# BUILDING STEM EDUCATION FRAMEWORK THROUGH NETWORKING COLLABORATION

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## ABSTRACT

The paper shares the experience of implementation of STEM-based learning in undergraduate programs, organized through networking collaboration between Siberian Federal University and STEM-Games LLC. Proposed gamification model is applied through the first year of Introduction to Engineering course as a stage of students' first acquaintance with the problems of engineering profession. STEM-based learning activities are shaped into two modules representing a team-based engineering design competition with emphasis on different aspects of engineering. The modules utilize the principles of CDIO bringing up project-based approach and active learning as primary educational techniques. The paper address major issues concerning seamless intercurricular integration of STEM-based learning. Finally, the paper shares the most recent results of the institutions' collaboration within CDIO-based programs of SibFU. Significant point is made in students' abilities for self-study and problem solving. Proposed contextual gaming activities put attention to practical importance of natural sciences, being as a starting point for developing students' engineering thinking and learning motivation.

## KEYWORDS

STEM, Gamification, Introduction to Engineering, Engineering Thinking, Standards 3, 4, 7, 8

## 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 reproducing a production cycle of engineering design throughout various educational practices and learning activities (Crawley et al., 2007). The CDIO approach requires substantial changes in traditional theory-based education resulting in the shift towards active and project-based learning.

The first challenge of designing CDIO-based curriculum is to overcome historically shaped paradigms and common attitudes concerning education process. The most probable conflict emerges at the point of rethinking the natural sciences – math, physics and chemistry, which are the basis of all technical knowledge. However, as the engineering problems become more complex and interdisciplinary, the body of conceptual knowledge of natural sciences is no more sufficient for an engineer to answer today's challenges (Kamp, 2016). Thus, the traditional theoretical mode of natural sciences 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 including games (Standard 8). The latter are the form of active learning based on a principle that students acquire experiential knowledge through acting simulated gaming patterns. Games are best known for learning efficiency caused by participants' emotional immersion in the process of reaching game goals and perceiving situations of success (Hamari et al., 2014). Adding gaming principles to non-gaming activity, referred as gamification (Herger, 2014), became a widespread phenomenon in diverse areas including education.

The concept of STEM (Science, Technology, Engineering, Math) was created to answer the needs mentioned: both to improve education quality in natural sciences and update methodological apparatus of these disciplines to the current needs, as well as to bring engineering context in learning process (Gonzalez & Kuenzi, 2012). Combining the conceptual basics of natural sciences and gaming principles, STEM learning aims to bridge theory and practice at high school level and earlier stages of higher engineering education. Despite the criticism of gamification phenomena (Fuchs et al., 2014), certain STEM techniques can be applied within engineering undergraduate programs as a stage of students' acquaintance with engineering professions at the beginning of their studies in university (Standard 4). In general, STEM games put attention to significance of natural sciences and demand for integrative application of their concepts in solving engineering problems.

The main idea of the paper is that applying the concept of STEM learning through the series of introductory modules at the first-year of undergraduate programme could facilitate students' interest in studying natural science and encourage them towards problem-based learning.

## A STEM MODULE CONCEPT

STEM-based practices within the current research were initially developed by STEM-Games LLC (formerly affiliation of Moscow Polytechnic University) and implemented in the educational process of Siberian Federal University (SibFU). Continuous collaboration between the institutions resulted in rethinking STEM-based learning and development of the STEM Module, which further expands the basic idea of combining natural sciences, engineering context, and gamification into an immersive learning activity.

The STEM Module is represented by two minor modules, each designed as a team-based engineering design competition for the first-year undergraduate students with emphasis on the certain aspects of engineering. Overall, the STEM Module is aimed to provide semester-long learning activity stressing both basic theoretical and practical knowledge of freshmen students.

### *"Engineering Cluster"*

The STEM Module starts with a STEM game "Engineering Cluster", which brings the content of natural sciences into gamified digital setting. The game represents an online market simulator, where student teams become competitive companies developing high-tech engineering products. Educational purpose of the "Engineering Cluster" is to utilize the content of physics, chemistry and math at the level of the first year undergraduate programme by using the project-based approach to emphasize engineering and economical context. The game plot suggests that students' companies must compete at the product market by means of their products quality and business strategy.

