

Digital Intelligence-Oriented Industry-Education Collaboration: A General Optimization Approach to the “Smart Ecological Chain” of Transportation Civil Engineering Core Courses

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Abstract: Against the backdrop of the digital transformation of transportation infrastructure and the deepening national strategy for smart transportation, the traditional civil engineering education faces three structural predicaments: lagging knowledge updates, misalignment between practical competence and industrial demands, and fragmentation of teaching resources. This paper proposes the concept of a “smart ecological chain” for course cluster optimization, with digital intelligence as the underlying technological driver and industry-education collaboration as the institutional nexus. An optimization framework is constructed for the core course cluster of transportation-featured civil engineering, covering the full life cycle of “design–construction–maintenance”. The research explores three dimensions: dynamic content updating mechanisms, reconstruction of virtual-real integrated teaching scenarios, and multi-stakeholder collaborative education pathways. A systematic solution characterized by “technology embedding, scenario integration, and ecological symbiosis” is developed. Preliminary practice shows significant improvements in students’ digital intelligence literacy, engineering practice ability, and cross-system thinking, providing a replicable reference for the transformation and upgrading of civil engineering programs in industry-characteristic universities.

Keywords: Digital Intelligence-Driven; Industry-education Collaboration; Transportation-featured Civil Engineering; Course Cluster; Smart Ecological Chain; Teaching Reform.

1. Introduction

The current situation of China transportation infrastructure building is at the crucial stage of shifting between scale and quality expansion and smart empowering. The National Transportation Work Conference in 2024 directly stated that it is necessary to expedite the establishment of smart transportation, which would be possible through the close integration of such emerging information technologies as BIM, GIS, IoT, and artificial intelligence with all processes within the sphere of transportation engineering [1]. Such a change places new demands on the training of civil engineering professionals: civil engineers of the future should not only have a sound understanding of mechanics and structural engineering, but also acquire inter-disciplinary skills in data perception, intelligent analysis and system decision-making [2].

Nevertheless, there has been a clear lack of response to this change in traditional civil engineering education. Graduates are confronted by the embarrassing scenario of not knowing how to apply information, comprehend smart processes, or be aware of cooperative environments when they start working in the transportation construction industry due to the slow renewal of curriculums, dominance of theoretical lectures, and weak ties between industry and education [3]. The question of how to restructure the curriculum system to keep up with industrial transformation has thus emerged as one of the most pressing issues that transportation-oriented civil engineering programs should deal with directly [4].

In the context of the conceptual framework of the so-called smart ecological chain, this paper discusses an overall

optimization strategy to the core course cluster stimulated by the digitization of intelligence and the cooperation between industries and education, which will provide a reform plan that is theoretically consistent and practically implementable in the industry-oriented institution.

2. Realistic Examination: Structural Dilemmas of the Core Course Cluster

The main courses in the core course cluster of transportation-themed civil engineering are usually Civil Engineering Materials, Structural Mechanics, Foundation Engineering, Subgrade and Pavement Engineering, Bridge Engineering, Tunnel and Underground Engineering, and Construction Organization and Management, with additional characteristic courses such as Introduction to Traffic Engineering and Road Survey and Design [5]. Although this is a curriculum that has remained unchanged over several years of practice, it has also developed three inherent contradictions.

2.1. The Time Lag Between Knowledge Updating and Industrial Digital Transformation.

The vast majority of courses continues to focus on conventional design processes and construction technologies, with newer methods like BIM-based forward design, operational and maintenance of digital twins, and AI-assisted inspection only rarely being mentioned at lectures or elective courses [6]. When finishing their core curriculum, students do

not have much knowledge about smart construction sites, automated monitoring, and health management of transport systems. This mismatch between the content taught and what is required has a direct negative impact on the correspondence between professional training and industrial needs [7].

2.2. The Tension Between Rigid Course Boundaries and the Holistic Nature of Engineering Scenarios

Structural Mechanics is more theoretical derivation-oriented; Subgrade and Pavement is more material oriented and mechanically responsive; Bridge Engineering is focused on structural details and calculations; and Construction Management focuses on the organizational processes. These courses are still relatively separate with respect to their teaching aims, content systems and assessment processes, and have not been vertically integrated to reflect real-life transportation engineering tasks [8]. It is hard for students to build a whole-life-cycle cognition model - survey and design, construction and maintenance - much less mobilizing multidisciplinary knowledge to resolve complicated engineering issues [9].

