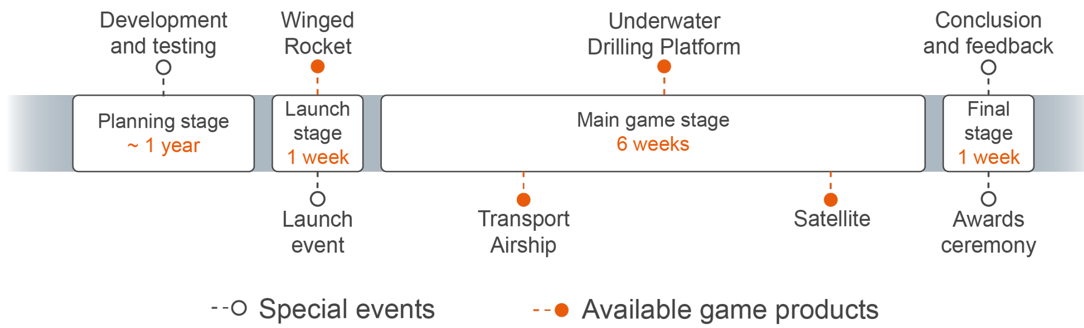


Figure 3. “Engineering Cluster” timeline

The module was preceded by a year of joint work of MPU and SibFU in developing the module structure: from staff training seminars and curricula design to results evaluation and awards ceremony. The key points of universities’ collaboration are explained in Appendix B.

STEM game “Engineering Cluster” as a part of educational process could be divided into three sub-processes:

1. Game Process
   - The overall module length is 8 weeks with the last week reserved for game conclusion, awards ceremony and feedback sessions
   - Main “Cluster Sessions” are organized on the regular basis as a part of Introduction to Engineering course (two classes per week)
   - Optional “Cluster Sessions” on students’ demand
   - Special “Troubleshooting Sessions” on a weekly basis
   - Overall classroom to self-study workload relation is approximately 40% to 60%

2. Game Support
   - Classroom support made by Introduction to Engineering teaching team
   - Coach-sessions of physics, chemistry and math teaching team
   - Senior-year student tutors support – game adaptation, strategy development, team building
   - “Natural Sciences Sessions” on students’ demand
   - Website 24/7 technical support for error reports

3. Game Management

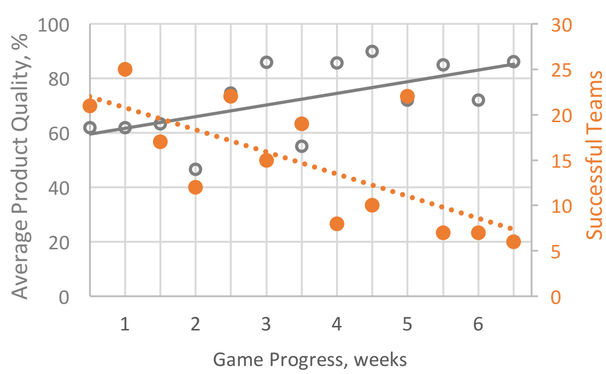
   Administrators
   - Website activity monitoring
   - Product Order pool supply based on game plot and activity
   - Regular meetings with teaching staff and tutors
   - Learning Outcomes Evaluation
   - Feedback collection

   Teaching staff and Tutors

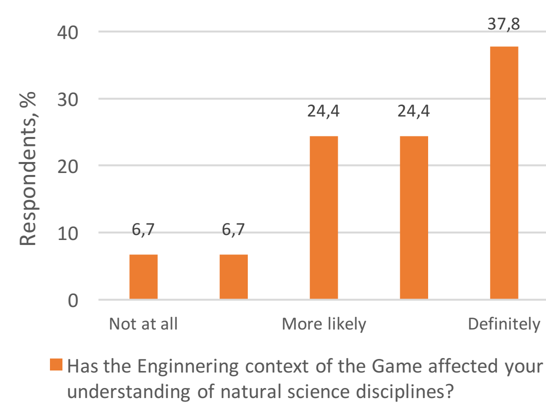
- Classroom teamwork monitoring, teams' sustainability
- Game rules violation monitoring and ethics issues
- Low progress teams support
- Dispute solving