The key features of the "Engineering Cluster" game are as follows:

- Digital setting
  The game developed as a website with simple and modern graphical structure, providing necessary commentaries and guides for navigation. Training missions are available for faster acquaintance with game mechanics.
- Content-integrated real-life products
  In-game products are represented by calculation models of real-life engineering products, adopted for the first-year undergraduate programme level. Each product represents a problem within a single topic of natural science discipline – physics, chemistry, or math. Additional products for technical drawing were introduced in the latest version of the game.
- Diversity and interdisciplinarity
  Game products are interdependent and ranged by difficulty: high-level products include several correlated low-level products. Each product has a multitude of potentially correct solutions. High-level product requires solving different problems from different areas in parallel 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 representing iterative process of planning-designing-simulating-production for each product (see Appendix A).
- Market economy
  Each team has its own economic potential influenced by the quality and complexity of their products. The teams maintain their own game budget and undertake business transactions with each other at the game market. An auction system is introduced in the latest version of the game providing deeper understanding of common market laws.
- Teamwork
  Considering a multitude of in-game sub-processes, strong teamwork based on effective role management is the only winning strategy.

The "Engineering Cluster" game can be exemplified with a production chain of one of the high-level products – Winged rocket (Figure 1). In order to produce a Winged rocket, the team must obtain its components: Rocket Engine and Accelerometer. The project requires a Rocket Fuel in order to produce the engine.

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

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

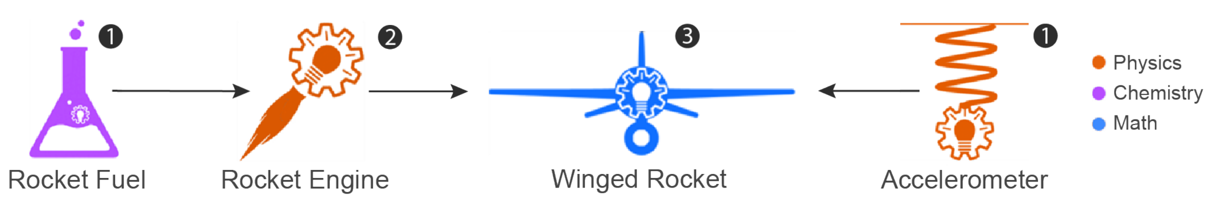



Figure 1. Winged Rocket production chain

To produce a correct solution for each product, students have to fulfil their theoretical knowledge in the problem area. In contrast with the traditional mode of study, the theoretical input is initiated by students themselves, providing teacher with full ready-to-learn class. Considering real-life context of the tasks, students can explicitly see the connection between natural science and engineering. However, being purely digital, the game lacks hands-on experience, grasping only the theory of natural sciences using STEM learning approach.

### *"Engineering Start"*

The "Engineering Start" game represents real-life design competition where student teams design and assemble various engineering products with specific requirements. Each product's functioning based on a different principle of math, physics, or chemistry, whereas the competition stresses the efficiency of its application to the final product. Generally, the game bridges basic theoretical knowledge of natural sciences with its practical application and facilitates the ground level of engineering design skills using STEM concept.

The key features of the "Engineering Start" game are as follows:

- Hands-on tasks
  The game task is a project of designing a physical model of an engineering product, capable of performing specified function. The competition requires student teams to complete several tasks during the game, resulting in a series of different products (usually 3-5).
- Requirements and limitations
  Each task has a diverse range of solutions; however, the main challenge is to meet technical requirements for each product. In-game limitations (e.g. financial, physical) allow to maintain the range of products' parameters and control requirements violation.
- Production cycle
  The projects are organized in a way which simulates an engineering cycle, including resource planning, designing, building and testing the product. Student teams are required to prepare technical report for each product, including description, drawings, and list of materials.
- Resource management
  Student teams are expected to plan, select and use the materials and tools according to their own project idea. Teams are also allowed to prepare an inquiry for specific materials and tools not presented in the workspace. Using materials not listed in the report is not allowed.
- Workflow
  Student teams use dedicated workspaces to work on their projects supervised by faculty and tutors. The access to the workspaces is time-bound in order to provide equal opportunity for every team. Each product is required to pass safety check prior to the final completion.
- The Competition
  The final competition is held for all the teams to demonstrate their products on a test site. The best products is selected using the design, test results, safety, and budget criteria.

The main point of the "Engineering Start" game is that students learn how the theoretical principles of natural science apply in real-life products as they build and modify them in order to meet the performance and safety requirements. For example, to design a catapult, students need to acknowledge themselves with the basics of mechanics, such as leverage, momentum, elasticity, and ballistics. Moreover, students can experiment on how these principles behave when they modify the catapult design or use another material while searching for desired performance. The requirements are that the catapult, for instance, should be capable of shooting the target at the distance of 5 m using tennis balls while the catapult itself should not exceed 0,5 m in each dimension. The accuracy and the shot distance are the performance criteria for the catapult project.

