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A novel cost analysis method for accelerator driven advanced nuclear energy system (ADANES) considering uncertainty throughout the R&D cycle

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HIGHLIGHTS

- A cost analysis approach is introduced for the disruptive ADANES nuclear energy system.
- It employs a logistic function-based evaluation method and stochastic differential equation to account for uncertainties.
- A case study validates the method, revealing the numerical relationship between time extension and cost overrun of ADANES.

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ABSTRACT

The Accelerator Driven Advanced Nuclear Energy System (ADANES) is currently undergoing research and development (R&D), presenting challenges in cost estimation due to significant uncertainties. Traditional nuclear power cost assessment methods, tailored for mature technologies, lack relevance for advanced systems like ADANES. To address this gap, our study proposes a unique cost analysis approach, dividing ADANES into two stages: the experimental research and development (ERD) stage and the industrial demonstration (ID) stage. Specifically, in the ERD stage, this study employs a Logistic function-based evaluation method that considers factors such as construction period extension, the proportion of fixed costs, and the upper limit of cost estimated by experts to address potential cost overruns. For the ID stage, this study utilizes a stochastic differential equation (SDE) to account for uncertainties. Monte Carlo simulation is employed to analyze the impact of parameter changes, including construction period extension and acceptable upper limits of cost and duration. Results reveal a substantial increase in expected cost during the ERD stage, ranging from 100% to 140% of the original budget when extending the experimental research duration by 10% to 50%. The ID stage demonstrates an even more significant impact, with a 50% construction period extension resulting in an expected cost of 182% of the original budget. The study suggests that judiciously extending acceptable cost and duration caps can enhance the project's success rate. This innovative cost analysis approach provides valuable insights for navigating the uncertainties associated with ADANES development.

1. Introduction

Nuclear energy, recognized for its stable, economical, and efficient energy source, has become a pivotal element in the pursuit of 'carbon peak and carbon neutrality' goals [1], attracting global attention and development efforts [2]. Currently, most operational nuclear power units globally employ second-generation nuclear technologies. Nevertheless, these technologies face various challenges, such as restricted

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nuclear fuel utilization, complexities in efficiently managing nuclear waste, and safety apprehensions. Consequently, the global nuclear energy community is actively exploring advanced nuclear energy technologies to tackle the economic, safety, and environmental challenges inherent in the progress of nuclear energy [3].

In response to the challenges associated with inefficient utilization of nuclear fuel and apprehensions regarding nuclear proliferation, the Chinese Academy of Sciences has proposed a pioneering solution—the Accelerator Driven Advanced Nuclear Energy System (ADANES). ADANES, consisting of a combustion system and a fuel reclamation system [4], could markedly improve the efficiency of nuclear fuel utilization, increasing it from <1% to around 95%. Simultaneously, it diminishes the radioactive lifespan of generated nuclear waste from several hundred millennia to only a few hundred years, compared to spent fuel from pressurized water reactors (PWRs). Nevertheless, ADANES is currently in the ERD stage, marked by significant technical uncertainties and considerable investment costs. Notably, the nuclear energy sector often encounters financial overruns due to prolonged construction durations. Recent data from the past decade indicates that over 60% of global nuclear reactors have faced delays and increased expenses [5]. Sovacool et al. (2014) analyzed the expenses and duration of constructing 180 nuclear power reactors. Among these, 64 ventures experienced cost overruns exceeding one billion dollars, with 14 projects surpassing 5 billion dollars in additional costs. Moreover, ten projects encountered cost escalations exceeding 400%, resulting in an overall average project cost increase of 117% [6]. Thus, in contrast to well-established nuclear technologies, this pioneering advanced nuclear energy system lacks historical antecedents, facing the potential risk of project termination due to setbacks in the ERD stage. Therefore, there is an urgent need to conduct in-depth research on cost analysis for ADANES, serving as a reference for ongoing cost analysis efforts in the development of other nuclear energy systems.

Previous studies on the cost assessment of nuclear power have primarily focused on well-established nuclear power technologies. Insufficient attention has been given to estimating the costs associated with developing advanced nuclear energy systems. To bridge the identified gap, this study presents a novel cost analysis method for ADANES, encompassing uncertainties such as time extensions and cost overruns. The proposed approach divides overall costs into two components, aligned with the two phases of ADANES. The initial phase is reinforced by implementing the Logistic function, while the subsequent phase is refined using stochastic differential equations (SDE) [7]. Furthermore, a Monte Carlo simulation is employed for probabilistic analysis. This refinement allows both phases to incorporate cost escalations arising from prolonged construction durations.

The rest of this paper is organized as follows: Section 2 reviews relevant literature. Section 3 outlines the principles underlying the proposed method. In Section 4, a numerical simulation analysis of the cost of ADANES is performed. Lastly, Section 5 presents the conclusion and outlines future directions.

2. Literature review

The prevailing methods for appraising nuclear energy costs encompass Code of Accounts (COA), Total Capital Investment Cost (TCIC), Levelized Cost of Electricity (LCOE), Levelized Unit of Electricity Cost (LUEC), Top-down cost assessment, and Bottom-up cost assessment. The widely adopted approach for evaluating nuclear power costs is the Code of Accounts (COA) from the U.S. Department of Energy (USDOE) Energy Economic Database (EEDB) [8]. COA facilitates the decomposition of major costs into individual systems and projects. The principal costs of nuclear power (total capital investment, fuel cycle, operation, and maintenance costs) undergo further subdivision [9]. This method is frequently employed for assessing the costs of mainstream Pressurized Water Reactors (PWRs) (Holcomb et al., 2011 [10]; Stewart and Shirvan, 2020 [11]; Maronati et al., 2020 [12]).