RESULTS AND DISCUSSION

Organization of STEM game module "Engineering Cluster" for CDIO-based undergraduate programs in the 1st semester of 2016 resulted in full-scale engagement of all the participants of educational process in effort to provide unique learning experience for students. Comprehensive statistics gathered from the game platform demonstrated positive dynamics in the number and quality of game products solved by students (Figure 4a). The chart shows the quality of every product introduced during the game and respective number of teams able to successfully produce it (see grey circles and orange dots aligned vertically). The increase of average quality of products could be explained through students' adaptation both to the game mechanics and required mode of learning along the game progress. Overall game difficulty resulted in gradual decrease of successful players. However, it could be clearly seen that this mode of learning formed six strong and sustainable groups of students able to answer challenges. The results of feedback also showed students positive attitude towards practice-oriented learning, when solving engineering problems increased their overall interest in natural science (Figure 4b).



a) Student teams' effectiveness evaluation



b) Students survey results

Figure 4. Game statistics and feedback results

"Engineering Cluster" in numbers

- 120 students from 3 engineering programs formed 29 teams;
- Solved 15 product models of 17 available in the game, with average quality of 67%;
- 7 of 29 teams solved max number of models – 15;
- Total count of products produced – over 3000;
- More than 50% of students spent 2-4 hours to "Engineering Cluster" daily;
- Coach Sessions organized – over 30 hours.

Learning effectiveness

- High-level product accomplishment is only possible if students successfully solved every component's problem;
- Average time spent in solving high-level product gradually decreased (from 14 days for the first available product, 10 days for second product, 7 days for 3rd and 4th) meaning the development of students' ability to analyze complex product and solve interdisciplinary problems;
- Most students had successful experience in solving complex and ambiguous problems (support materials and technical guides provided no instruction or algorithm);
- Acting as an engineering company, students could immerse in the problems of engineering profession and use project approach to solve them;
- The game created a learning process beyond timetable and built long-term rapport between students and teachers, forming unique teaching-learning experience for both students and teachers.

Proposed approach to STEM game implementation in the learning process allowed to achieve significant results due to thorough planning and curriculum integration. Earlier experience of SibFU in STEM games learning were based on the students' optional choice, lacking the motivation system and powerful support of the game process. The first launch resulted in disregarding the game by the students as non-obligatory activity, whereas most of them shifted their attention to another, "more important" courses. Teachers' active support and commitment allowed to make "Engineering Cluster" the most rigorous and important learning event for students, dramatically increasing their learning motivation and overall interest to engineering profession.

Inferring from the results obtained by MPU and SibFU, the practicability of STEM games use in the first year of studies is defined by the following:

1. The need to acknowledge students with project activity at earliest stage (Syllabus 2.1).
2. Positive change of students' personal attitude towards natural sciences (Syllabus 1.1).
3. In-game professional-oriented problems require integrated use of knowledge, methods and abilities of applying natural sciences (Standard 3).
4. Native for modern students form of education taking learning process beyond classroom
5. Using teamwork for solving in-game problems.
6. Personified learning with student's responsibility for product quality.
7. Fostering students' engineering vision of product as a complex system with lifecycle (Syllabus 2.3).

CONCLUSION

Implementation of STEM technologies combined with partial learning gamification for the first-year undergraduate students of SibFU demonstrated an opportunity to bring engineering context to the content of natural sciences. The "Engineering Cluster" game format allows to engage students with the problems of engineering profession, showing significance and necessity of integrated knowledge use for solving engineering problems. Intercurricular integration of the game and active staff support showed significant increase of learning effect. In general, the purpose of STEM games use could be formulated as creation of valuable and salient learning experience for young students, fostering engineering thinking and encouraging them for further active studying at university.

REFERENCES

Crawley, E.F., Malmqvist, J., Östlund, S., Brodeur, D.R. (2007). *Rethinking Engineering Education*. Springer US. ISBN 978-0-387-38290-6.

Fuchs, M., Fizek, S., Ruffino, P., Schrape, N., et al. (2014). *Rethinking Gamification*. meson-press. ISBN 978-3-95796-000-9.

Gonzalez, H.B., Kuenzi, J.J. (2012). *Science, Technology, Engineering, and Mathematics (STEM) Education: A Primer*. CRS Report for Congress. Retrieved January 14, 2017 from Federation of American Scientists: https://fas.org/sgp/crs/misc/R42642.pdf

Hamari, J., Shernoff, D. J., Rowe, E., Coller. B., Asbell-Clarke, J., & Edwards, T. (2014). Challenging games help students learn: An empirical study on engagement, flow and immersion in game-based learning. *Computers in Human Behavior*. 54: 133–134. doi:10.1016/j.chb.2015.07.045.