**STEM MODULE CURRICULUM INTEGRATION: A COLLABORATIVE EXPERIENCE**

Combining the two STEM-based games, the STEM Module offers salient educational potential to create an immersive engineering experience for first-year students. However, building a STEM educational framework requires complex and thorough planning within curriculum management. The following section shares the experience of building such a framework in terms of networking collaboration between SibFU and STEM-Games LLC.

The STEM Module is developed as a part of the Introduction to Engineering course with total workload of 14 weeks of the first semester including various events (see Figure 2).

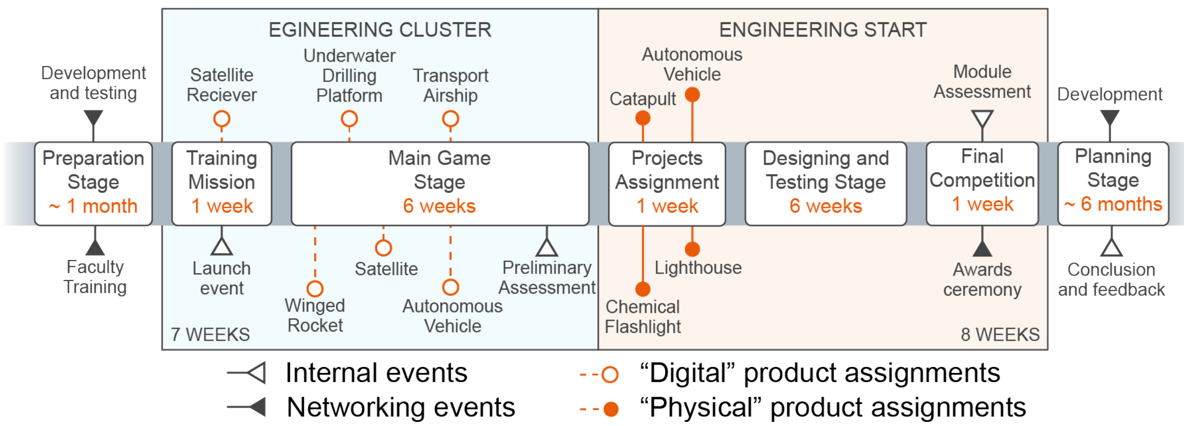



Figure 2. STEM Module timeline

The Module is updated each year after feedback and statistics data are collected, allowing to manage the reported issues, revise the content, and propose new ideas. The key points of institutions' collaboration cycle are listed in Appendix B. The STEM education framework, built around the STEM Module at SibFU, is best explained using sub-process structure:

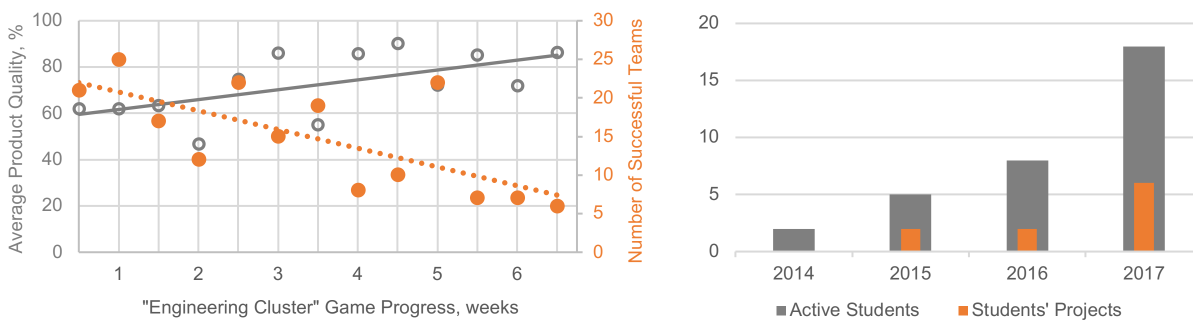
1. STEM Module
   - The Module includes both "Engineering Cluster" and "Engineering Start" games running sequentially throughout the first semester of studies
   - Regular "STEM Session" classes are a part of Introduction to Engineering course
   - "Troubleshooting Session" for teams' leaders on a weekly basis
   - The Module workload distribution is 40% classroom and 60% self-study