Additionally, the International Atomic Energy Agency (IAEA) introduced the Total Capital Investment Cost (TCIC) parameter [13], which denotes the cost incurred in the design, construction, and testing of nuclear power plants until commercial operation. TCIC chiefly comprises Fore costs, Escalation costs, and Interest costs. Fore costs encompass base costs, supplemental costs, the owner's capital investment, and services costs [14]. Globally, Overnight Capital Cost (OCC) and Levelized Cost of Electricity (LCOE) are commonly utilized indices to assess the economics of nuclear power (Lovering et al., 2016 [15]; Asuega et al., 2023 [16]; Riesz et al., 2016 [17]; Anadon et al., 2013 [18]). OCC is a pivotal index within TCIC, while LCOE is a widely acknowledged and applied economic model for power technology on a global scale. LCOE comprehensively considers the time value of various costs in cost estimation, including TCIC, operation and maintenance, and fuel costs. Additionally, Levelized Unit of Electricity Cost (LUEC) is a leading metric for gauging nuclear power costs [19]. This metric accounts for all life cycle costs and is expressed in energy currency, typically [$/kWh] [20]. LUEC is commonly used to compute the cost of commercialized second-generation and third-generation reactors.

Furthermore, nuclear power cost assessment methods and COA comprise top-down and bottom-up cost estimation methods [21]. Two-digit COA can be employed for bottom-up and top-down cost assessment methods, while three-digit and higher COA are generally reserved for bottom-up estimation methods. The bottom-up evaluation method necessitates supporting data such as unit labor cost, commodities, installation rates, construction labor hours estimation, and selection requirements. On the other hand, the top-down estimation method generally applies to projects in the early stages of development. Most fourth-generation nuclear energy systems utilize these methods, often considering the system and equipment costs used by similar projects. Notably, bottom-up and top-down cost estimation methods typically exclude the cost of the early ERD, typically funded by government or public organizations. The nuclear power cost assessment methods are summarized in Table 1.

Several studies integrate uncertainty into the assessment of nuclear power costs, utilizing project accounting standards proposed by USDOE. Maronati and Petrovic (2019) [23] devised a methodology grounded in the Iman-Conover approach. Typically, Monte Carlo simulation is employed to stochastically examine construction progress and cost accounting. Consequently, probabilistic evaluations were conducted on the construction cost and timeline for the representative PWR12-BE nuclear power plant. Subsequently, Maronati and Petrovic (2020) [24] explored the ramifications of accidents. In the research conducted by

Table 1
Nuclear power cost assessment methods.

Methods	Evaluation object and applicability
COA	A comprehensive accounting system developed by the International Atomic Energy Agency (IAEA) can handle a series of costs such as capital, fuel cycle, operation and maintenance, from the entire nuclear power plant to individual systems and components. COA has a high degree of flexibility and can be applied to all types of reactors, single or dual-use energy devices.
Top-down cost assessment method	Combined with COA, it is suitable for immature reactors, but requires data support for similar projects and costs (cost project data support for experimental reactors is required).
Bottom-up cost assessment method	Combined with COA, it is suitable for more mature reactors and requires a lot of data support.
TCIC	Combined with COA, TCIC consists of total overnight construction cost (OCC) and capitalized financial cost (CFC), which is suitable for more mature reactors.
LCOE	Combined with COA, it is often used to calculate the cost of commercialized second- and third-generation reactors.
LUEC	Combined with COA, it is often used to calculate the cost of commercialized second- and third-generation reactors.

Data source [22].

Egieya et al. (2023) [25], the IAEA nuclear power human resources (NPHR) modeling tool, constructed through the system dynamic modeling (SDM) method, was employed to model and assess the labor demand and wage components of a 300 MWe integrated pressurized water reactor (iPWR) from 2018 to 2055. Utilizing Monte Carlo simulation, the paper examines the impact of construction period uncertainty on the cost of advanced nuclear energy systems.

In the above studies, the assessed subjects exhibit a higher level of maturity, with computations relying on an intricately defined database. The methods are unsuitable for advanced nuclear energy systems typified by ADANES, most of which are in the research and development phase and lack historical precedents. To bridge this disparity, this study introduces a novel cost evaluation method tailored to ADANES.

3. The model framework and solution method

3.1. Analysis of nuclear energy research and development process

Technology Readiness Level (TRL) is an effective tool to evaluate the R&D process of nuclear energy systems, which is divided into nine magnitudes (US Government Accountability Office, 2016 [26]; Dovichi Filho et al., 2021 [27]; Xianya He et al., 2023 [28], Carmack et al., 2017 [29]) as shown in Table 2.

The ERD stage corresponds to TRL1 ~ TRL6 which main task is to carry out experimental research and development of related technologies., and the TRL in ID stage are TRL7 and TRL8 which main task is to verify the overall technology and to verify whether the feasibility and economy of the technology meet the commercial promotion conditions.

Table 2
Definition of nuclear energy technology maturity.