2.3. The Gap Between Superficial Industry-Education Cooperation and Deep Competency Development

The current university-industry cooperation is largely restricted to conventional modes like the guest lecture of an enterprise expert and student internships with inadequate detail [10]. Enterprise has a small role in shaping courses content, teaching material creation, or testing competencies. In turn, universities have difficulty converting real world information, cases and challenges on the construction site into educational materials. The segregation between education and industry is still very strong [11].

3. Theoretical Connotation of “Smart Ecological Chain” and Course Cluster Optimization Framework

In order to solve these dilemmas, the current research presents the concept of the smart ecological chain as an attempt to move out of the conventional way of making changes in one course towards a systematic ecological reconstruction [8].

The concept of the smart ecological chain can be defined in three levels of meaning. Firstly, smart indicates the digitization-intelligence revolution of the course material embedding BIM, digital twins, intelligent sensing, big data analytics, and other tool-based information into the main courses so that students can automatically gain digital literacy in the process of learning their profession [6]. Secondly, ecological means the natural inter-linkage and co-evolution of all the components of the course cluster, the elimination of the course borders and the establishment of the system of content integration throughout the entire life cycle of transportation infrastructure [12]. Thirdly, chain denotes the intense interdependence between industry and education which converts real-world requirements, information and situations into teaching materials and ultimately creates a positive cycle of talent development and industry growth [9].

In this idea, we develop a model of optimization as a one-core-three-wings structure. The center is an entire-life-cycle

competency diagram of the transportation infrastructure with five main capability modules: planning and survey, structural design, construction, inspection and monitoring, and maintenance [5]. Three wings are the layer of digital-intelligence technology embedding, the layer of virtual-real integration scenario, and the layer of industry-education collaboration mechanism that support each other and stimulate each other [10].

4. Digital Intelligence-Driven Course Content Restructuring and Scenario Innovation

The fundamental lever of the creation of the smart ecological chain is content restructuring. We are going to review and rebuild each core course in a systematic way based on the competency map.

Theoretical teaching modules have every principal course complemented by a special unit of the so-called digital intelligence applications. For instance, in Civil Engineering Materials, there is also a part of machine learning-based material property prediction, with the students working on strength prediction models through open data [6]; in Subgrade and Pavement Engineering, students learn about intelligent compaction control systems and long-term pavement performance monitoring data analysis; in Bridge Engineering, students learn about BIM forward design processes and parametric modeling activities [7]; and in Tunnel and Underground Engineering, students study case studies on the application of IoT-based real-time deformation monitoring and early warning during construction [1]. The new parts are not just simple superimpositions but follow a sequential perception-analysis-decision logic across various courses, which forms a gradation of competency development [4].

During practical teaching module, our emphasis is laid upon the construction of the so-called virtual-real integrated learning conditions. We have created projects like Full-process virtual simulation of smart construction of transport infrastructure and Digital twin-based bridge health monitoring simulation system with a virtual simulation experiment platform that allows students to experience all the steps of the smart construction and intelligent maintenance process in a virtual environment [13]. At the same time, we have built remote observation and training facilities on smart construction sites involving roads, bridges, and tunnels where students can see in real time what is going on in the area of intelligent equipment operation, data collection and control process, closing the gap between theory in the classroom and its application in engineering [12].

Besides, course assessments are being changed to provide more weight on the ability to model data, smart use of tools, and overall design projects, a close loop of assessment-driven learning is provided. Initial teaching statistics demonstrate that students in the reformed model achieve much higher results in problem decomposition, tool selection, and data interpretation compared to their peers in traditional cohorts [14].

5. Mechanism Innovation of Industry-Education Collaboration and Construction of Ecological Chain

Industry-education collaboration is the most important

institutional assurance in transforming the idea of the smart ecological chain into practice. This paper goes beyond the surface level of cooperation and develops a three-stage collaborative mechanism: demand alignment - resource integration - shared evaluation.

