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Simulation and prediction study of artificial intelligence education dynamics model for primary and secondary schools

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Abstract

Digital technology is profoundly transforming various aspects of life, thus highlighting the need to enhance digital literacy on a national scale. In primary and secondary schools, artificial intelligence (AI) education plays a pivotal role in fostering digital literacy. To comprehensively investigate the variables influencing AI education in primary and secondary schools, a dynamic system model was constructed based on the CIPP (Context, Input, Process, and Product) education evaluation model. We employed a mixed-method research approach, combining both qualitative and quantitative methods, to thoroughly investigate the influencing factors and perform predictive and simulation experiments. Firstly, we construct a system framework for AI education in primary and secondary schools based on CIPP model, utilizing qualitative methods such as literature review and expert interviews to identify influencing factors and define the system's boundaries. Secondly, we collect 814 questionnaire responses from 12 primary and secondary schools and employ Structural Equation Modeling (SEM) for quantitative analysis to explore the relationships between these influencing factors. Finally, these relationships are utilized to construct a System Dynamics model, allowing for an in-depth exploration of the development trends in AI education in primary and secondary schools through predictive analysis and control simulation. Controlled simulations allow us to predict and validate factors that influence the level of AI education development, aiding in the identification of high-leverage elements. Our findings underscore that AI education in Chinese primary and secondary schools is still in its initial stage with insufficient developmental momentum. Through controlled simulation results, it is found that the development of AI education in primary and secondary schools is influenced by both external systems and internal student systems, with national policy serving as the fundamental driving force. Among these influencing factors, societal factors play a predominant role in the external environment, followed by

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school factors, while the students' level of learning engagement is identified as the most crucial factor within the internal system. Based on the results of prediction and simulation studies, recommendations for improvement are proposed, including policy reforms and collaboration between schools and enterprises.

Keywords Artificial intelligence education · Primary and secondary school · Structural equation modeling · System dynamics · Developmental prediction

1 Introduction

The advancement of digital technology has led to profound transformations in various aspects of human life, including how people live, work, and acquire knowledge. Many nations have recognized the importance of digital literacy and have consequently integrated it as a fundamental component of their national strategies. Consequently, the digital literacy and skills of their populations are progressively emerging as pivotal metrics for assessing international competitiveness and soft power (Akgun & Greenhow, 2021; Borenstein & Howard, 2021). Primary and secondary schools play a pivotal role as the vanguard of educational practices (Yang, 2022). Therefore, in order to align with a digital economy characterized by AI predominance, the endeavor to develop AI education within primary and secondary schools and enhance the digital literacy and skills of students at this level has assumed a pivotal role as a critical national strategy (Kim & Lee, 2023).

With the continuous advancement of AI technology in the digital age, several governments have recognized the importance of AI education literacy programs that cater to the developmental and growth needs of students from kindergarten through twelfth grade (K-12) (Long & Magerko, 2020; Ng et al., 2022). Notably, governments in countries such as the United States, Japan, and member states of the European Union have instituted a plethora of incentive policies with the goal of fostering AI education and cultivating AI talent (Jobin et al., 2019; Laupichler et al., 2022). According to the United Nations Educational, Scientific and Cultural Organization (UNESCO), only eleven countries have officially endorsed AI curricula, and four countries have government-supported K-12 AI curricula (UNESCO, 2021). Moreover, the education of AI in primary and secondary schools has received significant attention in China. Therefore, China has implemented incentive policies, such as the "New Generation Artificial Intelligence Development Plan" (State Council, 2017, pp. 27) and the "Artificial Intelligence Curriculum Development Standards for Primary and Secondary Schools (Trial)," with the aim of introducing AI-related courses in primary and secondary schools and gradually promoting programming education (Wu et al., 2020). In conclusion, governments and institutions in diverse nations are actively spearheading the advancement of K-12 AI education, acknowledging its significance in equipping students for the digital era.

While there is considerable momentum in promoting AI education, it is important to acknowledge that AI education in primary and secondary schools is still in its nascent phase. Existing research has made noteworthy contributions, primarily centered on curriculum development, tool creation (Henry et al., 2021), and addressing definitional issues (Long & Magerko, 2020). However, numerous challenges, such as incomplete policy frameworks, inconsistent teaching resources, and a shortage of teaching staff, hinder its widespread implementation. Researchers, exemplified by the works of Huang (2021) and Lu et al. (2021), are actively engaged in assessing the current state and challenges of AI education development. Their efforts aim to propose practical implementation strategies and recommendations. While primary and secondary school artificial intelligence education research predominantly relies on qualitative methods like interviews, observations, and text analysis to explore complex phenomena, there's a notable gap in comprehensive quantitative analysis. The absence of robust quantitative assessment limits factors' quantification, hypothesis validation, and trend analysis. Incorporating more quantitative data analysis could unveil broader patterns and relationships, providing policymakers with valuable insights for informed decision-making.

In response to national policies and to address significant challenges in the implementation of AI education in primary and secondary schools, this study employs a mixed research approach that combines both qualitative and quantitative methods. Specifically, the research proceeds as follows: firstly, it conducts a comprehensive investigation of the factors influencing AI education based on the CIPP model. Secondly, it collects relevant data through questionnaire surveys and constructs a structural equation model (SEM) to validate the theoretical framework and perform path analysis. Subsequently, leveraging the coefficients from the SEM, a system dynamics model is developed to comprehensively examine the state of AI education in primary and secondary schools and predict trends. Finally, predictive analysis and controlled simulations are employed to explore developmental trends and high-leverage factors during the development process, thereby contributing to the optimization of education policies, resource allocation, and the promotion of the sustainable development of AI education in primary and secondary schools.

2 Related work

AI education in primary and secondary schools has received significant attention, prompting researchers to primarily explore two key areas: AI education and the factors influencing AI education.

2.1 Advancements and challenges in AI education

Hitherto, a series of studies have focused on theoretical and practical research regarding AI education in primary and secondary schools, and many results have been reported. In terms of practical research, the United States implemented the AI for K-12 Education Initiative (AI for K-12 Initiative), which developed and released a guide for teaching AI in K-12 education (Touretzky et al., 2019). This guide focused on the goals and content of AI teaching in basic education from elementary school to high school. In recent years, numerous primary and secondary schools have gradually initiated the implementation of AI-related courses, including Science, Technology, Engineering, Mathematics (STEM) education courses and creator education courses. Additionally, some schools have also introduced robotics education and courses associated with programming languages and other related subjects (Adams et al., 2023). The quality of AI education development depends on the content of the relevant curricula (Yang, 2022), and the orientation of AI education curricula in primary and secondary schools has attracted attention from many researchers (Kim & Lee, 2023). Ali et al. (2019) developed a K-12 AI education curriculum from a constructivist learning perspective to enhance students' creative thinking. Henry et al. (2021) developed a curriculum for 10-14-year-old students regarding the concept of intelligence in AI systems, which combined computer science education with media literacy education. Several scholars have contributed to the development of K-12 AI education curricula, focusing on nurturing students' creative thinking and understanding of AI systems.

Despite the advances in AI education, it is still in its infancy in primary and secondary schools. Its development is subject to various constraints, the most prominent of which is the lack of standardized definitions and planning. This shortcoming complicates the definition of educational goals, the control of teaching content, and the implementation of effective teaching methods. The AI4K12 initiative, a collaborative effort between the Computer Science Teachers Association (CSTA) and Association for the Advancement of Artificial Intelligence (AAAI), defined the "Five Big Ideas of AI" that K-12 students must know (AIK12, 2019). The five big ideas include Perception, Representation and Reasoning, Learning, Natural Interaction, and Societal Impact of AI. Lu et al. (2021) analyzed the current state of AI education in primary and secondary schools, both domestically and internationally. They identified six fundamental content areas – perception, reasoning, learning, decision, interaction, and morality – relevant to civic literacy in AI education at these levels. These basic elements are crucial to the successful integration and advancement of AI education in primary and secondary schools.