TRL	Description of TRL
TRL1	A new fuel concept is proposed.
TRL2	The technical options have been identified and preliminary evaluation is underway.
TRL3	Concepts are verified through laboratory-scale experiments and characterization.
TRL4	At TRL 4 fabrication of samples using stockpile materials at bench-scale yielding small fuel elements, rodlets, and small-scale pin configurations.
TRL5	TRL 5 is an advancement over TRL 4 with an increase in the fabrication of full-scale fuel elements using laboratory-scale fabrication capabilities with subsequent pin-scale irradiation testing conducted in relevant prototypic steady-state irradiation environments.
TRL6	Technologies at TRL 6 are at an intermediate step between the Proof-of-Principle and the Proof-of-Performance phases.
TRL7	TRL 7 represents the established capability to fabricate test assemblies using prototypic feedstock materials at an engineering scale and using prototypic fabrication processes.
TRL8	TRL 8 designates that a few core loads of fuel have been fabricated and full core operation of a prototype reactor with such fuel has been accomplished.
TRL9	TRL 9 designates that the fuel technology is routinely conducted at commercial-scale and normal operations are underway.

Source: Carmack et al. (2017) [29].

3.2. Technology R&D model and solution

Over time, the nuclear energy technology was escalated from lower TRL to higher TRL while this development process often does not happen exactly as expected (shown as path ② in Fig. 1) in reality, either earlier (shown as path ① in Fig. 1) or delayed (shown as path ③ in Fig. 1). The uncertainty of the success time of each TRL leads to the uncertainty throughout the construction period, and thus the expected cost of the actual expenditure is different from the original budget. The early arrival of time for technical success leads to cost savings, while time delays lead to cost overruns.

In the ERD stage the R&D cost include equipment cost, personnel management cost, R&D material cost, and so on. In its initial phase, the cost is slowly increasing which is mainly focused on the approval of land and other expenses. In the middle phase, the cost will rise rapidly which mainly relates to the construction of relevant laboratories and the experimental expenses. In the later phase, the cost grows slowly again, and the cost is associated to some key technologies that have not yet been overcome. This process is similar to the Logistic function as shown in Fig. 2. This paper attempts to use the Logistic function to describe the relationship between the time extension of the ERD stage and the cost overrun as in the study of Deeney et al. [30] the Logistic function was used to characterize the impact of technological breakthroughs on the unit cost of goods.

An improved Logistic function is proposed as shown in Eq.(1) where $R(\Delta t)$ represents the ratio of the expected cost to the initial budget in the ERD stage. When$R(\Delta t)>1$, it means that the expected cost overruns; When$R(\Delta t)<1$, it means that the expected cost savings; When$R(\Delta t)=1$, it means that the expected cost is equal to the initial budget. Δt represents the difference between the successful time of the actual technical maturity and the planned time. $\Delta t>0$ indicates that the construction period is prolonged, $\Delta t<0$ indicates that the construction period is advanced, and$\Delta t=0$ indicates that the construction period is the same as the planned time. a,b,c_1,c_2 are the coefficients that control the shape of the Logistic function.

$$R(\Delta t) = \frac{c_1}{1 + e^{-a\Delta t + b}} + c_2 \tag{1}$$

In ERD stage, the cost has the following characteristics:

First, when the construction period is advanced, the cost reduction is limited due to the existence of fixed cost expenditure. When the construction period is advanced for a long time, the cost will not be reduced to 0, that is, there is a lower limit of cost savings R^{min}, R^{min} represents the proportion of fixed costs to the initial budget. For example, equipment, laboratory construction, material costs, etc. in the ERD. ($\lim_{\Delta t\to -\infty} R(\Delta t) = R^{\min}$, $0 < R^{min} < 1$).

Second, there is an upper limit of the cost overrun R^{max}, R^{max} represents the ratio of the maximum estimated cost to the initial budget according to the technical characteristics of the experts in the ERD. With the extension of the construction period, the cost overrun will continue to approach this upper limit ($\lim_{\Delta t\to\infty} R(\Delta t) = R^{\max}$, $R^{max} > 1$). Therefore, the curve shape of the Logistic function is shown in Fig. 3.

Third, when$\Delta t=0$, it means that the technical success time point just arrived, the cost is exactly consistent with the budget, and the cost change range is$R(0) = 1$. The shape of Logistic function is determined by a, R^{min} and R^{max}, and its value is related to the complexity of technology. Taking $R^{max} = 2.2$ and $R^{min} = 0.8$ as an example, the characteristics of a are observed. As shown in Fig. 4(a), when a is larger, the technical complexity is higher and the degree of $R(\Delta t)$ change is greater, which means that the extension of the construction period and the advance of the construction period have a greater impact on the cost. Similarly, the higher the technical complexity, the longer the R&D time, the greater the input cost under the same R&D time to meet the cost requirements of the corresponding technical complexity. As shown in Fig.4 (b), the higher the technical complexity, the smaller the R^{min}, the smaller the proportion of fixed costs to the initial budget(the greater the uncertainty cost), which means that the greater the proportion of R&D costs to the initial budget, the same time in advance of the construction period, the more R&D costs are saved; As shown in Fig. 4 (c), the higher the technical complexity, the greater the R^{max}, the greater the expert's estimate of the total cost of the technology, which means that more costs are invested, and the same time for the extension of the construction period, more costs need to be invested to meet the technical complexity requirements.

