

Developing a Pace-Layered Agile Curriculum Architecture for Graduate Engineering Education: A Practice-Informed Case Study

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Developing a Pace-Layered Agile Curriculum Architecture for Graduate Engineering Education: A Practice-Informed Case Study

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Abstract The process of industrial digitization and intelligence is accelerating, which poses more and more challenges to the engineering education system that traditionally relies on a relatively stable curriculum structure and a long revision cycle. This study explores how curriculum architecture can be reorganized to better adapt to different knowledge update rhythms in the era of digital industry. Based on Pace Layering theory, this paper develops a practice-informed pace-layered agile curriculum architecture through a case study of graduate engineering education in the Industrial Machine Tool domain at Huazhong University of Science and Technology (HUST). By examining the characteristics of 10 core courses, including their knowledge foundations, interdisciplinary connections, and relationships with industrial practice, the study proposes three curriculum layers: the stable substrate, the integration nexus, and the agile interface. The stable substrate preserves foundational theoretical knowledge, the integration nexus facilitates interdisciplinary translation, and the agile interface connects curriculum development with evolving industrial technologies and engineering practices. *Engineering Ethics* is positioned as a cross-layer value anchor that supports responsible engineering development. Furthermore, the study discusses three digital education mechanisms that support curriculum agility: knowledge modularization, university–industry digital interfaces, and feedback-driven curriculum renewal. Rather than suggesting that all curriculum components should be updated rapidly, this study argues that curriculum agility requires differentiated update rhythms across knowledge domains. The proposed curriculum architecture provides a practice-informed perspective for understanding and designing adaptive engineering curricula in the context of digital transformation.

Keywords: layered agile architecture, university–enterprise collaboration, knowledge lag, Industrial Machine Tool

1.Introduction

1.1 National strategy and the practical need for digital and intelligent engineering education

In the context of Industry 4.0 and the broader transformation of Chinese manufacturing, outstanding engineers have become an important talent base for high-level technological self-reliance and modernization (Du, 2024). The cultivation of outstanding engineers is regarded as a national core task (Lin, 2022). At present, the field of Industrial Machine Tool is undergoing rapid digital and intelligent changes, and technological development is accelerating rapidly. For example, digital twin technology makes physical systems and virtual simulations more closely linked, and industrial big data is also changing the way of decision-making: in the past, it relied on experience, and now it relies more on data and intelligent analysis.

This change puts forward new requirements for the knowledge structure of engineering talents. However, the current engineering education system has changed slowly, still focusing on pure science education, and the discipline barriers are also obvious. Therefore, talent training often fails to keep up with technological development (Wu et al., 2017). For example, industrial technologies relevant to machine tools—such as multi-axis machining protocols and digital-twin-related specifications—are evolving at an accelerating pace under Industrie 4.0 (Kagermann et al., 2013; Zhong et al., 2017), whereas university courses often take three to five years to move from textbook compilation to classroom delivery. This knowledge lag means that acquired knowledge may no longer fully correspond to current industrial practices.

1.2 Core tensions in traditional engineering education

The problems faced by traditional engineering education are not only outdated content. The deeper contradiction lies in how to organize and govern the curriculum at the institutional level. Specifically, there are three aspects of tension.

One is the timing problem. The revision of university courses is usually based on an administrative cycle, with a comprehensive update every three to five years. However, in the digital industry, technology and cases are updated much faster than the development of basic theories, and a unified timetable is difficult to cope with this difference. For numerical control programming, students may spend a lot of time learning a set of standards, and the industry has changed to a new version when they graduate. This lag is hard to ignore.

The other is an interdisciplinary structural problem. Most of the courses are divided by departments. Mechanical engineering, control engineering and information technology are separated from each other, and there is no mechanism to connect them in series. However, many technical challenges in modern digital manufacturing, such as thermal error compensation of five-axis linkage and chatter suppression of complex surface machining, involve mechanical dynamics, signal processing and intelligent control. These fields do not cross each other in the course, and it is difficult for students to integrate knowledge when they really face engineering tasks.

There is also the issue of cooperation between universities and industry. Traditionally, corporate participation is mostly factory visits, short-term internships or occasional lectures, and is often maintained by teachers' personal relationships. This cooperation is unstable and limited in scope. Also, enterprise engineers have little voice in course content design. They also lack effective channels to turn

their feedback into timely course updates. As a result, universities and enterprises do not have a mechanism that can adjust and correct itself. This makes it difficult to solve knowledge lag at its root.

1.3 Research objectives and contributions

In view of the challenges discussed above, this study aims to develop a practice-informed curriculum architecture for graduate engineering education under the background of industrial digital transformation.

Specifically, this study has three objectives. Firstly, it seeks to explore how different types of engineering knowledge can be organized according to their different update rhythms. Secondly, based on the practice of curriculum reconstruction in the field of Industrial Machine Tool, a pace-layered curriculum architecture is constructed. Thirdly, it discusses the digital and organizational mechanisms that may support continuous curriculum renewal and university–industry knowledge exchange.

There are also three contributions of this study. First it extends the application of Pace Layering theory by exploring its relevance to engineering curriculum architecture design by introducing the time perspective of course organization. Second, it provides a practice-based curriculum architecture for understanding how stability and agility coexist in the engineering education system. Third, it provides practical implications for universities seeking to redesign their courses under the conditions of rapid technological change.

2. Literature Review

2.1 Digital and intelligent transformation of engineering education

In recent years, the development of digital industrial technology has continued to push engineering education reform. With the rapid update of artificial intelligence, the industrial internet, digital twins, and intelligent manufacturing, the speed of knowledge renewal in engineering has also increased greatly (Zhong et al., 2017; Tao et al., 2019). Traditional engineering education builds courses around a relatively stable knowledge system. Its main features are stable knowledge, clear discipline boundaries, and long update cycles (Lattuca & Stark, 2009; Kamp, 2016). However, engineering practice in the digital industrial age places more stress on cross-disciplinary teamwork, platform-based operation, and data-driven decision-making. In this context, traditional course systems can no longer fully meet the needs of complex engineering work and compound talent training (Borrego & Henderson, 2014; National Academy of Engineering, 2004).