Herger, M. (2014). *Gamification Facts & Figures*. Retrieved January 14, 2017, from Enterprise-Gamification.com: http://enterprise-gamification.com/mediawiki/index.php?title=Facts_%26_Figures

Jeschke, S. (2016). Engineering Education for Industry 4.0. *Proceedings of 2016 European CDIO Meeting, Delft, Netherlands*. Retrieved January 14, 2017, from 4TU: https://www.4tu.nl/cee/en/events/cdio_conference/presentations/engineering-education-for-endustry-4-0.pdf.

Kamp, A. (2016). Engineering Education in a Rapidly Changing World. 2nd Rev.Ed. TUDelft. ISBN: 978-94-6186-609-7.

BIOGRAPHICAL INFORMATION

Natalia Gafurova is a Professor in Education and Pedagogy, and a Counsel to the Rector of Siberian Federal University. She is currently the leader of CDIO project at SibFU. Her research focuses on education development, didactics, and digitalization of learning process.

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APPENDIX A

Table A. In-game production stages

Production Stage	Team activity	In-game situation
1. Project Start	Start a new product with custom parameters or picking up Product Order from game pool	Winged Rocket production chain is available with technical guides for each product. The order is due in 72 hours. Producing a rocket with 75% quality will make a profit of 250 GC (Game Currency: millions of Russian Rubles were actually used)
2. Requirements Analysis	Studying requirements and limitations of each product in the chain, analysing products' parameters cross-relations	The 'operative' rocket type defines the limitations in total mass and peak engine power. Land relief defines dynamic range of accelerometer. Engine thermal efficiency is influenced by the choice of fuel components
3. Designing	Calculation of product models. The challenge is in the lack of strategy given and product compatibility awareness	Considering the cross-related parameters, the best strategy is to solve all the models in parallel
4. Simulation	Game engine simulates product model using students' parameters. Simulation log shows product's resulting specifications. PDCA cycle allows students to make iterative corrections	Test rocket simulation (cost 20 GC) showed that rocket is operable. Comparing the results with product requirements revealed minor discrepancy, which could be corrected by increasing calculations accuracy.
5. Production	Checking if required products are in stock. Final product quality is defined by quality of components. After finishing the product, the production line could be built, allowing produce the same product for cost price	Time-saving decision is to buy Rocket Fuel on the market for 50 GC. Produced rocket quality is 85%, the production line costs 100 GC. Now the team can produce 85% grade operative rockets for cost price of 35 GC
6. Product Implementation	Two options for finished product: a) product is stored for market or further production b) product is utilized (deleted)	The profit for producing Winged Rocket is 80 GC. The team accomplished rocket production chain and can make custom rockets for other teams.

APPENDIX B

Table B. Roadmap of “Engineering Cluster” implementation

Stage	SibFU	MPU
Background for collaboration	Facing the need for new educational practices, education quality improvement	Development of educational products for engineering programs
Form of collaboration	Networking agreement for long-term joint educational projects realization	
Defining the structure *1 year before launch*	Learning module in the Introduction to Engineering course	“Engineering Cluster” format as an online STEM game
Defining the content *1 year before launch*	Introduction to Engineering and Natural sciences syllabi for first-year undergraduates. Learning outcomes planning	Developing context engineering tasks using requested content and workload
Planning *During the year*	- Designing the curricula - Documentation approval - Resources planning - Staff planning - Student tutors planning - Learning outcomes evaluation	Developing “Engineering Cluster” STEM game
Staff training *1 month before launch*	Training seminar for teaching staff and student tutors. Preliminary game testing	- Training seminar program - Expert visit to SibFU seminar - Feedback collection
Game testing *2 weeks before launch*	Test launch of the game played by teachers and tutors	Feedback collection
Game launch *1 week*	- Launch event - Forming student teams and registration - Introductory game session	Technical support and help desk
Module body *6 weeks*	- Regular classes and self-study - Teachers consultations - Troubleshooting sessions - Student tutors support - Activity monitor - Social and students mass media support	Technical support and help desk
Game conclusion *1 week*	- Evaluating the results - Defining winner teams - Awards ceremony support - Feedback collection	- Game data analysis - Awards ceremony for students - Expert visit to SibFU - Feedback collection
Further collaboration	Developing “Engineering Cluster” format based on feedback analysis. Expansion of collaboration range, further joint educational projects	