According to the description of the characteristics of the above function, the values of b, c_1, and c_2 in Eq. (1) can be solved.

$b = ln\frac{R^{\max}-1}{1-R^{\min}}$; $c_1 = R^{\max} - R^{\min}$; $c_2 = R^{\min}$.

Substituting these into Eq. (1), we get

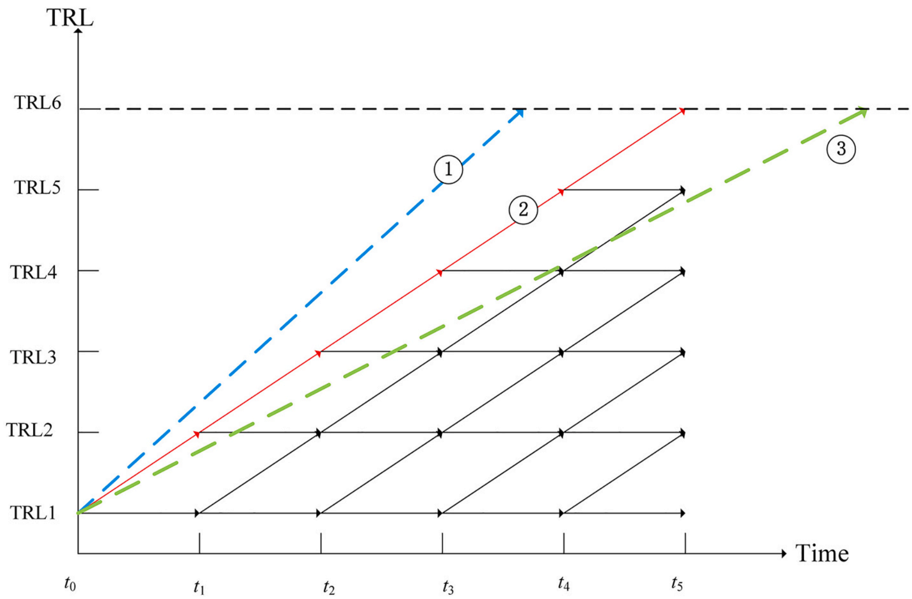


Fig. 1. Technology development paths in the ERD stage.

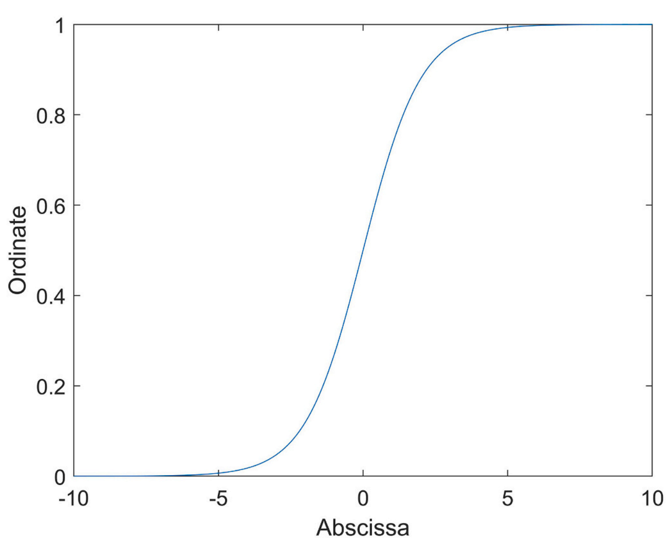


Fig. 2. Logistic function.

$$R(\Delta t) = \frac{R^{\max} - R^{\min}}{1 + e^{-a\Delta t + \ln\frac{R^{\max}-1}{1-R^{\min}}}} + R^{\min} \tag{2}$$

For the estimation of R^{max}, R^{min}, and a, the R&D team can refer to the R&D cost and time data of the same or similar technology for the estimation of parameters. For the original technology, when there are no same or similar technical data, the relevant data can be continuously observed and recorded during R&D, and the parameters can be estimated and continuously corrected in the Logistic function. Next, this paper defines$\Delta t_i$is random. In the study of Asuega et al. (2023) [16], it is assumed that the construction period obeys the probability distribution. This paper assumes that the generation ofΔt_iobeys the normal distribution$\Delta t_i \sim N\left(t_i - t_{i-1}, \sigma_i^2\right)$,$i = 1,2,3,4,5$. $t_i$is the starting point of the current technology maturity, then$t_i - t_{i-1}$is the expected time between each TRL. Since the timeΔt_ispent on the technical jump is random, σ_i controls the interval that generates random time points. The value of σ_i is usually estimated by experts based on the actual situation of technology and information on similar technologies, and its mean value$t_i - t_{i-1}$can be estimated according to the time of implementation of existing similar technologies. If the implementation time of existing similar technologies is generally delayed, the time can be increased depending on$t_i - t_{i-1}$. Considering that the first reactor of a nuclear energy system is often delayed, this paper allows the total time of the R&D stage to exceed the expected time, but there is a time limit. The distribution of technology arrival time in the ADANES experimental development stage is shown in Fig.5. In order to consider the impact of the extension of the construction period, we focus on the right part of the normal distribution mean(the red part in Fig.5).