Current engineering education reform around course construction faces three main problems. First, the speed of course updates does not match the speed of industrial technology updates (Kamp, 2016). Second, disciplines are not well integrated. Courses are still arranged by single disciplines, and there is not enough cross-disciplinary integration around real engineering problems (Graham, 2018). Third, enterprise participation is not deep enough. Fragmented university–industry cooperation mechanisms limit the systematic flow of industrial knowledge into teaching (Healy et al., 2014). These problems together make knowledge lag more serious. In China, Lin Jian also pointed out that rebuilding course systems for future industries has become an urgent task in the development of new engineering education (Lin, 2017).

However, the challenges of digital transformation are not limited to introducing emerging technologies into existing courses. More fundamentally, it needs to rethink how different types of

engineering knowledge are organized, maintained, and updated over time. Some knowledge components, such as basic theories and mathematical principles, have relatively long validity periods, while other knowledge components, such as industrial standards, digital tools, and application-oriented technologies, need to be updated more frequently. Therefore, curriculum reform in the digital age not only needs the expansion of content, but also needs a new perspective of curriculum architecture (Crawley et al., 2014).

2.2 Curriculum agility and knowledge lag

How to update university courses has always been a recognized contradiction—a problem often referred to as the knowledge lag dilemma. (Kamp, 2016; Lattuca & Stark, 2009). The problem is not individual teachers, but the bottleneck of the system, a structural constraint widely acknowledged by engineering faculty and institutional administrators alike (Besterfield-Sacre et al., 2014): a new syllabus or curriculum construction has to go through several rounds of discussion, certification and administrative approval processes to enter the classroom. When this process is completed, the technical situation that the course originally intended to reflect may have changed (Prados et al., 2005). The international community is paying more and more attention to this structural problem. The concept of curriculum agility has increasingly become a design goal and research agenda in international engineering education (Malmqvist et al., 2020), building on earlier discussions of the dual academic-professional nature of engineering curricula (Edström, 2017). Malmqvist et al. (2020) reflect several working principles from early practice: meaningful stakeholder participation, governance reform that shortens the approval chain, faster collective decision-making, and modular curriculum architecture that allows frequent local modifications without compromising the overall program.

Digital tools also add strength to these efforts at the practical level. Inspired by agile practices in software engineering, iterative workflows can provide a common rhythm for teaching teams to co-develop and update learning materials (Rico & Sayani, 2009; Stober & Hansmann, 2010). Knowledge graph-based approaches can further enable systematic identification of outdated content and knowledge gaps, supporting modular and targeted curriculum renewal.

Although curriculum agility emphasizes flexibility, stakeholder participation and continuous improvement, existing discussions often focus on the ability of the curriculum to respond quickly to changes. It pays less attention to whether different course components should adopt the same update rhythm. However, in engineering education, basic theory, interdisciplinary methods, and industrial practice have different knowledge evolution models. Treating them with a unified update cycle will either shake the essential knowledge or delay the integration of emerging practices.

2.3 Pace Layering theory and adaptive system design

The pace layering framework draws on a broader ecological view of universities as open systems that continuously interact with external environments (Barnett, 2017). Within this framework, different components of the curriculum evolve at different speeds, forming a layered structure that balances stability and responsiveness.

The theory of spatial stratification proposed by Stewart Brand was originally used to explain the difference in the rate of change in various parts of a complex system. The core is that a system to be both stable and adaptive often requires several different levels of rhythm: the slow layer provides

stability, and the fast layer responds to changes in the external environment (Brand, 1999; Brand, 1994). Later, the core idea of differentiated change rhythms was extended to organizational management and information systems, providing a conceptual basis for analyzing the temporal dynamics of complex systems. However, applications of Pace Layering theory in engineering curriculum design remain limited. Although existing studies have noticed that different types of knowledge in the curriculum are updated at different speeds, few studies have reorganized curriculum structures explicitly around these temporal patterns (Brand, 1999).

Applying Pace Layering theory to engineering curriculum architecture design can help us understand why different courses need different update rhythms, and also provide new ideas for dynamic adjustment of courses in the digital age. Based on this theory, postgraduate engineering education can combine stability and flexibility—the basic theory is placed at the bottom and the update is slower; cutting-edge technology and enterprise projects on the upper level, updating faster. In this way, it can not only maintain a solid theoretical foundation, but also keep up with the changes in industrial technology (Brand, 1999).

2.4 Positioning Pace Layering within Existing Curriculum Reform Frameworks

The existing engineering curriculum reform framework provides an important basis for curriculum design. However, they mainly focus on alliance, capacity development and learning process. Outcome-based education(OBE) emphasizes the relationship between learning outcomes and educational activities, while CDIO focuses on integrating engineering practice into curriculum design (Crawley et al., 2014; Biggs & Tang, 2011). The course map provides a visualization of the relationship between knowledge and ability. However, these frameworks generally assume that curriculum components are updated through relatively similar organizational processes. They pay less attention to the fact that different knowledge components may have fundamentally different update rhythms.

Pace Layering complements these methods by introducing a temporal perspective. It does not determine which knowledge should replace the existing curriculum elements, but explains how different knowledge components should maintain stability or flexibility according to their evolutionary characteristics. Therefore, the contribution of Pace Layering is to provide a perspective of time governance for curriculum renewal.

3. Case Context and Framework Development Approach

3.1 Research approach

This study adopts a practice-informed case study approach to develop a pace-layered curriculum architecture for graduate engineering education. The purpose of the study is not to statistically evaluate the applicability of a curriculum intervention, but to synthesize curriculum reconstruction practices and develop an analytical framework that explains how different knowledge components may be organized according to their update rhythms.

The case of engineering education in the field of Industrial Machine Tool at Huazhong University of Science and Technology is selected because it represents a typical situation in which stable theoretical knowledge, interdisciplinary technology integration and rapid development of industrial practice coexist. By examining the practice of curriculum development, curriculum structure and industry-

university cooperation mechanisms, this study develops an interpretive framework for curriculum agility in the digital era.

3.2 Case context

Materials examined in this case include the construction of 10 core courses (as shown in Table 1) in the Industrial Machine Tool domain at HUST, including three main categories. Syllabus materials record basic information such as course credit, positioning, teaching objectives and module setting, supporting classification of knowledge attributes and hierarchical division. Digital platform resources reflect online teaching operation and modular content updating mode. University-enterprise cooperation documents analyze industrial participation degree and knowledge source composition, exploring the correlation between cooperative mode and curriculum iteration rhythm. Multi-source materials provide contextual evidence and reduce dependence on a single information source.