In conclusion, the current landscape of AI education in primary and secondary schools reflects a blend of research and practical implementation. The AIK12 (2019) Initiative, along with the "Five Big Ideas of AI," has provided a crucial foundation for this evolving field. Nevertheless, AI education in primary and secondary schools is currently in a nascent phase, and its development faces certain limitations. the absence of national AI curriculum standards presents significant challenges that must be addressed for the effective progression of AI education within primary and secondary schools. In particular, the inconsistency of national artificial intelligence plans has brought major challenges that must be solved for the effective development of artificial intelligence education in primary and secondary schools.

2.2 Factors influencing AI education: a comprehensive review

In terms of theoretical research, studies on the factors influencing AI education in primary and secondary schools have gradually attracted the attention of educational researchers (Huang, 2021). Wong et al. (2020) combined the historical development of the computer industry with education to reshape the concept of AI education and provide a new direction for the implementation of AI education in K-12 contexts. Adams et al. (2023) reviewed ethical policies related to K-12 AI education and identified four new ethical principles: pedagogical appropriateness, children's rights, AI literacy and teacher welfare. Sanusi et al. (2022a) found that factors such as cognition, human-computer collaboration, skill competencies and ethics were influential in the development of AI education based on a survey of K-12 settings in Africa. Huang (2021) highlighted numerous challenges pertaining to AI education in China, such as a lack of teachers, geographical differences, and unreasonable AI teaching materials, and proposed specific ways to enhance students' key competencies. Chai (2020) examined the factors that affect students' behavioral intention to engage in AI learning, including literacy, confidence, social good and behavioral intention. Lin (2021) employed a structural equation model to test students' motivation to learn AI based on six motivational factors: intrinsic motivation, career motivation, attention, relevance, confidence, and satisfaction. Rozek et al. (2015) found that career motivation enhances students' willingness to learn science, for example, students who are interested in pursuing STEM-related careers were found to be highly motivated to learn science upon recognizing its utilitarian value. Yau et al. (2023) discussed the impacts of teachers' teaching philosophies on AI education. Sanusi et al. (2022b) found that cultural competence, human-tool collaboration competence, self-learning competence, skill competence and ethics significantly influence the content of AI. They used structural equation modeling, a quantitative research method, to analyze the relationships between the variables used in the study. Most of these studies are qualitative, with only a few collecting data for quantitative analysis. However, these studies mainly conduct a one-sided examination of specific influencing factors and lack a systematic quantitative analysis of the interrelated operating mechanisms between various influencing factors from a comprehensive perspective.

Accordingly, system dynamics modeling, as a quantitative method used to study complex social systems, can effectively address complex relationships by analyzing the nonlinear relationships among variables with the goal of explaining the behavior of complex systems; therefore, this approach has also received attention from researchers focused on educational systems (Biroscak et al., 2019; Forrester, 2016; Yang et al., 2019). From the perspective of system dynamics, this paper explores the development of AI education at the primary and secondary school levels, which represents a complex system that features interactions among elements such as national policies, the learning environment, and student factors. Furthermore, using predictive analysis as well as dynamic control simulation, this study contributes to the sustainable development of AI education in primary and secondary schools.

3 Methodology

The section comprises three main parts. Firstly, we will establish a conceptual framework and delineate research hypotheses based on the CIPP model to investigate the influencing factors of AI education. Secondly, we will employ structural equation modeling (SEM) for quantitative analysis of the relationships among these factors. Finally, we will conduct further analysis using a system dynamics model to explore the developmental trends of AI education in primary and secondary schools. These methods will assist us in comprehensively understanding the complexity of AI education and provide robust support for policy development and sustainability.

3.1 Conceptual framework and boundary definition

Based on the review of AI education research presented in Sect. 2, it is evident that the factors influencing AI education in primary and secondary schools are multifaceted and intricate. These factors encompass not only students' internal attributes but also elements within the external environment, including the school environment, family context, and societal conditions. Furthermore, in terms of sustainability, many educational settings necessitate government backing and support.

According to the theory of system dynamics, AI education in primary and secondary schools is considered a dynamic system. To comprehensively analyze and understand this dynamic system, a comprehensive system framework for AI education in primary and secondary schools is constructed based on the CIPP (Context, Input, Process, Product) educational evaluation model (Stufflebeam, 2000). The system framework examines factors affecting the development of AI education at the primary and secondary levels from the four perspectives of CIPP, thereby defining the boundaries of the system.

The system framework for AI education categorizes the factors influencing AI education's development into four crucial aspects: policy support (context), blended learning environment (input), student engagement (process), and development level (product). Government support, under the "context" category, acts as a driving force behind AI education's advancement. Government policies, including promotion, curriculum standards, and advocacy, guide and coordinate AI education development (Alivernini & Manganelli, 2015). The "input" dimension, represented by the blended learning environment, significantly impacts students' experiences. This multifaceted learning environment provides essential resources, including educational equipment, faculty, and teaching investments. In the "process" category, student engagement plays a key role in AI education's development level (Ng et al., 2022). Student engagement comprises extrinsic and intrinsic factors, such as practical experiences, motivation, and interest. Student engagement directly influences AI education's success (Chai et al., 2020). The "product" aspect, representing the outcomes of AI education, signifies the culmination of these efforts. It reflects the achievements, knowledge, and skills gained by students in AI education programs. Furthermore, this study established the framework's factors by reviewing domestic and international research on AI education in primary and secondary schools and conducting expert interviews, as displayed in Table 1.

In summary, this framework provides a comprehensive approach to understanding and evaluating the dynamics of AI education in primary and secondary schools. It acknowledges the complexity of the educational system and recognizes the significant impact of government support, learning environments, student engagement, and the outcomes they shape on the entire system. To comprehensively construct the system framework for the influencing factors of AI education in primary and secondary schools, the framework includes the following assumptions: based on the CIPP model framework, the contextual influence of government support affects the input of

Table 1 Factors influencing the development of AI education in primary and secondary schools

	Primary indicators	Secondary indicators
Policy (Context)	Government factors	Promotion efforts, policy support, financial support, related activity support, project application support, and teacher training support (Alivernini & Manganelli, 2015)
Learning environment (Input)	School factors	The school's perception of AI education, AI classroom settings, the school's faculty, the school's educational resources, and the school's competitions and activities (Dragoş & Mih, 2015; Roberts & Bybee, 2014; Yau et al., 2023))
	Family factors	Parental value perception, parental interest, parental attitude, parental financial support for AI products, and parental financial support for AI education (Reparaz & Sotés-Elizalde, 2019)
	Social factors	The society's venue equipment, number of educational products, number of training institutions, competition activities, and online educational resources (Kong et al., 2023)
Individual students (Process)	External conditions	Guarantees in terms of time commitment, faculty, educational resources, activity participation, and experimental equipment (Luu & Freeman, 2011)
	Intrinsic commitment	The needs for interest, happy learning, higher education, self-improvement, and self-esteem (Chai et al., 2020; Lin et al., 2021)
Level of development (Product)	Engagement, coverage, and learning effectiveness (Kim et al., 2014)	

the learning environment, and the input of the learning environment positively influences learning engagement; learning engagement affects the development of learning outcomes.

3.2 Validation of influencing factors through structural equation modeling

A quantitative approach was used to verify the impact factors and explore the structural features of the model. Therefore, this paper used questionnaire data to construct a structural equation model to perform an empirical investigation of the impact factors as well as the corresponding path relationships.