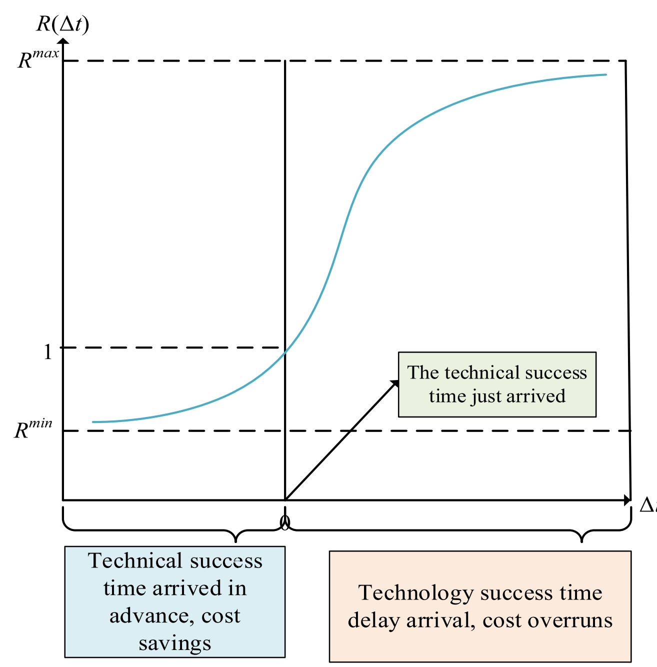


Fig. 3. Improved Logistic function of the ERD stage.

The total time of the ERD stage is $\Delta t = \sum_{i=1}^{5} \Delta t_i - (t_5 - t_0)$, and the total cost is shown in Eq. (3), where m denotes the number of simulated paths. We will use the idea of Monte Carlo simulation to simulate m cost paths.

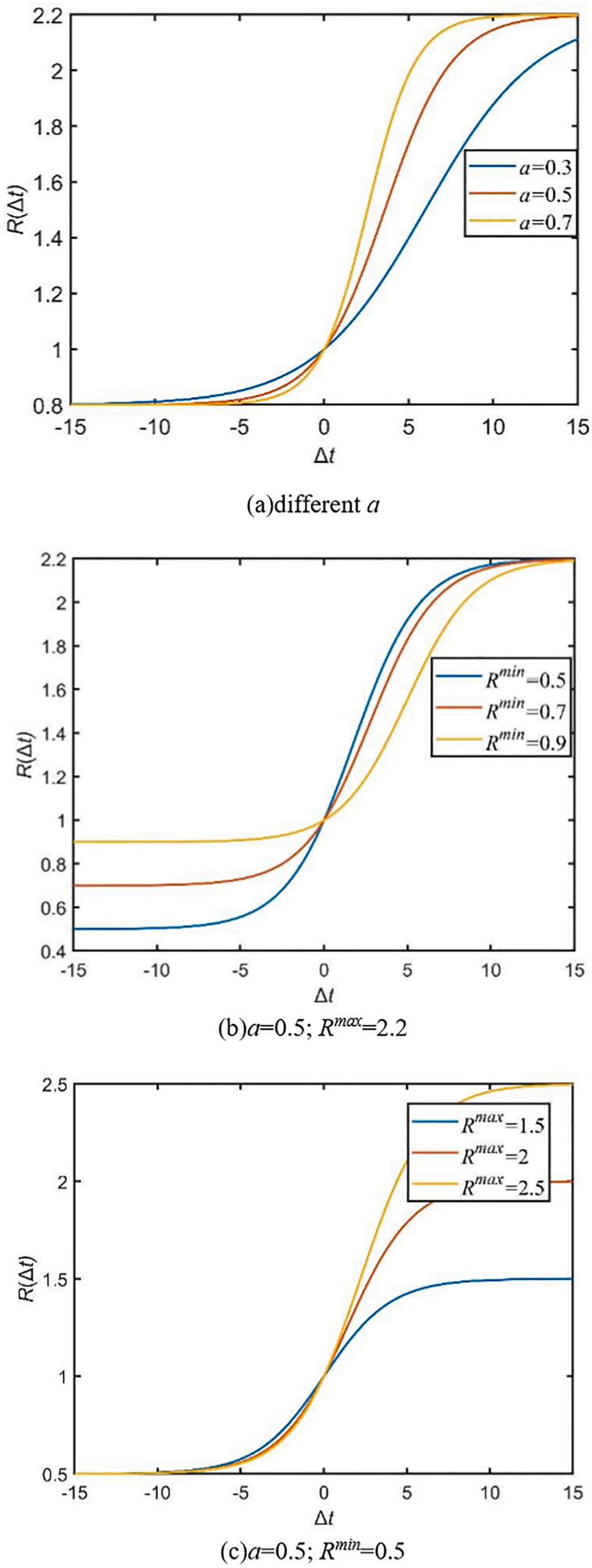


Fig. 4. The influence of different parameters on logistic function.

$$C_m = \sum_{i=1}^{5} C_i^{ERD}\left(\frac{R_i^{\max} - R_i^{\min}}{1 + e^{-a\Delta t_i + ln\frac{R_i^{\max}-1}{1-R_i^{\min}}}} + R^{\min}\right) \tag{3}$$

$C_m$represents the expected cost of the experimental development stage of an advanced nuclear energy system. C_i^{ERD} represents the initial budget of each TRL in the experimental development phase. In this study, the project termination conditions are also included in the R&D cost analysis framework proposed in this paper, and two project termination conditions are introduced: (1) when the actual R&D time exceeds the acceptable time, that is $\sum_{i=1}^{5}\Delta t_i > T + t_5 - t_0$, the project is terminated, which is judged as a failure of the R&D. Trepresents the acceptable duration extension time; (2) when the cost exceeds the upper limit of the acceptable budget, that is$C_m \leq C^{\max}$, the project stops, and$C^{\max}$is the upper limit of the acceptable cost.$C^{\max}$can be determined by industry experts according to national policies and related science and technology, enterprise funding efforts.