Table 1. List of Core Courses

Course	Hour	Credit
<i>Numerical Methods and Computational Mechanics</i>	32	2
<i>Dynamic Analysis and Control of Mechatronic Systems</i>	32	2
<i>Advanced Engineering Materials</i>	32	2
<i>Advanced Manufacturing Engineering</i>	64	4
<i>Control and Intelligence Engineering</i>	32	2
<i>Digital Signal Processing Theory and Practice</i>	48	3
<i>Optimization Design Methods and Practice</i>	32	2
<i>Numerical Control Technology and Practice</i>	32	2
<i>Technology and Practices of Manufacturing Processes</i>	32	2
<i>Engineering Ethics</i>	16	1

3.3 Framework construction process

This study is based on Stewart Brand's spatial stratification theory. According to this theory, complex systems are composed of layers with different speeds of change : the slow layer provides stability, and the fast layer helps the system adapt to external changes. Applying this theory to engineering education can explain why different courses should not follow a unified update cycle, but should adopt different organization and update methods according to the type of knowledge, application scenarios, and connection with industrial practice. In the context of the digital industry, the key issue of the engineering curriculum system is not whether a course should be updated, but whether different types of knowledge have different rhythms of change. Basic theoretical knowledge is relatively stable, which can provide long-term support for students ' later learning and future development. Interdisciplinary knowledge is between theory and engineering practice, which needs to integrate concepts, methods, and tools in different fields. Industrial practice knowledge is directly linked to enterprise technical standards, engineering projects and production sites, and often changes rapidly. Based on this perspective, this paper constructs a curriculum analysis framework from three dimensions: knowledge half-life, explicit knowledge source and teaching subject structure.

The first dimension is the half-life of knowledge, which measures the speed of change in the core knowledge of a course. As a course based on mathematical model, basic theory and control equation,

the core knowledge is stable and the update is slow. Courses that rely on digital manufacturing systems, intelligent algorithms, and enterprise cases are more affected by technology and industry and are updated faster. The knowledge half-life here is not an accurate time indicator, but an analytical concept used to compare the differences in the speed of updating different courses.

The second dimension is the explicit knowledge source, which focuses on the logic of curriculum knowledge. Some courses are based on mature subject knowledge (such as numerical methods, computational mechanics); some focus on interdisciplinary issues (such as digital signal processing, intelligent control); some come directly from industrial practice (such as numerical control technology, manufacturing process training). Different sources lead to different update drivers: discipline-led courses follow the development of disciplines, interdisciplinary courses rely on the integration of different fields, and practice-led courses are directly driven by technical standards, enterprise needs and engineering scenarios.

The third dimension is the teaching subject structure, which focuses on who leads the construction and renewal of the curriculum. The partial theoretical courses are mainly for college teachers. Interdisciplinary courses need the cooperation of teachers with different professional backgrounds. Practical courses are inseparable from the participation of enterprise engineers, industry mentors and real projects. The teaching subject structure not only defines the dominant force of the curriculum, but also reflects the relationship between the curriculum renewal and the external industrial system.

Based on these three analytical dimensions, course characteristics were identified and used to determine their corresponding curriculum layers. The classification criteria are summarized in Table 2.

Table 2. Course classification criteria based on the three analytical dimensions

Analytical dimension	Classification criteria	Typical characteristics	Evidence sources
Knowledge half-life	Stable knowledge	Fundamental theories, mathematical principles, and basic engineering concepts with relatively long validity cycles	Course syllabus, teaching objectives, textbook contents
	Intermediate-update knowledge	Interdisciplinary methods and integrated engineering approaches requiring periodic adjustment	Course modules, interdisciplinary teaching materials
	Rapid-update knowledge	Emerging technologies, industrial standards, engineering tools, and practical applications requiring continuous renewal	Enterprise materials, industrial cases, technical documents
Explicit knowledge source	Discipline-driven knowledge	Mainly derived from established academic theories and disciplinary knowledge systems	Academic curriculum documents, disciplinary frameworks
	Interdisciplinary integration knowledge	Generated through interaction among multiple engineering fields and knowledge domains	Joint courses, interdisciplinary projects
	Industry-driven knowledge	Originates from industrial practice, engineering problems, and technological innovation	Enterprise cooperation documents, engineering projects
Teaching subject structure	Academic faculty-led renewal	Curriculum maintenance mainly conducted by university teachers and academic teams	Course development records, faculty discussions

Analytical dimension	Classification criteria	Typical characteristics	Evidence sources
	Collaborative renewal	Curriculum improvement involving multiple disciplines or teaching teams	Interdisciplinary collaboration records
	Industry-connected renewal	Curriculum updates supported by enterprise experts and industrial feedback mechanisms	University–enterprise cooperation materials

The classification process does not assume that all courses within the same discipline should follow the same update mechanism. On the contrary, the curriculum is analyzed according to the explicit characteristics reflected by the three dimensions. When the three analysis dimensions show consistent characteristics, the curriculum is directly assigned to the corresponding layer. When different dimensions present different hierarchical characteristics, the dominant characteristics of knowledge evolution are considered, and the classification is further discussed based on the curriculum situation.

Accordingly, three curriculum levels are determined:

- (1) The stable substrate, representing the relatively stable theoretical and methodological basis ;
- (2) The integration nexus, representing interdisciplinary knowledge translation and integration ;
- (3) The agile interface, which represents the exchange of rapidly changing industrial knowledge and external knowledge.

3.4 Course layering

This study breaks the core courses in the key field into relatively independent functional modules. In the construction of the Industrial Machine Tool curriculum, the program uses a pattern of one leading university, multi-university collaboration, and university-enterprise cooperation. Huazhong University of Science and Technology leads the design of the curriculum plan. Several universities work together to share resources and complement each other's strengths. At the same time, the program works with Wuhan Huazhong Numerical Control Co., Ltd. (HNC) and China General Technology Group. These companies provide practice teaching sites and equipment. They also invite enterprise mentors to take part in course design and practice teaching.