3.2.1 Participants

This study collected data about AI education using a random sampling questionnaire. The data were analyzed using SPSS 26.0 statistical software. In terms of questionnaire screening, invalid questionnaires that featured missing content or identical answers to all questions were excluded. In this research, the questionnaire was distributed to 867 students, in which a total of 814 valid questionnaires were collected, which means the overall response rate was approximately 93.9%. Table 2 shows the specific demographic information analysis of the collected feedback.

In terms of the grade distribution of the study population, students were mainly in grades 1 to 9, aged from 7 to 16 years old. And the gender ratio is balanced. The specific demographic information is shown in the Table 2. In the collected data, there were 241 (29.6%) students in grades 1–3, 304 (37.3%) students in grades 4–6, and 269 (33.1%) students in grades 7–9, in which 422 (51.8%) were female and 392

Table 2 Demographic information

	Variables	Grade 1 ~ 3	Grade 4 ~ 6	Grade 7 ~ 9	Total (%)
Gender	Female	131 (54.4%)	155 (51.0%)	136 (50.6%)	422 (51.8%)
	Male	110 (45.6%)	149 (49.0%)	133 (49.4%)	392 (48.2%)
Total	Number (%)	241 (29.6%)	304 (37.3%)	269 (33.1%)	814 (100%)
Regional	Central	75 (31.1%)	53 (17.4%)	107 (39.8%)	235 (28.9%)
	Western	122 (50.6%)	183 (60.1%)	118 (43.8%)	423 (51.9%)
	Eastern	44 (18.3%)	68 (22.4%)	44 (16.4%)	156 (19.2%)
Total	Number (%)	241 (29.6%)	304 (37.3%)	269 (33.1%)	814 (100%)

(48.2%) were male. In terms of the geographical distribution of the study population, questionnaires were distributed in 12 primary and secondary schools across various regions of China. Population demographics associated with different geographical areas showed that 235 students (28.9%) were from the central region, 423 students (51.9%) were from the western region, and 156 students (19.2%) were from the eastern region. The gender distribution consisted of 392 (48.2%) male students and 422 (51.8%) female students.

3.2.2 Measuring tools

This study employs the "Questionnaire on the Influencing Factors of Artificial Intelligence Education Development in Primary and Secondary Schools" to investigate each influencing factor and its underlying mechanisms through quantitative analysis. The questionnaire design is based on a comprehensive review of relevant domestic and international studies, as well as established questionnaires tailored to the specific context of AI education development in China. It is structured according to the index system of influencing factors presented in Table 1, encompassing six dimensions: government support, school environment, social environment, family environment, external conditions, and internal commitment. The questionnaire aims to gauge the progress of AI education in primary and secondary schools by assessing factors such as investment levels, coverage rates, and learning outcomes.

3.2.3 Data collection procedure

To ensure the reliability of the questionnaire results, given the age of primary and secondary school students, parents complete questions related to government support, the social environment, and the family environment, while students respond to questions concerning the school environment, external conditions, and internal commitment. The participants were requested to specify their agreement level with each item on a 7-point Likert scale (7 = Strongly agree; 1 = Strongly disagree). Some of the subscales had more items to maximize the measurement reliability, even though some were deleted since they did not meet the threshold. This does not, however, affect the relations among constructs in SEM.

3.2.4 Model evaluation

Reliability test In this paper, to ensure the internal consistency of the scale, an internal consistency test is first conducted by calculating the *Cronbach's* α value of the internal consistency reliability coefficient of the scale before conducting the exploratory factor analysis. The *Cronbach's* α value for the overall questionnaire, as presented in Table 2, is 0.923 after analysis. (1) The *Cronbach's* α values for the seven subdimensions of government, school, society, family, external, internal, and development level are all above 0.8. This finding indicates that the internal consistency of the questionnaire structure is good, and the measurement results are credible and exhibit strong interpretability. (2) Composite reliability (CR) is employed to assess the measurement model's reliability, with each structure's CR value recommended to be greater than 0.70 (Hair et al., 2010). Table 2 The combined reliability (CR) of all seven dimensions is higher than 0.9, further demonstrating the high internal consistency of the questionnaire.

Validity test The econometric model is further evaluated using confirmatory factor analysis (CFA). The factor loadings (λ) for the unstandardized values should be statistically significant at the 0.05 level, with standardized values of 0.60 indicating acceptability and those greater than 0.70 indicating ideal values (Chin, 1998). Indicator items that did not meet the conditions were removed from this study. The KMO coefficient of 0.880, as presented in Table 3, which is indicated that the Bartlett sphericity test (Burkell et al., 1990) is significant and underscores the questionnaire's validity. (1) Most items associated with the subtopics demonstrate standardized loadings exceeding 0.7, with only two subfactors, XX2 and SH5, exhibiting standardized loadings of 0.695, implying that 34 items successfully pass the validity test. (2) A previous study (Fornell & Larcker, 1981) indicated that the model construct can be considered as acceptable if all the AVE for each factor is higher than 0.4. The convergent validity (AVE) for all seven dimensions surpasses 0.6, confirming that the scale satisfactorily meets the criteria for convergent validity.

3.2.5 Path analysis

The structural model of the factors influencing the development of AI education in primary and secondary schools is drawn using AMOS 26.0 software. Based on data drawn from 814 questionnaires, the estimation and significance tests of the path coefficients of the structural model are performed. The results are shown in Fig. 1.

To ensure that the structural model exhibits a sufficiently good model fit, the model fit is evaluated according to seven common metrics: χ^2/df, GFI, AGFI, CFI, TLI, SRMR and RMSEA. The results of the analysis are shown in Table 4. The evaluation results show that the model fit is acceptable because the GFI, AGFI and CFI are greater than 0.8, and the TLI is greater than 0.9, and the SRMR and RMSEA are less than 0.08. These fit indices for this model indicated a sufficient fit (Burkell et al., 1990; Henseler et al., 2015). The table lists the recommended and actual values of

Table 3 Validity and reliability tests of the observed variables

	Codes	Observed Variables	Standard Loads	Cronbach's α	AVE	CR
Government Support (ZF)	ZF1	Promotion Efforts	0.918	0.981	0.922	0.986
	ZF2	Policy Efforts	0.944			
	ZF3	Financial Support	0.985			
	ZF4	Related Activities Support	0.974			
	ZF5	Project Filing Support	0.986			
	ZF6	Teacher Training Support	0.953			
School Environment (XX)	XX1	Schools' Perceptions of AI Education	0.881	0.891	0.656	0.904
	XX2	AI Class hours	0.695			
	XX3	School Faculty	0.741			
	XX4	Educational Resources of the School	0.962			
	XX5	School Competitions and Events	0.738			
Social Environment (SH)	SH1	Field Equipment in Society	0.985	0.915	0.779	0.946
	SH2	Number of Educational Products in Society	0.983			
	SH3	Number of Training Institutions	0.889			
	SH4	Competitions in Society	0.829			
	SH5	Online Educational Resources	0.695			
Family Environment (JT)	JT1	Parental Value Perception	0.841	0.924	0.694	0.918
	JT2	Parents' Interest in AI Education	0.939			
	JT3	Parents' Attitudes toward AI	0.877			
	JT4	Parents' Provision of Financial Support for AI Products	0.744			
	JT5	Parents' Provision of Financial Support for AI Education	0.747			
External Conditions (EC)	EC1	Time Commitment Guarantee	0.760	0.858	0.762	0.941
	EC2	Faculty Guarantee	0.923			
	EC3	Educational Resource Guarantee	0.946			
	EC4	Event Participation Guarantee	0.850			
	EC5	Experimental Equipment Guarantee	0.873			
Intrinsic Commitment (IC)	IC1	The Need for Interest	0.972	0.933	0.838	0.963
	IC2	The Need for Happy Learning	0.971			
	IC3	The Need for Further Education	0.785			
	IC4	The Need for Self-Improvement	0.925			
	IC5	The Need for Self-Esteem	0.911			
Development Level (AI)	L1	Engagement	0.933	0.804	0.893	0.962
	L2	Coverage	0.953			
	L4	Learning Effectiveness	0.949			

the fit metrics, and all the fitted values are within the acceptable range, thus indicating that the collected data exhibits a good fit to the structural model.