2. Module Support (made by faculty, tutors, and staff)
   - Gameplay issues supported by Introduction to Engineering teachers
   - Content issues and coach sessions supported by natural sciences teachers
   - Teamwork and strategy issues supported by senior-year student tutors
   - Game website technical support and workspace maintenance

3. Module Management (made by program managers and networking partners)
   - Game activity monitoring and low progress teams support
   - Social events organization
   - Information flow, faculty and staff management
   - Game ethics and rules violation monitoring, dispute solving
   - Learning outcomes evaluation and Module performance assessment

## RESULTS AND DISCUSSION

The STEM-based gaming activities are being organized at SibFU since 2015 as a result of continuous networking collaboration between STEM-Games LLC and the University. Thus, the following section shares the current results of the STEM Module project, which is being revised and updated on a regular basis. Implementation of the STEM Module in the first semester of 2017 provided students with unique learning experience and proved the positive dynamics in overall students' performance since the launch of the STEM project in 2015. Figure 4a represents a sample of statistics gathered from the "Engineering Cluster" game platform showing the gradual increase in product quality along with establishment of several strong student teams. The data collected from students' feedback and annual faculty reports showed the interesting tendency when active students propose their own creative engineering projects inspired by the STEM Module experience. Figure 4b illustrates the data collected from Metallurgy Engineering programme. It could be clearly seen that STEM learning helps students to discover their creative potential resulting in formation of strong teams willing to undertake their own engineering projects after the Module is completed. It is also a remarkable result of change of students' attitude to learning process itself: The Module showed that it could be more involving, entertaining, and challenging.




a) Student teams performance overview

b) Number of projects proposed by students after the STEM Module

Figure 3. Game statistics sample and students' activity monitoring results

The STEM Module highlights:

- 120 first-year students of 3 undergraduate programs formed 26 teams
- "Engineering Cluster" resulted in 17 of 21 unique product models solved in 6 weeks with an average quality of 67 % and over 3000 of successful attempts
- "Engineering Start" resulted in 48 products passed the tests, with the total of 4 projects types: a catapult, an autonomous vehicle, a lighthouse, and a chemical-based flashlight
- The STEM Module working group included 14 student tutors, 12 faculty members, 3 staff members, and 5 program managers and officials

Learning outcomes and overall performance:

- Any product, successfully accomplished by students, is a result of applying the principles of natural sciences learned within the Module. Thus, considering Bloom's Taxonomy, it makes advanced learning result compared to traditional mode of studies
- By designing complex game products students had demonstrated the ability to solve interdisciplinary tasks, along with problem analysis and teamwork skills, although they all were stressed at the basic level. The most successful teams showed significant progress in self-study and could manage the situations of ambiguity and uncertainty during the games

- Most students reported that the engineering game context combined with project-based tasks had helped to learn the theory of natural science, along with providing teamwork experience
- The Module created a learning process beyond timetable, facilitating a long-term rapport between students and teachers, forming unique teaching-learning experience

Proposed approach for using STEM gaming activities as an educational framework proved an effective educational practice, providing freshmen students with the most rigorous and important learning activity throughout the first semester, dramatically increasing their learning motivation and overall interest to engineering profession. The potential discussed in the paper mostly depend on the effort made by institution to integrate the Module within a curriculum, including workload management, faculty training, and outcomes evaluation (Standard 3).

Inferring from the networking experience between STEM-Games LLC and SibFU, the benefit of shifting to STEM learning in the first year of studies is defined by the following:

1. Students get familiarized with project-based activities at the earliest stage (Syllabus 2.1)
2. Positive change of students' attitude towards natural science (Syllabus 1.1)
3. In-game projects require higher levels of knowledge attainment and their integrated application (Standard 7)
4. Native for modern students form of education which takes learning beyond the classroom
5. Personified learning with student's responsibility for product quality.
6. Fostering students' engineering vision of product within a lifecycle (Syllabus 2.3)

## CONCLUSION

Implementation of STEM technologies as a holistic education framework for the first-year undergraduate students of SibFU demonstrated an opportunity to integrate an engineering with the content of natural sciences, which fully complies with CDIO principles. The STEM Module games "Engineering Cluster" and "Engineering Start" allowed to engage students with the problems of engineering profession, showing significance of theoretical knowledge use for solving practical engineering problems. Intercurricular integration of the Module and active faculty involvement showed significant increase of learning efficiency. In general, the benefit of STEM learning is in creation of valuable and salient learning experiences for young students, fostering their engineering thinking and encouraging for further active study at university.