Based on the three-dimensional framework of knowledge half-life, dominant knowledge source, and teaching subject structure, the 10 core courses are divided into three layers with different speeds. When the three dimensions point to the same layer, the course is placed directly in that layer. When two dimensions point to the same layer, the course is placed according to the dominant dimension. When the three dimensions are scattered, experts discuss and decide the layer. Course classification was not determined by the presence of emerging technologies alone, but by the dominant knowledge-update mechanism of the course. The three layers are the stable substrate, which changes slowly; the integration nexus, which changes at a medium speed; and the agile interface, which changes quickly. A value anchor runs through the whole system. See Figure 1.

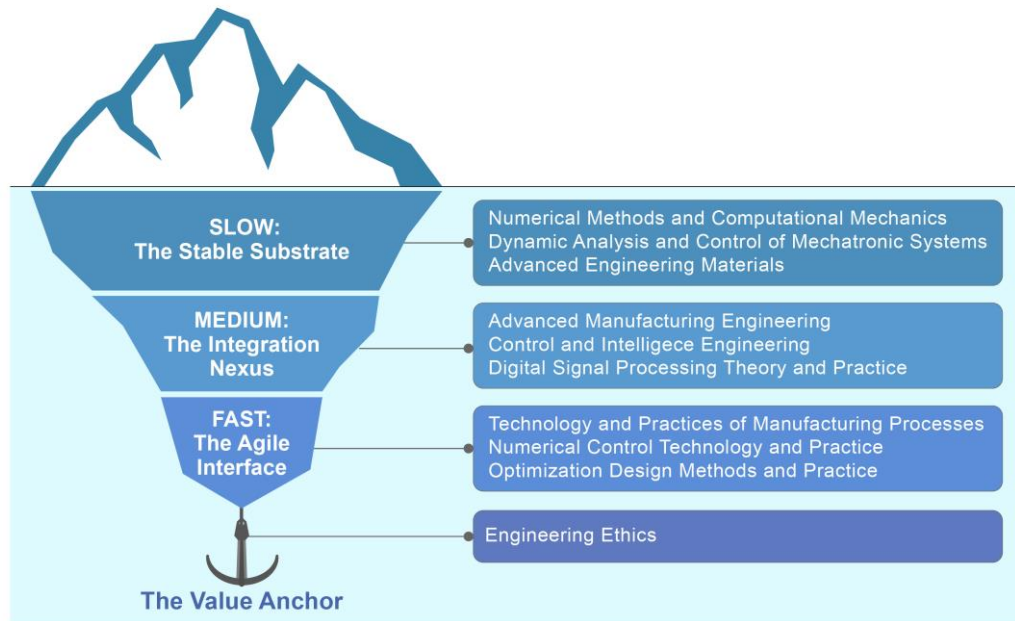


Figure 1. Pace layers of the layered agile curriculum system.

After the courses are placed into the three layers, the structure helps show how digital mechanisms support the decoupling of each layer. In this way, the curriculum can keep a strong theoretical base while responding quickly to industrial needs. See Table 3.

Table 3. Layered agile curriculum architecture

Curriculum Layer	Course Title	Attributes	Agile and Digital Mechanism
Layer 1: Stable Substrate	<i>Numerical Methods and Computational Mechanics</i>	Theory-based	Algorithmic foundation. The focus moves from manual derivation to methods for solving main equations in engineering numerical simulation. It improves engineering simulation ability and provides mathematical support for digital twin modeling.
	<i>Dynamic Analysis and Control of Mechatronic Systems</i>	Theory-based	System coupling. The shift toward mechatronic coupling is a key basis for modeling high-precision numerical control servo systems.
	<i>Advanced Engineering Materials</i>	Theory-based	Data-driven design. The course adds materials informatics and performance databases. It links material properties with design parameters.
Layer 2: Integration Nexus	<i>Digital Signal Processing Theory and Practice</i>	Theory and experiment	Signal-to-data. The course covers the design and use of signal processing software systems. It connects physical sensors with industrial big data analysis.
	<i>Control and Intelligence Engineering</i>	Theory and experiment	AI integration. The course combines classical control theory with intelligent algorithms, such as neural networks, to support intelligent control in complex

Curriculum Layer	Course Title	Attributes	Agile and Digital Mechanism
Layer 3: Agile Interface	<i>Advanced Manufacturing Engineering</i>	Theory and experiment	machining settings. Process integration. The course covers additive manufacturing, such as 3D printing; subtractive manufacturing, such as precision machining; high-performance and digital manufacturing; and the use of digital technology, robots, and artificial intelligence in intelligent manufacturing. It breaks the separation of traditional process knowledge.
	<i>Numerical Control Technology and Practice</i>	University-enterprise co-built	Protocol-driven design. The course works as a modular container. It can directly include the latest industrial instruction sets, such as those from Huazhong Numerical Control. The content updates with industry protocols.
	<i>Technology and Practices of Manufacturing Processes</i>	University-enterprise co-built	Case injection. The course is built with China General Technology Group. It builds a collaborative teaching system between the university and the enterprise. It combines classroom teaching with enterprise project practice and focuses on solving key problems in front-line production.
	<i>Optimization Design Methods and Practice</i>	University-enterprise co-built	Tool-based learning. The course organizes engineering practice cases on optimization design methods. It uses optimization design theory, computer programming, and numerical simulation tools to improve design optimization ability.
Value Anchor	<i>Engineering Ethics</i>	Value guidance	Digital responsibility. In the industrial internet age, the course improves engineers' ethical awareness and sense of responsibility. Enterprises provide cases on digitalization plus machine tools and new-generation AI plus machine tools. Students discuss how engineers can make ethical decisions in the digital age.

4. Formation and Operation of the Layered Agile Curriculum Architecture

4.1 Stable Substrate: the theoretical base for digital industry

The stable substrate is at the bottom of the curriculum architecture. It is mainly made up of theory courses with a long knowledge half-life. These include *Numerical Methods and Computational Mechanics*, *Dynamic Analysis and Control of Mechatronic Systems*, and *Advanced Engineering Materials*. Compared with traditional courses, this layer no longer focuses only on formula derivation and theory teaching. It gives more attention to algorithmic thinking, mathematical modeling, and digital expression. In this sense, the stable substrate builds the “digital cognitive base” for engineers in the digital industrial age. The numerical solution of partial differential equations used in digital twin modeling, and the dynamic modeling of mechatronic systems, both form an important base for students to understand and enter the digital industrial world.