The path coefficients among the latent variables are shown in Table 5. Government support is significantly and positively correlated with school support ($\beta = 0.724$, $P < 0.01$), indicating a strong correlation. School support is significantly and positively correlated with social support ($\beta = 0.790$, $P < 0.01$) and family support ($\beta = 0.124$, $P < 0.01$), with school support exhibiting a strong correlation with social support and

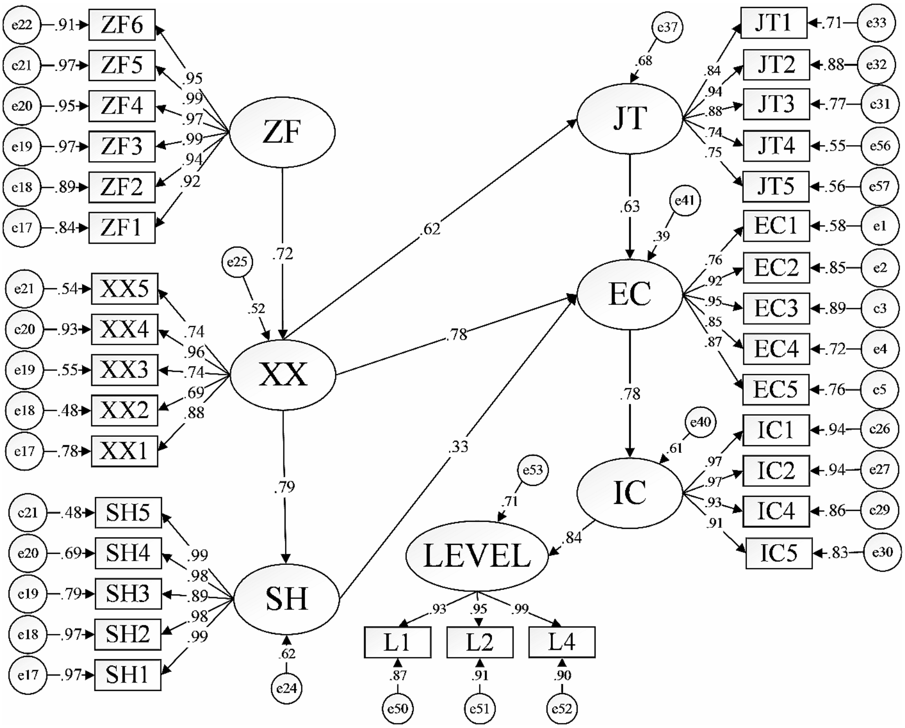


Fig. 1 Structural model of the factors influencing of AI education in primary and secondary schools

Table 4 Adequacy parameters of the structural model of AI education in primary and secondary schools

Indicators	χ^2/df	GFI	AGFI	CFI	TLI	SRMR	RMSEA
Standards	<5	>0.8	>0.8	>0.8	>0.9	<0.08	<0.08
Results	2.256	0.894	0.863	0.896	0.907	0.057	0.071

Table 5 Path analysis of the model of the factors influencing AI education in primary and secondary schools

Path Coefficients between Latent Variables	Standardized Path Factors	Estimate	C.R.	*P*	Significance
School Support ← Government Support	0.724	0.914	4.139	***	Significant
Social Support ← School Support	0.790	0.448	3.490	***	Significant
Family Support ← School Support	0.624	0.038	1.209	***	Significant
External Conditions ← School Support	0.782	1		***	Significant
External Conditions ← Family Support	0.625	1		***	Significant
External Conditions ← Social Support	0.330	0.467	4.763	***	Significant
Intrinsic Commitment ← External Conditions	0.779	1		***	Significant
Development Level ← Intrinsic Commitment	0.841	1		***	Significant

*** indicates $P<0.01$, which entails that the test result is significant a weak correlation with family support. School support (β=0.782, P<0.01), social support (β=330, P<0.01), and family support (β=0.625, P<0.01) are all positively related to students' extrinsic conditions, with school support being the most important factor with regard to meeting students' extrinsic conditions and social influence exerting a weaker impact in this context. Extrinsic demand is significantly and positively correlated with intrinsic demand (β=0.779, P<0.01), and intrinsic demand is also significantly and positively correlated with development level (β=0.841, P<0.01). P<0.001 for all path coefficients, indicating that all path analyses of this structural model are significant.

3.3 System dynamics model of AI education development

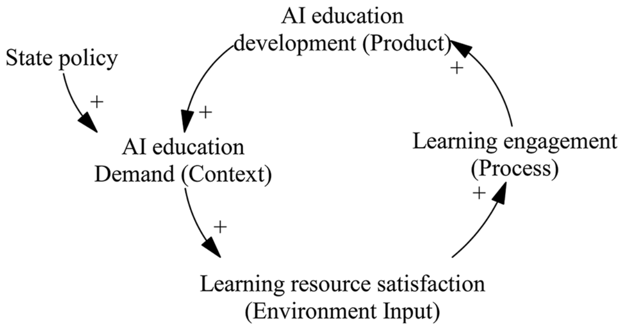
A system dynamics model for AI development in primary and secondary schools is constructed based on the path relationships developed using SEM. Firstly, Initial causal relationships are identified based on the path analysis results obtained from SEM. Secondly, the relevant variables are defined, and equations representing their interactions are formulated. Finally, with the defined variables and equations, a comprehensive system dynamics model is constructed.

3.3.1 Causality analysis

System dynamics theory believes that system behavior patterns and characteristics mainly depend on the internal dynamic structure and feedback loop mechanism. A feedback loop is a closed feedback loop composed of diverse relationships between factors in the system using causal relationships based on the path analysis results obtained from SEM.

Based on the system framework constructed by the CIPP model, Fig. 2 presents the core feedback loop diagram for AI education. The key elements include "AI education demand," "learning resource satisfaction," "learning engagement," and "AI education development level," each corresponding to the CIPP model categories of context, input, process, and product, respectively. This feedback loop shows the

Fig. 2 Core Loop of AI education in primary and secondary schools



impact of national policies on the development of artificial intelligence education in primary and secondary schools.

Conducting SEM path analysis, we initially derive the feedback loops for all variables based on the core feedback loop. Before conducting causal analysis, it is necessary to identify variables. Initially, variables in the causal diagram are determined based on the core elements in the core loop. Subsequently, the associations between influencing factors and variables within SEM are established, and the specific relationships are detailed in Table 6.

Subsequently, this process allows us to unveil the causal relationships among all variables. Analyzing the causal relationship of AI education in primary and secondary schools can study the interaction between various elements of the system and between the whole and the part. This causal relationship diagram qualitatively can be reflected by the feedback loop. The causal relationship diagram of the AI education development system in primary and secondary schools is as shown in Fig. 3.