3.3. Industrial demonstration

As mentioned above, in the ERD stage, with the extension of the construction period, the total cost growth trend is like the shape of the Logistic function curve. The ID stage is to build a gigabit (>1000 MW) level demonstration reactor on the basis of the 100 MW (>100 MW) level in the ERD stage. There will be less technical research and development work in ID stage. The cost overrun in this stage is mainly due to the increase of equipment cost and labor cost caused by the design changes of different types of equipment and the extension of delivery time. At this time, the growth of the total cost tends to be linear. The SDE formula proposed by Pindyck (1993) is used to simulate the uncertainty of the construction cost of demonstration reactors in ID stage, shown in Eq. (4). .

The SDE formula has also been used by many studies to describe the random diffusion behavior of R&D project costs, such as Whalley (2011) [31]and Wang et al. (2020) [32]. The second term on the right of Eq. (4) represents the cost disturbance caused by technical uncertainty, such as the cost disturbance caused by different manufacturing time of different types of equipment during the construction of gigawatt demonstration reactor. The third item on the right side of Eq. (4) represents the cost disturbance caused by market uncertainty, such as the cost disturbance caused by the market price of materials such as cement and steel bars during the construction of demonstration reactors.

$$dC = -Idt + \beta(IC)^{1/2}dz + \sigma Cdw \tag{4}$$

Where C represents the remaining cost of the industrial demonstration of the project, I represents the investment rate, which is the cost of annual expenditure cost, and β is the degree of technical uncertainty. σ denotes the exogenous uncertainty of cost, which is related to the market, and dz and dw denote the independent Wiener process , $dz = \varepsilon_1\sqrt{dt}$, $dw = \varepsilon_2\sqrt{dt}$, $\varepsilon_1$and$\varepsilon_2$obey normal distribution, $\varepsilon_1 \sim N(0, \sigma_z^2)$, $\varepsilon_2 \sim N(0, \sigma_w^2)$. There is a technology jump phenomenon in the ID stage, and the residual cost C of the technology jump is shown in Eq. (5).

$$dC = \begin{cases} -Idt + \beta(IC)^{\frac{1}{2}}dz + \sigma Cdw & \text{for TRL6} \\ -I\theta dt + \beta(I\theta C)^{\frac{1}{2}}dz + \sigma Cdw & \text{for TRL7} \end{cases} \tag{5}$$

I and $I\theta$ can be considered to be the cost of each year for TRL6 and TRL7. Referring to the study of Schwartz [33] and Zhu [34]**,** the discrete form of the simulation path of Eq.(5) is approximately the following two forms.

$$C(t+1) = \begin{cases} C(t) - I(t)\Delta t + \beta\varepsilon_1\sqrt{I(t)C(t)\Delta t} + \sigma C(t)\varepsilon_2\sqrt{\Delta t} & \text{for TRL6} \\ C(t) - I(t)\theta\Delta t + \beta\varepsilon_1\sqrt{I(t)\theta C(t)\Delta t} + \sigma C(t)\varepsilon_2\sqrt{\Delta t} & \text{for TRL7} \end{cases} \tag{6}$$

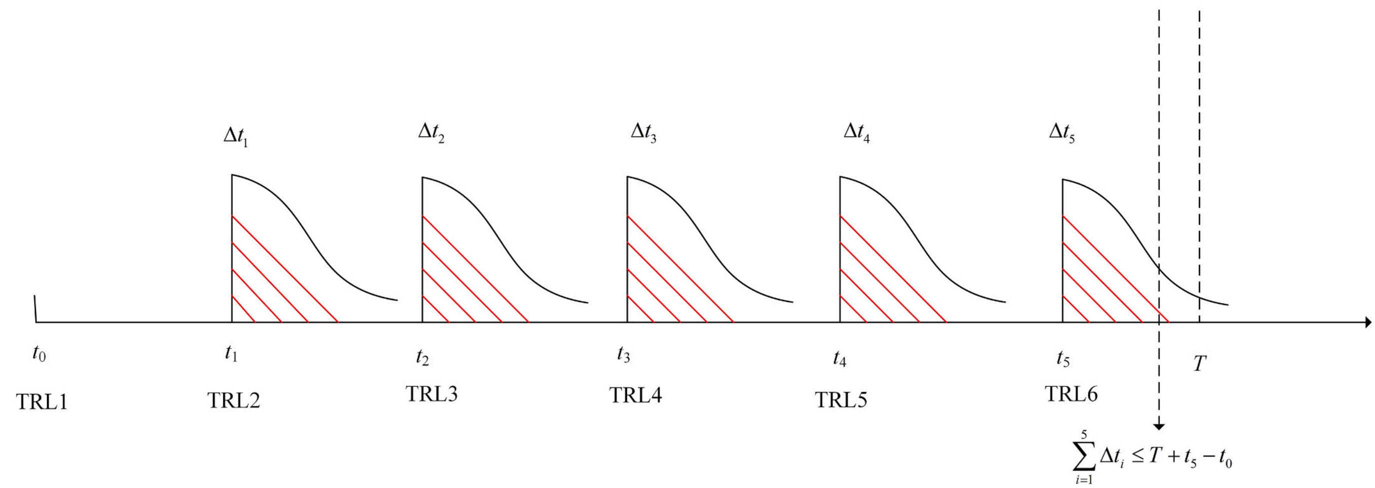


Fig. 5. The actual arrival time distribution of different TRLs.