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## APPENDIX A

Table A. "Engineering Cluster" Production Stages

| Production Stage | Team activity |
|---|---|
| 1. Project Start | Start a new product with custom parameters or picking up Product Order from game pool |
| 2. Requirements Analysis | Studying requirements and limitations of each product in chain, analysing products' parameters cross-relations |
| 3. Designing | Calculation of product models. The challenge is in the lack of strategy given and product compatibility awareness |
| 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 |
| 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 |
| 6. Product Implementation | Two options for finished product:<br>a) product is stored for market or further production<br>b) product is utilized (deleted) |

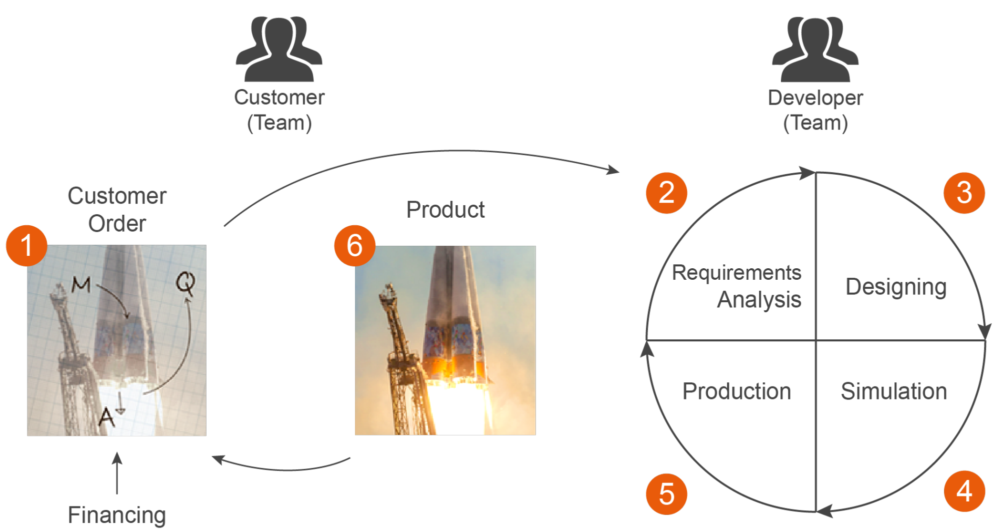


Figure A. In-game production cycle

**APPENDIX B**

Table B. STEM Module Development Cycle

| Stage | SibFU | STEM-Games LLC |
|---|---|---|
| Background of collaboration | Facing the need for new educational practices, and curriculum development | Development of educational games and engineering competitions for youth |
| Form of collaboration | Networking agreement for developing joint educational practices | |
| Defining the structure *6 months before launch* | The Module of two STEM-based games as a part of "Introduction to Engineering" course for the 1st year students | "Engineering Cluster" game as a theory-based online STEM game, and "Engineering Start" game as a practice-based project competition |
| Defining the content *6 months before launch* | Introduction to Engineering and Natural Science courses integration. Syllabi development, incl. learning outcomes planning | Selection of contextual engineering tasks based on the requested content and workload |
| Module Development *3 months before launch* | - Curriculum design<br>- Documentation approval<br>- Resources planning<br>- Assessment planning | Module tasks and activities development |
| Faculty training *1 month before launch* | Training seminar for faculty and student tutors. Game preliminary testing | - Training seminar agenda<br>- Expert visit to SibFU<br>- Feedback collection |
| Module launch *1 week* | - "Engineering Cluster" launch event<br>- Registration of student teams<br>- Introductory game session | Documentation and manuals supply. Technical support and help desk |
| "Engineering Cluster" game *6 weeks* | - Regular classes and self-study<br>- Troubleshooting sessions<br>- Activity monitoring<br>- Preliminary assessment | Technical support and help desk |
| "Engineering Start" game *7 weeks* | - Projects assignment<br>- Workspace organization<br>- Materials and Tools supply<br>- Activity monitoring | Documentation and manuals supply. Technical support and help desk |
| Final Competition *1 week* | - Event hosting<br>- Awards ceremony<br>- Feedback collection<br>- Learning assessment | - Game data analysis<br>- Expert visit to SibFU<br>- Feedback collection |
| Module Development *After Module conclusion* | Troubleshooting session based on feedback analysis.<br>New ideas proposal. Module development strategy based on needs analysis. Expansion of collaboration range, further joint projects. | |