A Case Study of Thoroughly Integrated STEM PBL Course of Mechanics

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Abstract. Along with the wide spread and deep penetration of STEM theory in China, the imperative task is to develop compatible courses with thorough interdisciplinary integration. The aim of this paper is to present a project-based learning (i.e., PBL) case study for college mechanics courses, in terms of the global structure, target analysis, activity design, comprehensive evaluation and implementation process. The features of this study can be summarized as follows. Firstly, in combination of students’ activity experience, the content of this study derived from a real-life problem truly realizes the interdisciplinary integration. Secondly, other than simply mixing the subject knowledge with hands-on skills, the objective of this study attaches specific importance to the stimulation of students’ interests and potentials in learning science and technology. Thirdly, the genuine research resources are adopted for implementing the project during the whole course. Fourthly, in order to urge students to form deep self-analysis, the course evaluation is composed of process and result assessments. In all, this study provides a reference for the development of an integrated STEM course. It may contribute to the acceleration of training professionals and construction of building innovation-oriented country.

1. Introduction

1.1. STEM educational concept

Stemmed from tide of education reform in the 1980s in US, STEM is the abbreviation of four disciplines’ initials: Science, Technology, Engineering and Mathematics. SMEM education is not the simply combination of those four subjects. It is a problem-oriented, reality-based, knowledge-correlated, prudent and systematic learning pattern, which intends to promote personal quality and cultivate career interests by training people’s professional skills in settlement of the real problems [1]. Therefore, STEM education is deemed as an effective path to enhance students’ creativity and competitiveness nowadays.

The kernel concept of integrated STEM education is placed in the realistic and attractive problem situation rather than a traditional siloed education condition [2], concentrating on the interdisciplinary fusion in solving problems. In this learning mode, the student’s study is a real, contextualized and meaningful process. By investigating the synergistic effects among subjects, the students can enhance the learning capability for the existing courses. So, the teaching of the integrated STEM presents the modes of student-centering, discipline-combination and problem-inspiration, as well as the stress of equal importance on both practice and knowledge. In the end, it would prove significant values in
mentoring talents with innovative thinking and professional skills, by means of understanding the connections cross subjects, obtaining the technological skills in engineering designs and experiencing the disciplinary values[3].

1.2. Development status of integrated STEM courses

Thus far, the integrated STEM courses in China are developed mostly in the fields such as 3D printing, robot, visualized programming and gizmos that are implemented in the form of Maker Movement or comprehensive practice class which focuses on students’ active participation and principal status in a certain degree[4]. The problem is that the integrated extent among subjects is far from enough. In some courses having deep theories such as mechanics, the attempts for interdisciplinary fusion are very rare. Some reasons are behind. One is that, the involvement of vast mathematical computations in mechanics makes most students feel difficult and short of interests to participate in the learning activities at the beginning. In order to attract students’ attention, some courses overly stress on the operations from field practices and cut down the class hours of the theory instruction. However, this motivation is not only incapable of promoting the study interests, but also against the basic rule of “theory guiding practice”. The second reason is the inadequacy of relevant knowledge. Most teachers have insufficient recognitions regarding the STEM theory and lack the competence in guiding the students cross subjects. Many course reforms only concern the external integration of instructional mode, but ignore the internal penetrations of interdisciplinary concepts which hinder the development of students’ deep study and high-order thinking skill. Finally, a few reasons may come from outside. For instance, some mechanics are school-based curriculum without consolidated and inter-connected content systems. The deficiency of social cooperation and support sometimes has effects as well.

1.3. The integration of PBL and STEM

Traditional PBL model means that a student can carry on the study by accomplishing of one or several projects highly relevant to the real world in a corporative way. Basically this study process is assemblies of series actions, such as design, production, operation, evaluation, reporting and presentation[5]. In the teaching model with the integration of both PBL and STEM, the emphasis is placed more on the comprehensive applications across the subjects through a project. During this education process, knowledge from the courses of science, technology, engineering and mathematics needs to be synthesized effectively. In general, the STEM PBL course could be classified in line with the depth and difficulty of the integrated STEM knowledge[6]. For example, the simplest level is the one-subject based course. That is, only one of four STEM subjects is needed to finish the project. The middle level course needs two or more STEM subjects and further on, the top level course involves all of them. The reason why the top level course has the most difficulty is because its designers or teachers for this STEM PBL course need not only solid knowledge for each of those four subjects, but also the experiences and capabilities for their systematic integrations. Regarding the thoroughly integrated mechanics, the case study presented in this paper belongs to the top level course.