3.3.2 Model flow diagram

Based on the cause relationship diagram, a flow diagram of the AI education system in primary and secondary schools can be constructed This flow diagram serves as a visual representation for quantitative analysis, effectively portraying the system's structure and dynamic characteristics. The transition from a causal relationship diagram to a flow diagram signifies a qualitative shift in how we describe system

Table 6 Variables of causal relationships

Core elements	Variables	Influencing Factors
AI education demand (Context)	State Policy	ZF2
	Social Demand	ZF1, ZF5
	School Demand	XX1
	Family Demand	JT1, JT2, JT3
	Student Demand	IC1, IC2
Learning resource satisfaction (Input)	School-based Teaching Resources	XX4,
	School Capital Inputs	XX5,
	Number of Hours Offered	XX2,
	Social Capital Inputs	ZF3,
	Family Capital Inputs	JT4, JT5
	Network Resource	SH5
	Number of National Science Museums	ZF4, SH1
	Off-campus Organizations	SH3, SH2
	AI competition	SH4, EC4
Learning engagement (Process)	Student Motivation	IC3, IC4, IC5
	Learning Inputs	EC1,
	Teachers' Strength	ZF6, XX3, EC2,
	Number of Teaching Resources	EC3, EC5
AI education development level (Product)	Amount of AI Knowledge in Primary and Secondary Schools	L1, L2
	Level of development of Artificial Intelligence Education in Primary and Secondary Schools	L3

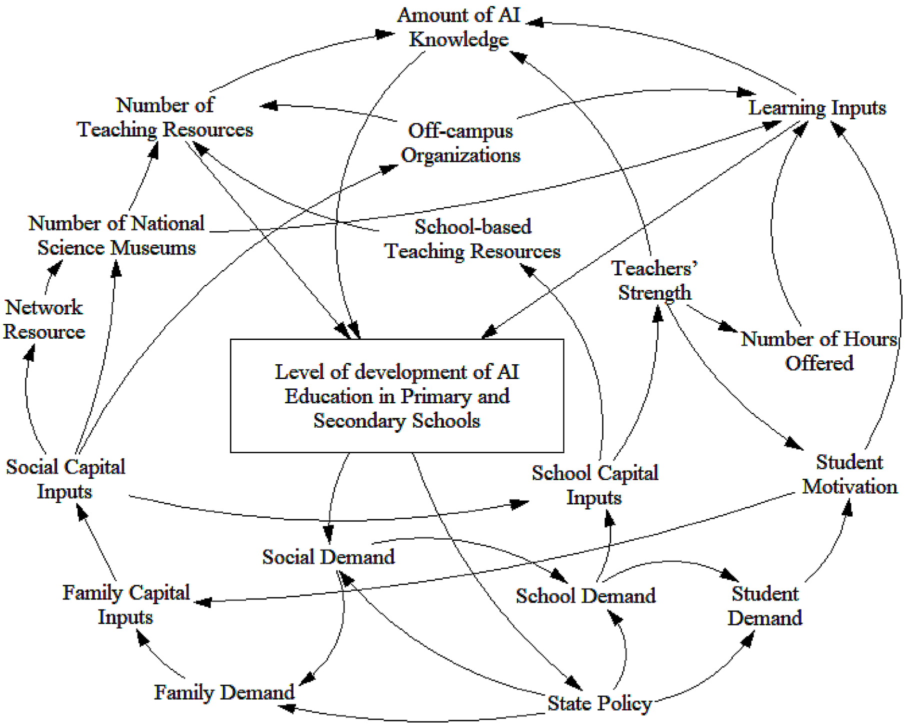


Fig. 3 Cause relationship diagram of AI education in primary and secondary schools

intricacies. To facilitate quantitative analysis, it becomes imperative to define state variables, rate variables, and auxiliary variables, laying the groundwork for a comprehensive understanding of the system dynamics.

The state variables represent the cumulative variables of the system, i.e., the stock, which is usually the element of most concern and represents output required by the decision-maker. This study considers "AI education development level," "learning resource satisfaction," "learning engagement," and "AI education demand" as state variables.

The flow rate variables are the amount that increases or decreases a state variable over time, which can be set based on state variables. We set "rate of change in AI education development", "growth rate of learning resources", "growth rate of learning engagement" and "growth rate of AI education demand" as the flow rate variable.

Auxiliary variables are intermediate variables that express the decision-making process and are also an effective means of analyzing feedback structures. Auxiliary variables are obtained based on variables in the causal relationship, as shown in Table 7.

The constant is that remains constant or changes slightly during research is called a constant. We set the initial value of the state variables, i.e., "Initial value of the development level of AI education", "Initial value of learning resources", "Initial value of learning engagement", and "Initial value of learning demand", to constant.

Table 7 Main dynamic equations of the AI education system model for primary and secondary schools

Variable Type	Variable Name	Equation Expressions
State Variables	AI Development Level	INTEG (AI education development growth rate, AI development level preliminary value)
	AI Learning Resources Satisfaction	INTEG (AI learning resource growth rate, initial value of learning resources)
	AI Learning Engagement	INTEG (degree of AI learning input growth rate, degree of learning input initial value)
	AI Education Demand	INTEG (Growth rate of demand for AI education, initial value of learning demand)
Rate Variables	Change Rate of AI Education Development	0.4*AI educational resource satisfaction degree+0.6*AI education degree of learning input
	Growth Rate of AI Learning Resources	0.2*social teaching resources+0.1*internet teaching resources+0.3*family teaching resources+0.4*school teaching resources
	Growth Rate of the Degree of AI Learning Input	0.1*National Science Museum+0.1*Artificial Intelligence Competition+0.2*Number of out-of-school trainings+0.5*Number of school hours
	Growth Rate of AI Education Demand	0.05*social demand+0.15*family demand+0.35*school demand+0.45*student demand
Auxiliary Variables	National Policy	UPLOOK(TIME)
	College Admissions Policy	UPLOOK(TIME)

This paper uses the time function to represent the trajectory of each variable over time in the model simulation process and constructs the simulation flow diagram of the system dynamics model of AI education in primary and secondary schools using *Vensim* software, as shown in Fig. 4.

3.3.3 Equation construction

For each type of variable listed above, the quantitative relationships among state variables, level variables and auxiliary variables are constructed based on the correlation coefficients among the variables in the structural equation model of the system, the functional characteristics and the fits of the intrinsic relationships of related indicators based on questionnaire surveys. Furthermore, the constant values are calculated based on the initial mean values revealed by the questionnaire surveys. Some of the kinetic equations pertaining to the AI education system for primary and secondary schools are shown in Table 7.

4 Results of simulation study

Based on the dynamics model of the AI education system in primary and secondary schools, *Vensim* software is used to predict and analyze the development level to explore the development trend, and comprehensive controlled simulation is used to explore the relevant high-leverage influence factors (Qudrat-Ullah, 2010).