At this level, the classical laws of mathematics and physics are reorganized as the basis for digital engineering practice. Taking *Numerical Methods and Computational Mechanics* as an example, the course focuses on the algorithmic realization of control equations from manual formula derivation, covering basic problems such as linear algebraic equations, ordinary differential equations, and partial differential equations. Taking the finite element method as the core, it introduces its application in statics, dynamics, heat transfer and other fields.

The course also adds topics such as topology optimization. This helps students understand the numerical logic behind structural design and performance improvement. It helps students in the field of Industrial Machine Tool master the basic principles, implementation paths, and programming methods of numerical methods commonly used in engineering simulation software. It also provides the mathematical support needed for later study of digital twin technology. *Dynamic Analysis and Control of Mechatronic Systems* focuses on dynamic modeling and control analysis of mechatronic coupling systems. It provides a theoretical basis for system modeling in digital twins. *Advanced Engineering Materials* no longer only explains material properties in a static way. It also includes materials informatics and turns material properties into parameterized inputs for digital design databases.

The role of the stable substrate is to maintain the basic stability of the curriculum system. No matter how upper-layer courses update with industrial change, the governing equations, numerical logic, and basic modeling methods in this layer remain the slow variables in engineering knowledge. But this does not mean that foundation courses do not change. In fact, their content and focus have already been rebuilt. They no longer only teach traditional theory. Through algorithmic, modeling-based, and digital expression of theory, they give students deeper support for using digital tools, understanding digital systems, and joining complex engineering practice.

This shift toward digital delivery is also supported by empirical evidence. Matzakos and Kalogiannakis (2018) report high satisfaction among first-year engineering students in a digitally supported distance mathematics program. They provide evidence that digitally supported foundational learning can complement traditional engineering education. These findings support the stable substrate's move from purely theoretical instruction to algorithmic and digitally mediated foundational learning.

4.2 Integration Nexus: cross-disciplinary knowledge integration and digital logic building

The integration nexus is located between the stable substrate and the application practice layer, which is responsible for connecting basic theory and engineering application. It mainly includes *Advanced Manufacturing Engineering*, *Control and Intelligence Engineering* and *Digital Signal Processing Theory and Practice*. The goal is to break the boundary between mechanical engineering and information science, and help students translate, integrate and reorganize knowledge in different fields. 'Signal is data' is the key idea of this layer. Traditional mechatronics courses often teach mechanical structure, control system and data processing as independent modules, but the digital industry requires them to be connected between modules. "*Digital Signal Processing Theory and Practice*" is precisely from here to guide students to transform the output of industrial sensors into an analytical, modeling, and controllable data stream.

Specifically, students should learn to extract effective information from sensor signals, process noise, clean data, and eventually become structured data that can be directly identified by the control system. Through this process, physical manufacturing problems such as vibration and heat are no longer only experience-based phenomena. They can be translated into digital control logic. Topics such as ICA(Independent Component Analysis) and PCA(Principal Component Analysis) also help students understand how to turn concrete engineering problems into mathematical problems and then analyze them through algorithms. *Control and Intelligence Engineering* further connects structured data with intelligent algorithms. The course does not stop at classical control theory. It also introduces neural network control, intelligent optimization and control, deep neural networks, value-based reinforcement learning, policy-based reinforcement learning, and adaptive dynamic programming control. These topics help students understand how intelligent algorithms can be embedded in modern engineering control systems. *Advanced Manufacturing Engineering* moves from micro-nano manufacturing and high-performance manufacturing to digital manufacturing and the use of artificial intelligence in intelligent manufacturing. It supports the integration of traditional process knowledge and digital technology.

Therefore, the key value of the integration nexus is not only that it adds several cross-disciplinary courses. More importantly, it builds channels for translation among mechanical structure parameters, industrial signals, data models, and digital control commands. It helps students cross the gap between traditional engineering language and digital technology language. It also helps them build a systematic understanding of complex engineering problems and the ability to connect knowledge across fields.

4.3 Agile Interface: updating together with industry

The top layer of the curriculum system is the agile interface. Compared with the stable substrate, this layer updates faster and is more directly connected with industrial sites. It mainly includes *Optimization Design Methods and Practice*, *Numerical Control Technology and Practice*, and *Technology and Practices of Manufacturing Processes*. Its basic features are frequent updates, modular organization, and deep university-enterprise co-construction. The purpose of this layer is to enable the course content to respond more quickly to changes in industrial technology and corporate needs. The course here not only repeats the existing training process, but also becomes the teaching carrier of the latest industrial rules, process data and real engineering problems. Taking *Numerical Control Technology and Practice* as an example, enterprises can directly put specific multi-axis machining scenarios, new numerical control instruction sets or typical production site problems into course chapters or practice modules, and some of the contents are also taught by enterprise experts. This design conforms to the current trend of deep integration of schools and enterprises and modular development of courses, and shifts practical teaching from 'verifying known' to 'responding to real problems and exploring the current industrial environment'. The relevant construction mechanism of the National Graduate College for Excellent Engineers also provides institutional support for the continuous updating of this layer. Through university-enterprise cooperation, the existing courses are upgraded, the teaching project case base is constructed, and the latest industry cases, technical standards and engineering projects are introduced into the teaching system in the form of module

update. The course team can also regularly convert new technical rules, project cases and engineering data into teaching resources according to the development of the industry.

The value of digital education in the agile interface is reflected in two aspects. First, the course content is directly connected with the digital industry frontier : Computer Numerical Control system instruction set, real-time digital twin simulation, industrial big data acquisition and analysis, etc., are all key knowledge in digital transformation. Students are not exposed to abstract and simplified cases, but to real problems and real data closer to the industrial site. The second is the digitization of the teaching method itself : the relevant practical courses have been developed into online courses, using modular digital content, and enterprise partners can update asynchronously to add the latest industrial knowledge to the platform ; students are also not limited by time and place, and can obtain knowledge and cases from the industrial site at any time.

4.4 Engineering Ethics: the value anchor in the digital industrial age

In the whole hierarchical curriculum system, *Engineering Ethics* not only belongs to a certain layer, but also runs through as a value anchor. The *Engineering Ethics* in the digital industry era has long gone beyond traditional safety responsibilities and professional rules, and also involves new issues such as algorithmic bias, industrial data privacy, responsibility for intelligent decision-making, and responsibility boundaries in human-machine collaboration. Therefore, *Engineering Ethics* courses need to be reorganized around the digital industry environment. Through the analysis of enterprise cases, students not only understand the professional responsibilities of engineers in technical systems, but also understand the social impact of data collection, algorithm use and intelligent decision-making. In the end, the role of this course in the system is to remind students that stronger digital capabilities cannot be separated from value judgments. Only by combining technical rationality and value rationality, engineering education can truly meet the training requirements of outstanding engineers in the digital industry era.