1.4. Innovations of this study

Although the STEM and its related instruction model have been widely studied and reported in decades by numerous researchers, most of investigations focus on the educational theories, including the methodology of STEM teaching design[7], construction of quality evaluation indicator[8], comparison and optimization of STEM curriculum[9], introspection on ecology of educational practice[10] and the extension from STEM to STEAM, by involving arts subject with the efforts to connect the culture connotation with the creative thinking and innovative practical ability[11]. It is quite rare to have a real case study based on the theoretical curriculum system with the backgrounds of actual demands from industry, as well as the objectives of thoroughly integrating STEM knowledge by means of practical operations. Aiming at the application of mechanical courses in college and taking a project as the implementing platform, this study strengthens the connotation of education and teaching by performing a whole project-life cycle, i.e., design-build-operation-evaluation within a period of
teaching procedure. The expectation is to enhance the students’ abilities in the aspects of aggregate analysis, modelling calculation, comprehensive evaluation, and hands-on operations.

2. Project Design

Taking civil engineering as an example, college students need to finish core mechanics course such as theoretical mechanics, material mechanics, structural mechanics, fluid mechanics, soil and rock mechanics, as well as supplementary courses such as advanced mathematics, computer-aided design, hydraulic structure, engineering economics and construction management. In order to effectively integrate the above courses in line with STEM theory, a project called optimal aqueduct (or water pipe) system is designed, as shown in Fig.1. In this project, water is pumped from a tank, flowing through a tube and finally going back to the tank. The students are required to select the pipeline first, then design and produce a support system to hold the tube. It is obligatory that the aqueduct has to pass the irrigation spot A and B. In order word, the orthographic projection of the water tube has to cover A and B. The difficulties of this project are embodied in several aspects. One is that the supporting system can only be made by bamboo papers attached by given glue. No other materials are allowed. Two, other than the stability of the supporting system, the design of aqueduct should also consider the conveyance efficiency, as well as the project cost. That is, the faster water flows in pipe and the lighter the support system is, the better the evaluation for project is.

Figure 1. Schematic diagram of the optimal aqueduct design project (left: top view, right: vertical view). 1-bucket; 2-electronic scale; 3-pump; 4-water inlet; 5-vent-pipe; 6-water pipe; 7-water outlet; 8-supporting system; 9-irrigation spot; 10-valve; 11-platform; 12-platform bracket; 13-inlet bracket; 14-outlet bracket

2.1. Project Objective Design

Optimal aqueduct design (i.e., OAD) project mainly places focus on an object chain to which students would apply mechanics into the engineering reality and use theories flexibly to guide the practice on the premise that they have a good command of mechanics knowledge. Specifically, this project can be disassembled to the following ten sub-objectives: (1). Get familiar with the operating principles of aqueduct; (2). Understand the project requirements for both structure and hydraulics; (3). Decompose the original task into two functional sub-modules: pipeline configuration and structure design; (4). Arrange the pipeline by analyzing the efficiency of water routing in terms of fluid mechanics; (5). Select the structure forms of the supporting system using static analysis knowledge; (6). Conduct numerical simulation for the aqueduct supports to meet both load and deformation requirements; (7). Render 3D CAD models for supporting system and conduit according to the results of mechanical study; (8). Produce and install the bamboo model in accordance with the design layout; (9). Carry out water delivery experiment and verify the consistency between design and reality; (10). Summarize the achievements from design, production and experiment, make a self-reflection and self-
evaluation and finish the project report. The teaching aims decomposed according to STEM are listed in Table. 1.