The demand alignment mechanism is advanced to the level of curriculum planning. The Course Cluster Construction Steering Committee is formed with the participation of enterprise chief engineers, university lecturers, and industry specialists. Every year a survey of the competencies needed by the digital-intelligence staff takes place, which results in a dynamically changing list of competencies that are required, and this directly forms the basis of the changes in the course materials. As an example, due to the recent need to have interdisciplinary skills in novel contexts like smart prefabrication yards and unmanned paving, we quickly included a section on the optimization of intelligent construction organization in the Construction Organization and Management course [6].

The mechanism of integration of resources is aimed at co-construction and sharing of teaching resources. The university-industry joint digital resource library has been established along with some of the best transportation construction companies in which de-identified typical engineering cases, intelligent construction method videos, and monitoring datasets are converted into learning materials. Course designers packages that are based on real data are developed by enterprise engineers and faculty members together whereby students can directly apply settlement monitoring data, strain measurement data among other things in their design and analyses thereby increasing authenticity and a lot of challenge to the tasks given.

Shared evaluation mechanism is represented by a multi-stakeholder academic evaluation system. Enterprise mentors engage in topic review, process guidance, and outcome evaluation during extensive practice sessions like course design and graduation design. There are some courses that experiment a project-based learning approach of enterprise-proposed problems - joint teacher-student solution - on-site verification whereby the students go through all the stages of the scheme design until the analysis of the data within the framework of actual engineering limitations and enterprise mentors conduct all-embracing evaluations in terms of feasibility, economy, and innovation.

The joint action of such mechanisms has first produced a good ecological circle of "teaching-industry-research"; the demand of industries prompts the improvement of teaching, the results of teaching are reflected in the talent pool of enterprises, and cooperation with research strengthens the relationship between universities and industries, all of which support each other.

6. Practical Effectiveness and Future Prospects

The suggested reform has been introduced in steps to the undergraduate students of civil engineering of batches 2022-2025 in a transportation based university. Initial tracking assessment indicates that in terms of digital intelligence literacy, the pass rate of students in the reformed curriculum on specialized test including BIM modelling and intelligent monitoring data analysis is about 20 percentage points higher than the traditional cohort. In the discipline competitions, including the National College Student Structural Design

Competition and the Transportation Science and Technology Competition, students have been well appreciated by judges in their ability to apply digital tools when solving complicated engineering problems and there has been a significant improvement in their awards and rankings.

Even more importantly, student advancement in full-life-cycle thinking and cross-course knowledge integration has been significant. Graduation design has seen a growing proportion of students actively embracing BIM-based finite element analysis processes and trying to bring information continuity between the design, construction, and maintenance phases into their solutions. The change indicates that the systemic thinking promoted by the concept of the smart ecological chain is being absorbed as a mental habit in students.

With regard to the future, there is still much work that needs to be done in the area of the development of the so-called smart ecological chain in the following directions: firstly, to improve the interaction between data interfaces and knowledge links between the courses in the cluster, create more intelligent learning analytics tools, and reach accurate capability profiling and individualised learning path recommendations; secondly, to increase the width and length of industry-education cooperation, research substantive operational models like joint creation of a Smart Transportation Industry College and create an integrated collaborative educational system of both admission and employment; and thirdly, to spread the idea behind smart ecological chain philosophy to other engineering fields in the university, creating a scalable systemic reform solution.

7. Summary

The digitalization of transportation-based civil engineering is not just an additive process of adding courses and digital intelligence, but rather a structural change that entails changing knowledge systems, re-engineering the model of teaching, and restructuring educational processes. The optimization plan of the smart ecological chain course cluster presented in the paper, which is led by the digital intelligence as the technological engine and backed by the industry-education cooperation as the institutional infrastructure, has systematically examined the dynamic restructuring of content, the integration of virtual-real scenarios, and the multi-stakeholder cooperation mechanisms. Initial application has shown that this scheme is feasible and effective in addressing changes in industries and improving the quality of talent cultivation. It is only by long-term deep interlocking and dynamic adjustment between professional education and industrial development that transportation-based civil engineering programs will be able to revive and prosper in the digital intelligence age.

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