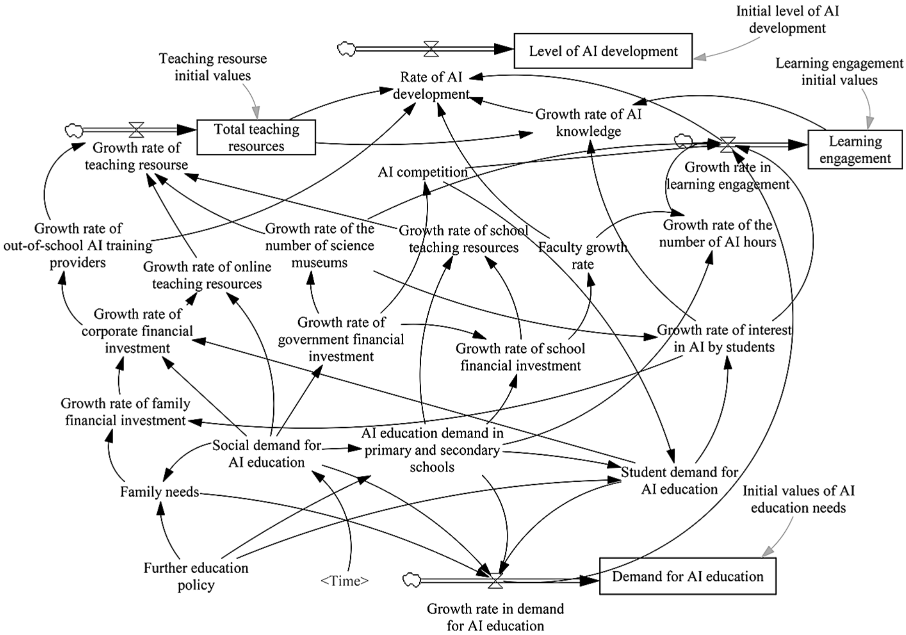


Fig. 4 System dynamics model of AI education in primary and secondary schools

4.1 Parameter settings

The influencing factors of the development of AI education in primary and secondary schools are relatively complex, and the data collected for each influencing factor are not of the same dimension. In order to evaluate the role of each influencing factor at the same scale, we use the 7-point Likert scale data (7 = Strongly agree; 1 = Strongly disagree) in the questionnaire survey and calculate the average value of each variable as simulation data to conduct simulation analysis. Therefore, the range for all variables is [1, 7]. The system dynamics model empowers us to engage in predictive and controlled simulations of AI education development in primary and secondary schools. This process is inherently dynamic as it encompasses changes and interactions occurring at various time points. Within this model, we consider the interplay among diverse factors and simulate the evolution of these relationships across different time intervals. This approach yields a more profound understanding of the dynamic nature of AI education development in primary and secondary schools.

Controlled simulations entail the manipulation of specific variables while maintaining other factors as constants. This method enables us to dynamically investigate the role of specific factors in the development of AI education in primary and secondary schools, providing valuable insights into how these factors influence the overall system and how their effects evolve over time. We systematically varied the constant values of learning demand, educational resources, learning engagement, environmental, and state policy factors by increasing and decreasing them by 10%. This analysis aimed to examine their respective impacts on the development of AI education in primary and secondary schools, elucidating factors with significant leverage.

4.2 Prediction analysis result

The level of development of AI education in primary and secondary schools was determined to be [1, 10], with 1 indicating the initial value of AI education in primary and secondary schools and thereby representing the starting stage of development; the higher the level is, the higher the development level. Based on the set parameters and variable equations, the development level of AI in primary and secondary schools from 2017 to 2022 was fitted, and the baseline development level in 2017 was set as 1. The results showed that the development level in 2022 was close to the mean value of the development level of all students in the questionnaire data; thus, the model was considered to exhibit a high goodness of fit and could be used to predict the development of AI education in primary and secondary schools. Overall, based on the strong promotion effects of the government and the joint efforts of schools, families and society, the development trend of AI education in primary and secondary schools in China is predicted, as shown in Fig. 5. Regarding the overall trend, the developmental momentum of AI education in primary and secondary schools in China is not strong. Since 2017, the development level has been influenced by the national policy at a rate ranging from 1 to 2.35, and the overall development level ranges from 1 to 3.75 over a period of 100 months. However, the momentum remains insufficient, and thus far, this trend has not reached the general development level.

4.3 Controlled simulation analysis results

In this paper, to study the influence of various factors in the system on the overall development level, the simulation of the factors influencing AI education in primary and secondary schools is studied in terms of several dimensions, including (1) a con-

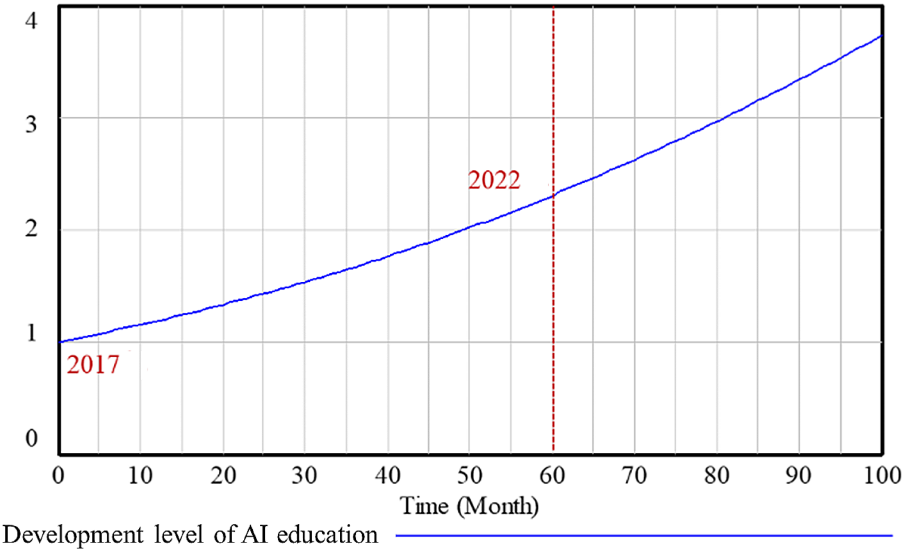


Fig. 5 Overall development of AI education in primary and secondary schools

trol simulation of the development of AI education in primary and secondary schools with regard to the intrinsic factors affecting AI education; (2) a control simulation of the development of AI education in primary and secondary schools with respect to the factors affecting the learning environment; and (3) a control simulation of the development of AI education in primary and secondary schools from the perspective of policy optimization.

4.3.1 Control simulation analysis based on the intrinsic elements of the system

The internal factors influencing the AI education system in primary and secondary schools are analyzed, and the control simulation is mainly focuses on three factors: learning demand, teaching resources and degree of learning input. The related constant parameter values of learning demand, teaching resources and degree of learning input are increased or decreased by 10% to analyze their effects on the development level of AI education, the simulation results are shown in Fig. 6. Firstly, the simulation results show that the degree of learning input has the greatest influence on AI education in primary and secondary schools for example, increases in class time and teachers greatly promote the effect, followed by the influence of learning demand. Second, educational resources serve as a fundamental foundation for the development of AI, the simulation results are shown in Fig. 6 (b). At present, with regard to the impacts of teachingeducational resources, the positioning of AI education is not uniform enough; thus, teaching resources also vary, as does the quality, and teaching content is insufficiently uniform, resulting in certain problems. Therefore, the problems associated with teaching resources largely restrict the development of AI education in China. Finally, the demand for AI education is the fundamental driving force for the development of AI education in primary and secondary schools, the resulets is shown in Fig. 6 (c). If there is no demand, society, schools, etc., does not practice or make capital investments in AI education, thus fundamentally restricting the development of AI education.