Table 1. The decomposition of teaching aims in OAD project

| STEM    | Knowledge                                      | Ability                                      |
|---------|------------------------------------------------|----------------------------------------------|
| Science | theoretical mechanics                          | force analysis                               |
|         | material mechanics                             | stress analysis                              |
|         | structural mechanics                           | deformation analysis                         |
|         | fluid mechanics                                | hydraulic analysis                           |
|         | theoretical mechanics                          |                                             |
| Technology | Production and installation of supporting system | experiment design                           |
|         | experimental debugging                         | model installation                           |
|         | data measurement                               | detail adjustment                            |
|         |                                             | material production                          |
|         |                                             |                                             |
| Engineering | scheme selection                               | scheme comparison                           |
|         | pipeline arrangement                           | CAD drawing                                  |
|         | project cost                                   | economic analysis                            |
|         | operation evaluation                           | project evaluation                           |
|         |                                             |                                             |
| Mathematics | data processing                                | data collection                              |
|         | mechanics modelling                            | data processing                              |
|         | numerical analysis                             | mechanical simulation                        |
|         | CAD build-model                                | result analysis                              |

2.2. Project Activity Design

2.2.1. Engineering cognition. In this phase, four learning activities are put forward: project recognition, idea presentation, team organization and task confirmation. At the beginning, the teacher introduces the basic functions of aqueduct by means of pictures or videos collected from the built projects. This would help students fit in a perceptible scene and develop an intuitive knowledge towards the aqueduct. Next, the students are led to think several questions: What are the main characteristics of this project? What are the major and secondary functions of this project to be fulfilled? What methods or potential knowledge would be needed in resolving the problems? On the condition that students have fully understood the challenges of this project, they are encouraged to form teams based on personal willing, interests and specialties. Afterwards, each team is given instructions for this project. On top of those obligatory items, the project is evaluated from four perspectives: weight, efficiency, outlook and report with different weighting factors.

2.2.2. Pipeline arrangement. As the starting point of the project design, this phase requires students to apply the knowledge of fluid mechanics to analyse the rationality and possibility of different layouts. Since the length and material of pipe are given, teacher could direct students to consider the evaluation of conveyance efficiency from the following aspects: (1) the straightness of the pipeline, (2) the angle of curve sections and (3) hydraulic gradient of the pipeline. In view of the convenience of model installation and smoothness of water flow regime, straight pipeline seems more superior in the project although more supporting stands could be needed. In addition, according to hydraulics, the milder turning angle of the pipe has the less energy losses.

2.2.3. Model selection. In this phase, teachers would instruct students to connect the current project with the already built structure forms so that model selection and comparison can be carried out based on theoretical mechanics analysis. The ideal structure should be of material-saving, lightweight, large stiffness and easy constructability. The common structure forms are truss-frame, arch, cable-stayed and suspension. For truss-frame structure, the girders in truss structure only bear axial loadings. It is feasible to adjust the positions of chords and webs appropriately so that the distribution of moments and shears can be adaptable in the structure. For arch structure, the rib in arc structure bears most of compressions. Being spread and transferred to the abutments, such pressure is decomposed to the
component forces horizontally and vertically, making the structure very dependent on the foundation. For cable-stayed structure, the cable pulling out from bridge towers can be regarded as an elastic support, which reduces the bending moment on the cross sections and increases the spanning capability of the main structure. However, the unbalanced stress in the cables may jeopardize the structure stabilization. For the suspension structure, the steel cable comes into a curved shape due to the gravity. Students needs to take the factors, such as the ease of design, behaviour of material and time of production into account so as to make a final decision on their model selection.

2.2.4. Structure analysis. In this phase, students need to construct mechanical models to analyse the selected structure by numerical simulations through which their analytical and computational abilities can be exercised and improved correspondingly. Teachers would remind students of several factors in the modelling. One is the form of the cross section. Two is the treatment of dynamic loading when pumping the water. Three is the instability problem when long rod pieces are under compression. Four is the inertia force produced by directional flow due to altitude differences along the pipeline. The horizontal force would impact the supporting structure heavily. Five is the torsional moment yielded by eccentric force when water is passing through a curved pipe segment. Six is the unbalance loading when water is flowing towards one direction in irrigation and another in drainage. Seven is the structure deformation and resonance problem. To answer those problems, students should review the basic mechanical theories thoroughly. Then, the physical intuitions can be developed to help them find engineering solutions quickly. Moreover, some structure analysis software would be introduced in this phase.