We allow the duration to be extended, in practice, the budget may be spent in advance(See Fig.6), and additional costs C^{add} shown in Eq.(7) is introduced, similar to applying additional R&D funds to cope with budget shortfalls.

$$C(t+1) = \begin{cases} C(t) + C^{add} - I(t)\Delta t + \beta\varepsilon_1\sqrt{I(t)\left(C(t) + C^{add}\right)\Delta t} + \sigma\left(C(t) + C^{add}\right)\varepsilon_2\sqrt{\Delta t} & \text{for TRL6} \\ C(t) + C^{add} - I(t)\theta\Delta t + \beta\varepsilon_1\sqrt{I(t)\theta\left(C(t) + C^{add}\right)\Delta t} + \sigma\left(C(t) + C^{add}\right)\varepsilon_2\sqrt{\Delta t} & \text{for TRL7} \end{cases} \quad (7)$$

The total cost of ID stage C^{ID} is shown in Eq. (8)

$$C^{ID} = \begin{cases} C(1) + C^{add} - C(t_i - t_{i-1}) & C(t) < 0\&t < t_i - t_{i-1} \\ C(1) - C(t_i - t_{i-1}) & else \end{cases} \quad (8)$$

The variance of residual cost volatility of Eq. (4) is shown in Eq. (9).

$$Var(dC/C) = \beta^2\left(\frac{I\theta}{C}\right)\sigma_1^2 + \sigma^2\sigma_2^2 \quad (9)$$

With an increasing technical uncertainty β and market uncertainty σ, the variance increases, and the dispersion of the residual cost change rate also increases, which means that the project team will face more budget management risk. When the investment rate becomes larger after the technology jump, that is, $\theta > 1$, the variance of the residual cost change rate will increase, because the annual expenditure is more and the risk will become larger. In contrast, when$\theta < 1$, the risk of the project will be smaller.

4. Case study and analysis of results

4.1. Data sources

Considering fluctuations in long-term demand, ADANES extends beyond power generation, encompassing diverse applications like hydrogen production, seawater desalination, and collaborative production endeavors, exemplified by medical isotopes. ADANES primarily comprises a burner and a spent fuel regeneration system. Following the established principles of an Accelerator-Driven System (ADS), the Accelerator-Driven Burner (ADB) is constructed to achieve waste transmutation, proliferation control, and power generation within the burner propelled by a neutron source external to the accelerator. The spent fuel regeneration system involves processing spent fuel and creating regenerated fuel, ensuring that key components of the spent fuel matrix—uranium, plutonium, and transmutable minor actinides—remain in a solid state. Ultimately, the conversion and preparation of nuclear fuel elements are executed. The parameters of ADANES are shown in Table 3. The preliminary funding of ADANES comes mainly from government support.

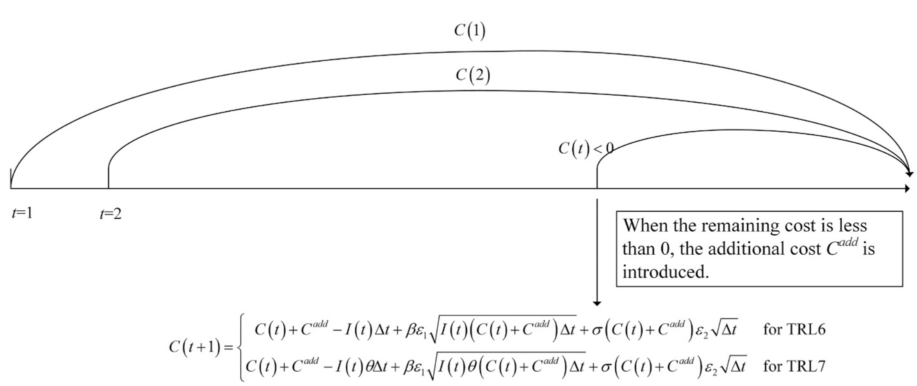


Fig. 6. The remaining period of ID stage is extended.

Table 3
Input data.

stage	variable	implication	numerical value	source
ERD stage (TRL1 ~ 6)	a	Inflection point control coefficient of the logistic function	0.1,0.3,0.5	Appointed
	t_i-t_{i-1}	Expected time (years)	2,6,4,5,5	Provided by ADANES R&D team
	C_i^{ERD}	Budget for TRL1 ~ 6 (billion yuan)	0,1.8,1,4.5,5	Provided by ADANES R&D team
	σ_i	Variance of technology success time	1	Assumed value
	T	Time allowed to exceed the upper limit (years)	1–5	Provided by ADANES R&D team
	R^{max}	The maximum ratio of expected cost to the initial budget	2–5	Appointed
	R^{min}	The minimum ratio of expected cost to the initial budget	0.5, 0.7, 0.9	Appointed
	θ	Cost change after TRL Jump	2.14	Calculated value
	σ	Market uncertainty	0–0.1	Pindyck(1993) [7]
	β	Technical uncertainty	0–1	Pindyck(1993) [7]
	m	The number of simulated paths	10,000	Appointed
ID stage (TRL7 ~ 8)	σ_z	Variance of the Wiener process	0.1	Assumed value
	σ_w	Variance of the Wiener process	0.1	Assumed value
	C^{add}	Costs increased when the budget runs out (billion yuan)	25	Appointed
	T_1	Time required for TRL7 to succeed (years)	3–5	Provided by ADANES R&D team
	T_2	Time required for TRL8 to succeed (years)	5–8	Provided by ADANES R&D team
	I_i	Budget for TRL6 and TRL7 (billion yuan)	0.7,2.5	Provided by ADANES R&D team