4.5 Knowledge transfer between layers: from static layering to dynamic coupling

The layered curriculum system is not just a way to classify courses. It forms dynamic coupling through knowledge flow between layers. The stable substrate, the integration nexus, and the agile interface have both a bottom-up path of theory operationalization and a top-down path of problem feedback. The first path shows how basic theory becomes engineering practice ability. The second shows how industrial problems push course content to update.

4.5.1 Bottom-up path of theory operationalization

Knowledge first forms a mathematical and theoretical base in the stable substrate. After the completion of interdisciplinary translation in the integration nexus, these contents are applied to the specific engineering practice of the agile interface. In the stable substrate, the finite element solution framework of partial differential equations is built by *Numerical Methods and Computational Mechanics*. The *Dynamic Analysis and Control of Mechatronic Systems* provide a mathematical modeling method for electromechanical coupling systems. These courses train students to abstract and model engineering problems, equivalent to the underlying code of the entire knowledge chain. After entering the integration nexus, abstract theory begins to be translated into workable engineering language. *Digital Signal Processing Theory and Practice* guides students to extract signals from raw

industrial sensor outputs, identify noise, clean data, and form structured data flows. *Control and Intelligence Engineering* connects these structured signals with intelligent algorithms such as neural network control and reinforcement learning. It completes the shift from physical quantities to control commands. In this sense, the integration nexus has a translation function. It turns lower-level mathematical language into operational logic that upper-level engineering systems can use. When this knowledge reaches the agile interface, it is placed into concrete engineering settings. For example, in *Numerical Control Technology and Practice*, students can understand the relationship among interpolation algorithms, motion control, and machining errors in multi-axis machining. When an interpolation algorithm causes contour errors in actual machining, students do not only look for causes at the operation level. They can also return to numerical methods and control models to analyze the problem and try to propose better solutions. In this way, theoretical knowledge truly enters engineering practice through layered transformation.

4.5.2 Top-down path of problem feedback

Contrary to the bottom-up path, the real problems in the industrial field can also penetrate from the upper layer to the lower layer, stimulating updates in the theoretical layer and the middle layer. This feedback mechanism is very important to maintain the openness and vitality of the curriculum system. In the agile interface, the enterprise tutor brings real production bottlenecks into the classroom, such as the failure of thermal error compensation in five-axis machining and the failure of flutter suppression in complex surface machining. These problems first enter the practical course as engineering cases, and students need to use the existing knowledge to analyze and solve them. When the existing knowledge framework cannot fully explain or solve these problems, the requirements are moved down to the integration nexus. For example, the intelligent optimization module in '*Control and Intelligence Engineering*' may need to introduce new algorithm models, and the process knowledge in *Advanced Manufacturing Engineering* also needs to be included in the latest research on error compensation. These requirements may also further affect the teaching focus of the stable substrate- '*Numerical Methods and Computational Mechanics*'. When teaching the finite element method, more numerical solutions of the thermal-structural coupling field can be involved, providing a theoretical interface for the upper engineering problems. Through this top-down problem feedback, the curriculum system is no longer a closed knowledge container, but a dynamic system that can continuously respond to industrial needs. Real enterprise engineering problems are not only the case materials of practical teaching, but also an important driving force to promote curriculum renewal and evolution.

5. Digital Education Mechanisms Supporting Layered Agility

It can be seen from the above analysis that the effective operation of the hierarchical agile curriculum architecture is inseparable from the digital education mechanism. However, the digital education here is not simply adding online resources or intelligent teaching tools, but changing the organization and updating logic of the curriculum from the bottom through knowledge modularization, industrial interface, data feedback and so on.

5.1 Digital technology drives knowledge modularization

Through the online course platform and modular teaching unit, the course content can be split into relatively independent and interrelated knowledge nodes. For example, in the numerical method course,

the algorithm principle, calculation steps and engineering simulation cases can be organized into different modules, which can be flexibly combined according to the needs. The core value of knowledge modularization is to change the basic unit of curriculum renewal-not to retake a course or a set of training programs as a whole, but to accurately adjust a knowledge node, case module, project task or practical activity. For the stable substrate, modularization helps to transform abstract theories into visual, interactive and transferable learning resources ; for the integration nexus, it is convenient to establish a correlation between different knowledge fields ; for the agile interface , it helps enterprise cases and industrial projects enter the classroom more quickly. Digital education thus improves the openness and renewability of the curriculum structure, and lays the foundation for agile curriculum renewal.

At the same time, effective use of modular digital resources requires more than technical infrastructure. It also depends on sound pedagogical management of learning objects and digital tools.

Poultsakis et al. (2021) examine how teachers manage digital learning objects and digital experiment simulation tools. They find that intentional pedagogical organization and teacher capacity are key conditions for these resources to deliver their intended value. This confirms that curriculum agility requires both digital infrastructure and sound pedagogical governance, not technology deployment alone.

5.2 Digital interfaces for industry

The traditional university-enterprise cooperation mostly relies on practice bases, enterprise lectures or short-term projects. Although it can provide practical resources, it is often out of touch with the curriculum system. With a long time, the impact on curriculum content and teaching organization is limited. This is especially true in the field of Industrial Machine Tool. Industrial knowledge is closely tied to the actual production environment and changes rapidly — equipment upgrades, process optimization, numerical control system iteration, on-site manufacturing problems, etc., are difficult to fully present through traditional teaching materials. In this context, the industry-oriented digital interface has become a key channel between the curriculum system and engineering practice. Enterprise cases can enter the course in digital form, and enterprise engineers can participate in teaching through online collaboration. The design scheme, simulation results, analysis report and improvement suggestions made by students in the course project are not only learning results, but also the basis for curriculum improvement in turn. With this mechanism, there is a two-way flow between the curriculum system and industrial practice: industrial issues enter the curriculum, and student outcomes and learning feedback promote curriculum renewal. University-enterprise cooperation is no longer just an additional item outside the curriculum, but gradually becomes the infrastructure for curriculum operation.