2.2.5. CAD drawing. In this phase, students need to convert the results from mechanical studies to 3D CAD models that would provide the base for production and installation in the next phase. It requires students to have spatial perception ability. With a proper selection of CAD platform, a solid model would be constructed methodically. Several key points should be stressed by teachers prior to their practices. That is, the geometric dimension and spatial location of the model components should be specified clearly. The design for some special parts, such as piece joint and supporting foot needs certain refinement. Modes of labour cooperation and modularization design are preferable as the modelling procedure could be accelerated. The finished model would better be embellished to improve artistic quality. It is nature that students would have new cognitions or different thoughts during this phase once they are inspecting the previous work. Teachers should urge students to modify their model, reapply the mechanical analysis and examine the new designs. Such an iterative process promotes the model to an optimal status piece by piece.

2.2.6. Model production. In this phase, models made of bamboo paper would be produced, installed and tested. It is expected that students’ manipulative ability could be enhanced consequently. Teachers would give students some guidance, as what follows. The first one is about the paper-cutting skill. It can ensure the straightness of the load-carrying component. Two, the method of coiling bamboo paper guarantees the quality of rod piece. A good craftsmanship can prevent rod from being twisted, which is prerequisite to make the actual model be consistent with the theoretical design. The third notable point is about the method of piecing model components. Since each part can only be attached together by glue, the contraction distortion is not completely evitable due to the air-dried effects. However, as long as the shrinkage is uniform from all the directions, the inconsistent deformation induced by strain is able to be prevented mostly. The fourth one is about the reinforcement for foot stalls. Fixed on the platform, the supporting system requires the foot stalls to be stable, light and handy. The last one is with regards to the approach of adjusting model during the instillation. Carefully regulated water tube can not only satisfy the requirement of pipeline smoothness, but also distribute the loads evenly on the supporting system. It usually takes a while for students to acquire proficiency for manufacture crafts. Some individuals are even able to create small tools to facilitate the production once they get the hang of those skills.
2.2.7. Project report. The objective of this phase is to evaluate the students’ learning attitudes and effects so that the problems can be found and teaching methods can be improved. When evaluating students’ project reports, teachers should pay attention to the following subjects. The first one is regarding the project layout because it reveals the students’ ability in the comprehensive engineering thinking. Computation book is another key place since it reflects the correctness of understanding the theories, as well as the capability of applying them. Thirdly, CAD drawing can serve as a scale to measure students’ generalizability from abstract mechanical analysis to concrete 3D solid model. The last aspect should be focused is the description about how model is made because its clarity, logicality and creativity can reflect students’ potentials in the work of construction organization and coordination.

2.3. Project Evaluation Design

It is critical to have objective evaluation criteria for participants to reflect their learning outcomes in terms of STEM PBL mode. Classified by readiness evaluation, formative evaluation and summative evaluation, it intends to inspect the achievements of the expectant learning target. Different from the traditional scalable standards, the flexibility and ununiqueness of the science and industrial activities make the evaluation hard to be measured distinctly. Hence, STEM education cares more about students’ engagement in the study process. That is, process evaluation is of the essence, which should take into account all the information collected in the process of students’ practices, such as discovering problems, suggesting ideas, decomposing steps, describing schemes, drawing drafts, computing data, discussing results, summarizing conclusions and etc. After synthesizing the above events, teachers should have an overall assessment towards student on the extents of understanding the projects, depth of mastering the theories and positivity of joining the activities. Teacher should organize all the teams to carry on personal reflection and peer reviewing so as to complete the form of competency assessment after the project is accomplished, which includes problem solving ability, planning and design ability, production ability, resource and time management ability, teamwork ability and achievement demonstration ability. Being dynamic and consecutive, this process should penetrate into every aforementioned activity. Teachers’ final evaluation would help students reconsider the whole project intension by means of a deep self-analysis and eventually, enhance their self-learning abilities. Table 2 includes some of evaluation methods in this project.