4.3.2 Control simulation analysis based on environmental factors outside the system

To study the influence of the learning environment on the AI education system, the values of the constants related to the social environment (including social and online education), the family environment, the school environment and internal student factors were increased by 10% to analyze their influence on the development level of AI education. The simulation results are shown in Fig. 7. These results show that when the internal parameters of each environment are increased by 10%, the level of development of AI education in primary and secondary schools also increases accordingly, but differences are observed in the degree of growth. The factors that cause changes in the level of development are as follows, in descending order: social factors, school factors, student factors, and family factors. This result indicates that the social environment and the school environment are the main factors affecting the development of AI education in primary and secondary schools. Since AI education in primary and secondary schools remains at an early stage, the lack of teachers, edu-

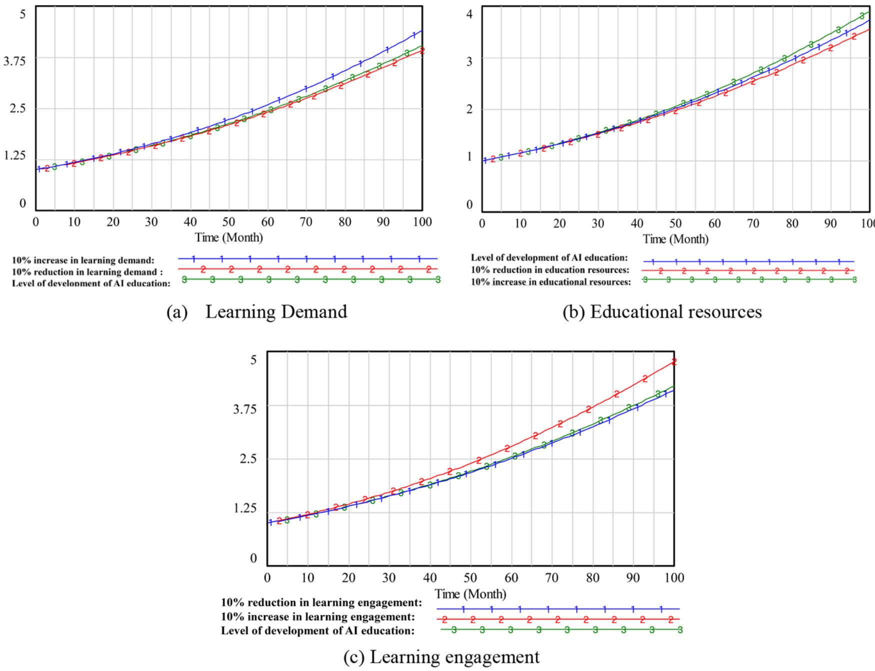


Fig. 6 Control simulation of the impacts of intrinsic factors on AI education in primary and secondary schools. **(a)** Demonstrates the influence of learning demand on AI education, indicating the second-highest impact among the factors. **(b)** Shows the impact of educational resources, which is identified as the least influential factor in this context. **(c)** Highlights the effect of learning engagement, which is shown to have the most significant impact on AI education

cational resources, and educational equipment in schools entails that the current level of development in schools is lower than it would be otherwise. In contrast, based on the promotion and implementation of policies, many enterprises in society are committed to AI education in primary and secondary schools, and more educational resources and intelligent equipment are invested in institutions other than schools, such as science and technology venues, off-campus programming training sites and other institutions. Therefore, the social environment has a significant impact on promoting the development of AI education in primary and secondary schools.

4.3.3 Control simulation analysis based on the factors influencing policy optimization

Relevant national policies set guidelines for the development of AI education in primary and secondary schools. Controlled simulations were conducted to investigate the influencing factors of national policy, promotion policy, and national financial investment with the goal of exploring their impacts on AI education in primary and secondary schools; the results of these simulations are shown in Fig. 8. The strengths of the national policy, the promotion policy, and the government financial investment were increased by 50% to analyze their effects on the development of AI education in primary and secondary schools. The simulation results show that, first, the promo-

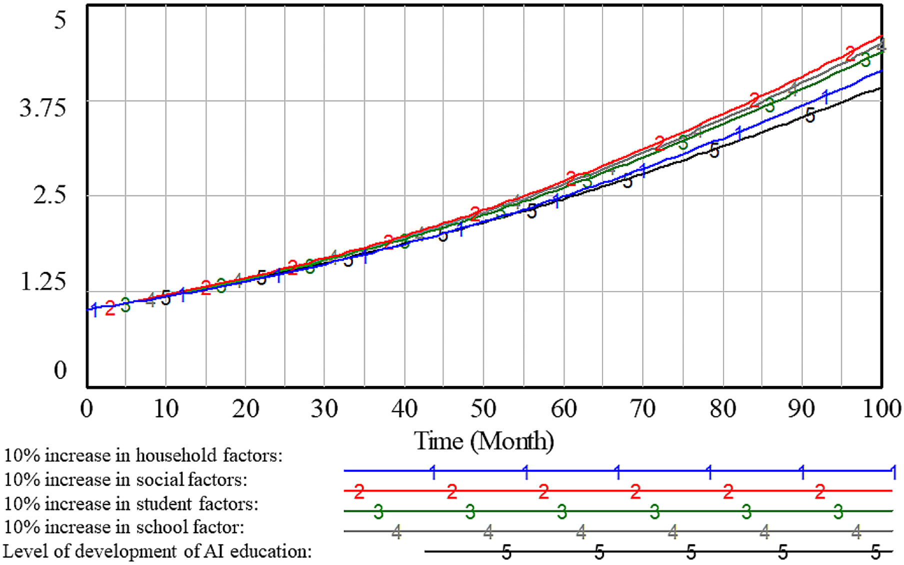


Fig. 7 Control simulation of the impacts of environmental factors on AI education in primary and secondary schools

tion policy plays an important role in promoting the development of AI education in primary and secondary schools, and the AI development level increases from 3.75 to 6. The current AI curriculum is not related to students' pathways to higher education and is not a major course; thus, there is no demand for the development of AI education, which makes such development insufficient. Second, the optimization of relevant national policies also plays a role in the development of AI education and has a driving effect in this context, increasing the development level to 9. Therefore, in response to problems associated with policies related to AI education in primary and secondary schools in China, such as the lack of curriculum standards, unclear positioning, and imperfect means of evaluation, currently used primary and secondary school AI education teaching materials are not standardized, teaching quality varies, and class time cannot be guaranteed. This situation urgently requires optimization. Finally, the state's financial investment guarantees that the steady development of AI education in primary and secondary schools is based on sufficient teaching resources, teaching equipment and teachers' strengths, and such investments also promote the steady development of AI education in primary and secondary schools.

5 Discussion and implication

5.1 The demand for AI education is the internal driver underlying the development of AI education

The needs associated with AI education can be divided into the internal needs of the learners and the external needs of the social environment. The internal needs of learners

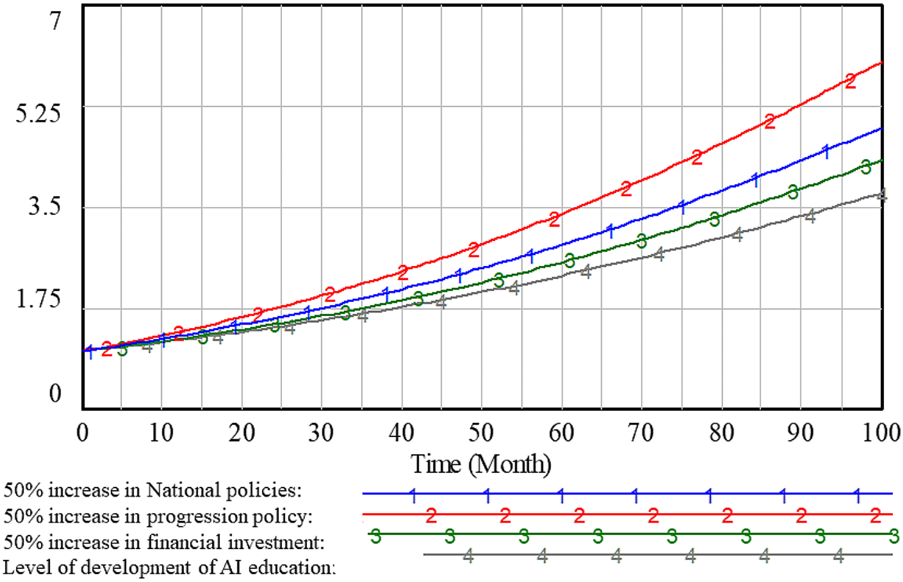


Fig. 8 Control simulation of the impact of policy optimization on AI education in primary and secondary schools

are expressed in the objective needs of learners with regard to AI learning goals, which affect the motivation of learners to engage in course learning as well as their learning commitment. The external needs of the social environment are expressed in macrolevel requirements resulting from the social environment and the overall mechanism underlying learners' learning goals, which play a guiding role in the development of AI education in primary and secondary schools. Influenced by the emergence of the smart era and national policies, society's demand for AI talent has become an urgent issue, which to a certain extent affects not only the demand exhibited by schools, teachers and parents but also learners' attitudes toward and demand for AI education. The factors influencing social demand are complex and diverse, including national policy on further education and the investment of education funds. Therefore, improving national macrolevel policies on AI education is an important way to improve the country's ability to satisfy the demand for AI education in primary and secondary schools.