5.3 Dynamic course updating

In the hierarchical agile curriculum architecture, the digital platform can record the process data of students ' course learning, online resource use, simulation experiment, project task, collaborative learning, etc., help teachers understand students ' learning difficulties, judge whether the content meets the needs, and then adjust the teaching strategies. For example, if students frequently make mistakes in a certain theoretical module and their test scores continue to be low, the stable substrate may need to

increase visual interpretation, case support or basic training ; if students have difficulties in integrating knowledge in cross-disciplinary projects, the integration nexus may need to strengthen the connection between courses ; if students are difficult to adapt to the real engineering constraints in enterprise projects, the agile interface may need to adjust the task design, supplement the pre-knowledge, or strengthen the guidance of the enterprise mentor. The source of feedback is not only student data. Enterprise tutors can feedback students ' performance in finding problems, designing schemes and communicating and cooperating in practical engineering tasks. Course teachers can judge students ' mastery of theories and tools. Students themselves can also give opinions on course difficulty, resource practicability and project task rationality. After the digital platform integrates these different types of feedback, the curriculum team can establish a more stable continuous improvement mechanism. Under this mechanism, curriculum updates no longer rely mainly on teacher experience or administrative requirements, but are more based on learning process data, project performance, and industry feedback. The curriculum system thus presents the characteristics of a certain learning system. It can not only perceive external industrial changes and internal learning problems, but also continuously improve itself through module adjustment, case update, task reorganization, and assessment optimization. The data feedback mechanism thus becomes the key to the dynamic operation of the hierarchical agile curriculum architecture, helping the curriculum system to maintain basic stability while continuously responding to industrial changes and learning needs, and forming a dynamic balance between the two.

6. Discussion

The purpose of this study is not to empirically evaluate the effectiveness of specific curriculum reform interventions, but to develop a practice-informed curriculum architecture to understand how engineering courses can remain stable while responding to technological change. Based on the case of Industrial Machine Tool course, the proposed pace-layered agile curriculum architecture provides an analytical perspective for examining the relationship between knowledge evolution and curriculum organization.

The case shows that curriculum agility should not be understood as a requirement for rapid change in all courses. On the contrary, agility depends on the establishment of differentiated update mechanisms for different types of knowledge. Basic theory, interdisciplinary methodology and industrial practice have distinct evolutionary characteristics. Therefore, the curriculum system needs to coordinate stability and adaptability through differentiated structures.

From the perspective of curriculum practice, the development of digital curriculum resources, industry-university cooperation mechanism and modular teaching structure provides an operational situation for the implementation of this differentiated update strategy. The online courses developed under this architecture have been launched for just over a year, yet their potential for knowledge sharing and inter-institutional dissemination has been observed. The online courses platform information shows that 17 Double First-Class Universities, including Shanghai Jiao Tong University and Zhejiang University, are using these courses, and a company with postgraduate training qualifications is also involved. Each online course contains about 50 lessons, supporting an average of about 40 other classes, covering about 1700 students, involving about 30 teachers. These information suggest that the curriculum resources do not stop at the stage of 'built and finished', but enter the inter-

school teaching scene in a short time, resulting in a real sharing of use. This provides preliminary evidence that the architecture has practical relevance in broader educational contexts.

6.1 From content updates to curriculum architecture reconstruction

The current reform of engineering education often equates curriculum renewal with adding new content - such as adding artificial intelligence, big data, digital twins, intelligent manufacturing, etc., to existing courses. Doing so can indeed make the course look more fashionable, but the problem of knowledge lag has not been fundamentally solved. The reason is that knowledge lag is not only about some knowledge points becoming outdated. It is more about a mismatch between the organization of the curriculum system and the update rhythm of industrial technology. Therefore, the curriculum system should not be seen as a static course list. It should be seen as a dynamic structure with different update rhythms. Basic theory, cross-disciplinary knowledge, and industrial practice knowledge have different levels of stability and different speeds of change. If the same update method is used for all courses, two problems may appear. Basic courses may lose their long-term support function because of short-term technology trends. Practice courses may lag behind real engineering settings.

This is the value of the layered agile curriculum architecture. It does not require all courses to change quickly at the same time. Instead, it arranges different update rhythms based on knowledge type. In this way, curriculum agility is not the quick adjustment of a single course. It is the coordinated updating ability of the whole curriculum system.

6.2 Balancing stability and agility in engineering curriculum systems

Engineering education in the era of digital industry has always faced a dilemma: it is necessary to keep up with the update of industrial technology quickly, and to cultivate talents by stable basic theoretical training. If courses updates occur too rapidly, universities may overemphasize short-lived technological trends at the expense of students' foundational knowledge and competencies; however, if courses renewal is too slow, curricula may gradually become disconnected from evolving industrial practices. The layered agile curriculum architecture just responds to this contradiction. The basic layer ensures the depth and long-term value of the discipline, the agile interface retains the ability to respond to industrial changes, and the middle layer is responsible for translation, integration and coordination. The three layers add up to form a 'bounded agile' -courses will not blindly pursue fast, but update interdisciplinary knowledge and industrial practice knowledge hierarchically under the premise of maintaining the relative stability of basic theory.

This also means that agility in engineering education is not just 'fast', but adjusted at the right speed and at the right level. Basic theoretical courses need to be stable, but they can be made clearer and easier to migrate by digital means; interdisciplinary courses should be moderately updated to maintain the connectivity of knowledge; industrial practice courses need to be updated more frequently, closely following the enterprise site and technical standards. The real curriculum agility comes from the synergy between different levels.

6.3 Reunderstanding university-enterprise collaboration as curriculum infrastructure

The traditional university-enterprise cooperation is often regarded as the 'external support' of engineering education-post practice, enterprise lectures, practice base, graduation design joint guidance, these forms are valuable. However, if enterprise participation is always outside the curriculum system,

it is difficult to really affect the students' knowledge structure and ability development for a long time. In the hierarchical agile curriculum architecture, university-enterprise cooperation is more like the infrastructure of curriculum operation, which is particularly evident in the agile interface. Enterprises are an important source of industrial knowledge, engineering cases, technical standards and practical problems. Without the participation of enterprises, practical courses can easily become simulated, textbook and outdated. Without a digital platform, it is difficult for enterprise knowledge to enter the curriculum continuously and systematically. Therefore, the key is not only whether the enterprise participates or not, but also whether the enterprise engineers, industrial data, real projects, technical cases and assessment feedback can be embedded in the curriculum structure, digital platform and update mechanism. Only by entering teaching in an institutionalized and digital way can university-enterprise cooperation move from temporary cooperation to the basic conditions for agile curriculum operation.