| Evaluation Method          | Evaluation Detail                                                                 |
|----------------------------|-----------------------------------------------------------------------------------|
| Readiness evaluation       | info collection, team organization, material preparation                          |
| Formative evaluation       | note taking, classroom organization, attendance record, independent thinking, question posing, communication, data analysis, working habit |
| Summative evaluation       | model functioning, report writing, project presentation, competency assessment     |

3. Project Implementation

3.1. The implementation process

Under teachers’ instructions, the project is implemented independently. In the following sections, a successful team is selected as an example to present how the group members realize the targets of each phase in line with the thoroughly integrated STEM PBL concept.

3.1.1. Computational fluid dynamics. When students are planning the layout of pipeline, they recognize that the key factor influencing the routing efficiency is the hydraulic gradient because in theory, the gravity drives water to flow as long as the heads of cross sections are varying. By meeting the requirement for irrigation, scenario A, B and C are proposed, as shown in Fig. 2, among which the biggest difference is the way of how water head declines. The evaluation for conveyance efficiency of A, B and C is determined by the time for discharging water from full to empty in water tube. The less time it takes the high efficiency the scenario has.
It can be known from hydraulics that flow in the pipe is unsteady. In order to quantitatively and accurately compare the efficiency among scenario A, B and C, FLOW3D, a CFD program widely used in the industry is introduced to students for hydraulic simulations. Figure 2 compares the flow patterns at the end of 10 seconds for all the scenarios. It is observable that at this instant, much water still remains in the horizontal pipe segment in the scenario A, while B is nearly empty and C has very little water left. From this sense, the routing efficiency of scenario B is the highest, followed by C and A in sequence. Fig. 3(a) compares the water volume variation with respect to time. So scenario A can be excluded for now. Fig. 3(b) demonstrates the history of kinetic energy per unit water volume. It shows that the peak of kinetic energy of scenario B is almost three times than the one of scenario C. As water kinetic energy is associated with the velocity, more kinetic energy must produce larger hydrodynamic pressure. As a result, stronger supporting system is needed to absorb excessive energy. From this perspective, although scenario B has slightly less efficiency, it is more suitable in this project because it simplifies the design and production for the supporting system.
3.1.2. **Computational structure dynamics.** Students decide to select truss frame to realize the long-span structure of this project after considering all other alternatives. The stress status is quite simple under the bending moments. So the truss members can be adjusted in different combinations so that the system loading can be optimized. For example, a proper arrangement of web members can transfer the shear force to the abutment smoothly and gradually. In this sense, the material strength of truss member can be fully utilized for the sake of either bending or shear resistance. In order to reduce the structure weight, the classical quadruple legs of the stand are replaced by a design with symmetry triple legs connected with beams underneath for strengthening.

The quantitative analysis is based on the mechanical modelling in SAP2000, as shown in Fig. 4. In light of simplicity and stability, the supporting legs are all fixed to the platform by screws, which is equivalent to the stiff end constraint condition. Besides, the shape of cross-section of all members is set to be triangle. The major cause is still the attempt of saving material.

![Figure 4. Mechanics modeling for (left): truss-frame long-span structure and (right): tower-type stands with triple legs](image)

3.1.3. **Solid modelling design.** According to the results of mechanical simulations for both hydraulic and structure dynamics, students start solid modelling by AutoCAD. To create a 3D solid model, the model composition needs to be clarified first. Students realize that no matter how sophisticated this model is, it is composed of small and simple components basically. Apart from the direct commands of AutoCAD, another method to generate simple solids is through the stretch and rotation from 2D shapes. Those solids are further combined to a complex one in terms of Boolean operations such as merge, subtraction and intersection. Then the solid models of the whole project can be assembled piece by piece according to their mutual positional and logical relationship. Finally, by modifying the texture, colour and other surface features, the generated 3D model can have a photorealistic result. Fig. 5 shows the solid modelling and the scales for the truss-frame large span structure and tri-legs supporting stand.