5.1.1 AI teaching resources provide key support for the development of AI education

The successful development of AI education in primary and secondary schools cannot be ensured without the support of necessary teaching resources, especially human and nonhuman resources that can support AI education; these resources mainly include school-based resources, social resources and network resources. School-based resources currently face problems such as limited resources, a lack of teachers, untimely resource updates, and the inability to maintain equipment, which to a certain extent restrict the development of AI education in primary and secondary schools. Influenced by the policy, many high-tech enterprises have invested in the development of AI educational resources. Social resources offer advantages such as diverse forms, abundant resources and advanced equipment; however, they also entail certain problems, such as uneven quality and a lack of uniform standards. The development of AI educational resources requires continuous exploration and experimentation. Many companies choose to cooperate with primary and secondary schools to explore AI education and develop more teaching resources that are in line with the cognitive rules and learning interests of primary and secondary students. Many educational resources on AI are available on the internet, but online course resources by themselves cannot meet the equipment needs for conducting experiments, and a combination of online and offline teaching methods is needed to promote the development of AI education. In summary, on the one hand, with regard to the use of educational resources, a combination of online and offline teaching methods and a teaching mode that features cooperation between schools and enterprises can enable relevant actors to take full advantage of teaching resources and maximize value in the development of AI education; on the other hand, with regard to the content of teaching resources and issues such as uneven quality and inconsistent standards, there is an urgent need for both national and regional policies to provide guidance in this area as well as for the development of uniform standards and quality educational resources.

5.1.2 Student engagement in learning is an important guarantee for the development of AI education

Learning engagement is a necessary condition for learning effectiveness, and students' current learning in AI courses is mainly the result of education in school. Although the country is vigorously developing AI education in primary and secondary schools, AI courses are not mandatory and are included only as special courses in most schools. Due to the influence of promotion policy, it is impossible to take class time from other traditional subjects. Class time for AI courses cannot be guaranteed, and the lack of teachers limits students' learning time and commitment; thus, the learning effect cannot be guaranteed.

5.2 Development suggestions

5.2.1 Optimizing AI education policies from multiple perspectives to enhance learning needs

The development of AI education in primary and secondary schools is currently being promoted to a certain extent by the influence of national macrolevel policies. However, the purpose, content, and implementation path of AI education in primary and secondary schools as well as the corresponding system of teachers, facilities, funding, and evaluation have not yet been guided by a standardized policy. The development of AI education is still in its nascent stages, and measures associated with AI education have not been systematically put into practice. Neglecting the guiding role of the policy system in AI education is impeding the progress of AI education in primary and secondary schools (Huang, 2021). Therefore, it is necessary to enhance the corresponding evaluation policies to strengthen the evaluation of incentives related to AI education from the perspective of learning needs. In addition, the vitality of AI research and teaching can be stimulated through policies, titles, advancement, and other forms of motivation to address learning needs pertaining to AI education in primary and secondary schools.

5.2.2 Multisectoral collaboration to develop AI education and secure educational resources

The practice of AI education at the primary and secondary school levels requires the support of professional equipment, which is highly costly. At present, the development of AI education in primary and secondary schools in China faces problems such as non-uniform curriculum resources, a lack of teaching resources and a shortage of teaching equipment, which restrict development in this context. The multisubject nature of the development of AI education in primary and secondary schools entails that it is difficult to ensure the overall advancement of AI education by relying on a single subject alone and thus requires the full mobilization of relevant social forces. Therefore, it is necessary to comprehensively coordinate the joint collaboration of multiple sectors, such as governments, primary and secondary schools, enterprises and research institutions, to develop teaching resources that are suitable for the primary and secondary school stages, build an open system for the common construction and sharing of high-quality educational resources, provide solid institutional support and stable financial support for the allocation of educational resources and ensure realistic conditions for the implementation of AI education on the ground.

5.2.3 Develop an all-around AI education environment and strengthen learning input

The development of AI education in primary and secondary schools is not only focused on theoretical knowledge but also requires students to experience and practice AI to enable them to experience and feel AI in their lives. Therefore, it is not enough to teach in school; rather, the support of the social environment and family environment is also necessary. To facilitate primary and secondary school AI education, first, strong support from the school in terms of teaching objectives, class settings and teachers is needed to ensure that students are committed to learning. Second, strong support from society, in forms such as science museums, laboratories, research centers and other science and technology venues, is also an important way of establishing a learning environment in which students to learn AI. In addition, support from the family environment is very important. Families have a tremendous influence on students' investment in AI education as well as their supportive attitudes. Based on the different learning contents and learning methods provided by "society, school, and family", we establish a learning environment in which students can learn anywhere and anytime, thus ensuring their engagement in learning.

6 Conclusion

The development of AI education in primary and secondary schools is a critical requirement in today's context, playing a pivotal role in fostering digital literacy and enhancing skills across all segments of the population. However, there is still a lack of comprehensive understanding regarding the influencing factors, dynamic mechanisms, and development strategies associated with the AI education system in the context of basic education in China. In this paper, we have delved into the intricate factors that influence AI development in primary and secondary schools, and have constructed a dynamic model of the AI education system. The development of AI education in the realm of primary and secondary schools is inherently dynamic, necessitating an exploration of the dynamic evolutionary process that unfolds through interactions among various elements of the system, achieved through a combination of qualitative and quantitative methods. We used simulations to forecast the development of AI education in Chinese primary and secondary schools. Our controlled simulations identified intricate factors influencing this development, allowing us to predict and validate elements crucial for progress. Our findings show that AI education in these schools is still in its early stages, lacking momentum. The results indicate that the development of AI education is influenced by external and internal student systems, with national policy as the driving force (Lu et al., 2021). In the current state of China, societal factors play a predominant role in the external environment, followed by school factors, while students' learning engagement is crucial internally (Sanusi et al., 2022a). Based on these findings, we propose improvements, including policy reforms and school-enterprise collaboration. Addressing these challenges requires a multifaceted approach, optimizing national policies and fostering collaboration among various stakeholders.

The research presented in this paper represents a pioneering endeavor to apply the system dynamics model to the realm of AI education development. While this study has provided valuable insights, there exist certain limitations that suggest avenues for further improvement in future research. One of the limitations lies in the assumption that the coefficients within the system dynamics model remain constant over time. For future research, it is imperative to address this limitation by considering the dynamic nature of these coefficients. The introduction of time-varying coefficients within the model can help us gain a more nuanced and accurate understanding of the evolving dynamics of AI education. This would not only enhance the comprehensiveness of our findings but also contribute to a more precise assessment of AI education's development trajectory in primary and secondary schools. Incorporating the dimension of time into the model's coefficients offers an exciting avenue for future research, with the potential to yield deeper insights and a more accurate representation of AI education's multifaceted development.

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Data availability The datasets used and analyzed during the current study are available from the corresponding author on reasonable request.

Declarations

Competing interests The authors declare that they have no competing interests.

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