This perspective also broadens the research boundary of digital education—digital education not only supports classroom teaching and resource construction, but also reshapes the knowledge flow between universities and industries. Through the digital platform, industrial knowledge can be transformed into curriculum content, modules and teaching resources, and students' learning outcomes, project performance and multi-subject feedback can in turn promote curriculum improvement. Digital education has thus become an important bridge between university courses and industrial scenes.

6.4 Boundary conditions and transferability of the pace-layered architecture

Although this study is based on the case of Industrial Machine Tool engineering education, the proposed pace-layered curriculum architecture is not limited to disciplines characterized by rapid hardware or equipment iteration. The fundamental logic of this architecture is not the speed of technological change itself, but the existence of different knowledge-update rhythms within a curriculum system. In other words, the key question is not whether a discipline changes rapidly, but whether different components of disciplinary knowledge require different mechanisms and frequencies of renewal.

From this perspective, the stable substrate, the integration nexus, and the agile interface represent functional categories rather than fixed disciplinary modules. The stable substrate refers to the knowledge elements with a relatively long validity period, including the basic theory, mathematical principle, conceptual framework and so on, which support long-term professional development. The integration nexus includes knowledge that connects multiple disciplines and needs to be adjusted regularly with the emergence of new methods, analytical tools, and interdisciplinary approaches. The agile interface involves knowledge that is closely related to the external environment, such as industry standards, professional tools, emerging technologies, regulations, and real application scenarios, and often require more frequent updates.

Therefore, the applicability of pace-layered curriculum architecture depends on several boundary conditions. First, disciplines should contain identifiable differences in knowledge update rhythms. Disciplines with a completely unified knowledge structure may gain limited benefits from differentiated update mechanisms. Second, curriculum content should be modular, allowing specific knowledge units, cases, tools, or project tasks to be updated without reconstructing the entire

curriculum system. Third, there should be effective channels for external knowledge input, including industry collaboration, professional communities, research developments, or social demands. Without continuous external interaction, the agile interface may lose its connection with real-world changes.

However, the transfer of this curriculum architecture should not be understood as a direct copy of the three-tier classification. On the contrary, each discipline should determine its own knowledge update mode, dominant knowledge source and teaching participants before constructing an appropriate pace-layered structure. Future research needs to involve multiple institutions and disciplines to examine how the architecture can be adjusted in different educational, technical, and organizational contexts.

6.5 Faculty Roles and Institutional Conditions for Curriculum Agility

The operation of a pace-layered curriculum architecture requires not only the structural adjustment of the curriculum components but also appropriate institutional support. Although teacher development is not the main focus of this study, the change of curriculum organization will inevitably affect the role of teachers and the mechanism of supporting curriculum renewal.

In traditional engineering education system, teachers often play the primary role of subject knowledge providers, and curriculum updates are mainly carried out through periodic administrative procedures. However, the layered agile curriculum architecture requires teachers to be more actively involved in curriculum integration, knowledge transformation, and collaboration with external stakeholders. Different curriculum levels involve different teacher responsibilities. In the stable substrate, teachers mainly maintain the rigor and continuity of basic knowledge, while exploring digital representation and application-oriented teaching methods. Interdisciplinary collaboration becomes more and more important in the integration nexus, because teachers need to connect knowledge from different fields and design learning activities around complex engineering problems. In the agile interface, teachers act as coordinators between academic knowledge and industrial practice by transforming enterprise cases, engineering problems and emerging technologies into structured learning resources.

The shift in these roles does not mean that every faculty member must continue to master all emerging technologies. Instead, universities may consider providing organizational conditions that enable teachers to collaborate across disciplines, engage with industrial partners, and participate in the curriculum renewal process. Possible supporting mechanisms include interdisciplinary teaching teams, industry-university cooperation platforms, and flexible procedures for updating modular curriculum components.

7. Conclusion

This paper focuses on how to deal with the problem of knowledge lag in the era of digital industry in engineering curriculum system. Taking 10 core courses in the field of Industrial Machine Tool at Huazhong University of Science and Technology as an example, this paper constructs and analyzes the hierarchical agile curriculum architecture by using Pace Layering theory.

The case analysis suggests that this curriculum system is not a simple patchwork of several courses, but a structure with three different update rhythms: a stable substrate, an integration nexus, and an agile interface. The stable substrate covers courses such as numerical methods, computational mechanics, system dynamics, engineering materials, etc., providing long-term theoretical support and

basic ability training ; the integration nexus includes courses such as *Digital Signal Processing*, Control and Intelligence Engineering, *Advanced Manufacturing Engineering*, etc., supporting interdisciplinary integration and digital logic translation ; the agile interface covers courses such as numerical control technology, manufacturing process practice, and optimization design practice, connects the course with the industrial environment, and supports rapid knowledge update. *Engineering Ethics*, as a value anchor, runs through all levels to ensure that agile curriculum updates serve responsible engineering practice.

The research further shows that digital education supports curriculum agility through three mechanisms: First, knowledge modularization makes the course content a recognizable, composable and renewable knowledge unit ; the second is to build an industry-oriented curriculum interface, so that enterprise cases, industrial data, real projects and technical standards can continue to enter the teaching ; the third is to support dynamic updating with learning analysis and multi-feedback, so that curriculum adjustment is more based on learning process, project performance and industry needs.

The main contribution of this paper is to advance the problem of curriculum renewal from the content level to the architecture level. The reform of digital engineering education is not only to add digital technology content to the curriculum, but also not only to build online resources or intelligent tools, but to reorganize the curriculum system according to the different update rhythms of different knowledge types. The layered agile curriculum architecture provides a new analytical framework for understanding and managing the knowledge lag in engineering education, and also provides a practical path for the curriculum system reform in the digital industry era.

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Declaration on the Use of AI Declaration on the Use of AI Large language models were used only for language polishing and grammar correction during manuscript writing. The authors retain full accountability for all content, arguments, and conclusions in this paper.

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