![Figure 5. Solid model rendered by AutoCAD for (left): truss-frame long-span structure and (right): tower-type stands with triple legs](image)
3.1.4. Model production. Students find that the production quality of truss member is the key factor to the success of the whole supporting system. From this, some experiences have been gathered to facilitate the model production. In particular, for making a straight rod with consistent triangle cross-section, the bamboo paper needs to be cut three times along steel rule. The first two cuts only leave deep traces or notches and the final cut needs to set the paper apart. Similar to folding mark, the presence of notch is easy for coiling. The parallel notches ensure the consistency of the cross-section and prevent the rod from being twisted (Fig. 8). By this way, only one seam needs to be glued along the rod. This method saves lots of time and reduces the failure possibility in contrast to the conventional method by cutting the paper into three separate pieces and then attaching them one by one.

Joint is also the key for the quality control. Unstable joint would let rod foot have large deformation and impact the stability for the whole system consequently. A simple solution is to make use of some extra glue, which could become rigidified when dried out, to strengthen the weak positions. For the joint between two vertical rods, it can be done by excavating a triangle hole on one rod and inserting the other into the indentation afterwards. Using glue to seal the surrounding gaps would easily strengthen the joint.

3.2. Effect of project implementation

The STEM PBL course was first implemented in extracurricular activities in 2007 and generally embraced by most students. Since then, it has been taken as a practical training (about 2 weeks) in structure design course for the sophomore students for the last 2 years. Approximately 500 students have taken part in this course and they were all given questionnaire survey after the training program was over. The statistics shows that over 95% of students thought this STEM PBL course is much more interesting than the traditional exercise-based studying mode. Over 90% of students participated in the model production, installation and adjustment. Many of them mastered the utilization of at least one set of tool, such as hand drill, sculpting knife and glue gun. 85% of students felt fruitful by comprehensively applying mechanical knowledge to solve the engineering problem in reality. About 65% of students took full participation in the process of data collection, report writing and slides preparation. 50% of students attained proficiency in AutoCAD 3D modelling and 40% of students grasped the basic operation of at least one set of mechanical software, such as Flow3D and SAP2000. Few individuals (i.e., 5 students) even developed their own codes to facilitate the data processing work. In all, it can be concluded that this deep integrated STEM course can effectively support and supplement the traditional mechanics class teaching.

4. Conclusions

Starting from the core ideology of STEM PBL course, this case study has following characteristics \(^{[13]}\): (1). Interdiscipline. This case study integrates mechanics, mathematics, computer and other specialty courses and focus on the employment of correlative knowledge to solve actual problems. (2). Enjoyment. The challenging and life-related substance of the project would motivate the learning initiatives of students from inside. (3) Embodiment. Stressing on the process of students’ practicing and thinking, this case study provides learning experience of creation, design, construction, cooperation and solution based on actual problem. (4). Situationality. The study believes the ultimate teaching has to return and merge theoretical knowledge to the life in which some interesting and challenging questions are settled by students’ ability of transferring knowledge. (5). Cooperativity. The knowledge construction in this study is achieved by mutual aid and inspiration in a group. (6). Designability. Design is the process of cognitive construction, as well as the precondition of learning emergence. Through the process of design, students would truly comprehend the project connotation and solve the open-ended question as a result. (7). Artistry. The artistry of this study means that science and technology can be interpreted from the perspective of engineering and art based on the mathematical elements. (8). Verifiability. The fundamental expectation of this study is that students recognize and understand scientific laws by testing their engineering designs with the experiment in an attitude of prudence. (9). Improvement. New knowledge and technology in the study improve
students’ ability in the fields of information management, modeling construction and data computation, which gives rise to the occurrence of prospective in-depth learning.

In sum, this case study is based on the theory of thoroughly integrated STEM education. Combining the science, mathematics, technology and engineering, it is a new trial to convert the fragmented knowledge and rigid learning process into a comprehensive ability of investigating the real world. It may have reference and significance in many aspects, such as the construction of other STEM curricula, teaching experiments and enrichment of project connotation in the future.

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