Table 4
Construction information for some nuclear powers.

Nuclear power model/ country	Budget (USD/ kWh)	Expected time(years)	Actual cost (USD/ kWh)	Actual time (years)	Reference
AP1000/ China	2044	5	3154	9	NEA Report [35]
AP1000/ USA	4300	4	8600	9	
APR1400	1828	5	2410	10	
EPR/ China	1960	4.5	3222	9	
EPR/ Finland	2020	5	>5723	16	
EPR/ France	1886	5	8620	15	
Average time overrun (%)	Number of projects	Average cost overrun (millions of US)	Average time overrun (months)	Average cost escalation (%)	Sovacool [6]
64	180	1282	35.7	117.3	

The coefficients a, R^{max} and R^{min} are cross-referenced with other nuclear technologies outlined in Table 4, as there is no historical precedent for the development of ADANES.

(1) First of all, we assume that R_i^{max} and R_i^{min} are the same under different TRL. R^{min} are appointed to be 0.5, 0.7 or 0.9 for analysis. And R^{max} can be seen in Table 4 where the EPR construction period in Finland was extended by 11 years and the cost overrun was at least 2.8 times. The period of EPR construction in France was extended by 10 years and the cost overrun was at least 4.58 times. ERD stage is to carry out low-power experiments and the ID stage corresponds to amplifying the low-power reactor type successfully developed by the experiment. This paper assumes that the cost overrun in ERD stage is the same as that in the ID stage. Therefore, the sensitivity analysis of the R^{max} value among 2–5 may be different in practice. For a, by fixing the values of R^{max} and R^{min}, we take the data in Table 3 into Eq. (3) and take the average value. Let (R^{max}, R^{min}) to be (5,0.5) and (5,0.9) respectively, we get the value of a as 0.244 and 0.455. Then we appoint 0.1, 0.3 and 0.5 to a for the sensitivity analysis.

(2) The average annual initial budget of TRL6 and TRL7 are 2.33 billion yuan and 5 billion yuan. The expected time point t_i and budget I_i are derived from the ADANES budget book, and T_1 and T_2 are estimated by experts of the ADANES R&D team.

4.2. Technology R&D Result and analysis

This paper first examines the influence of different values on the cost of ERD stage (fixed $R^{max} = 3.5$, $R^{min} = 0.7$), as shown in Fig. 7.

With an increase in a, the cost dispersion is constantly increasing, which indicates an increase in technical complexity, the project is more sensitive to cost overruns, and the risk of the R&D team for cost budget management will also increase. In particular, R&D projects such as ADANES, have high investment costs and high technical uncertainty. Estimated by simulation, the largest cost of TRL4 ~ 6 reaches 11.57 billion yuan when $a = 0.1$, 1.657 billion yuan more than the initial budget over . And the construction period is 15.31 years, 5.31 years longer than expected. When $a = 0.3$, the largest cost of TRL4 ~ 6 reaches 16.176 billion yuan and the construction period is 15.12 years which is extended by 5.12 years and overrun by 6.676 billion yuan. The the largest cost of TRL4 ~ 6 reaches 22.777 billion yuan when $a = 0.5$ and the construction period is 15.10 years accordingly.

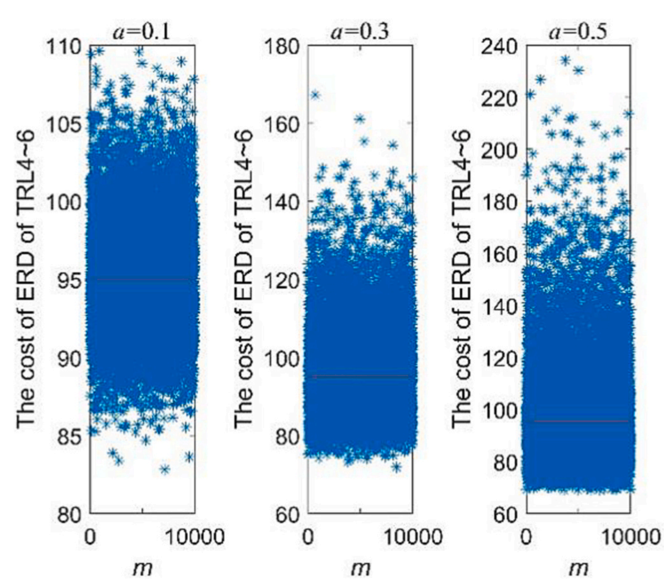


Fig. 7. The impact of different a on costs(the red line represents the budget). (For interpretation of the references to colour in this figure legend, the reader is referred to the web version of this article.)

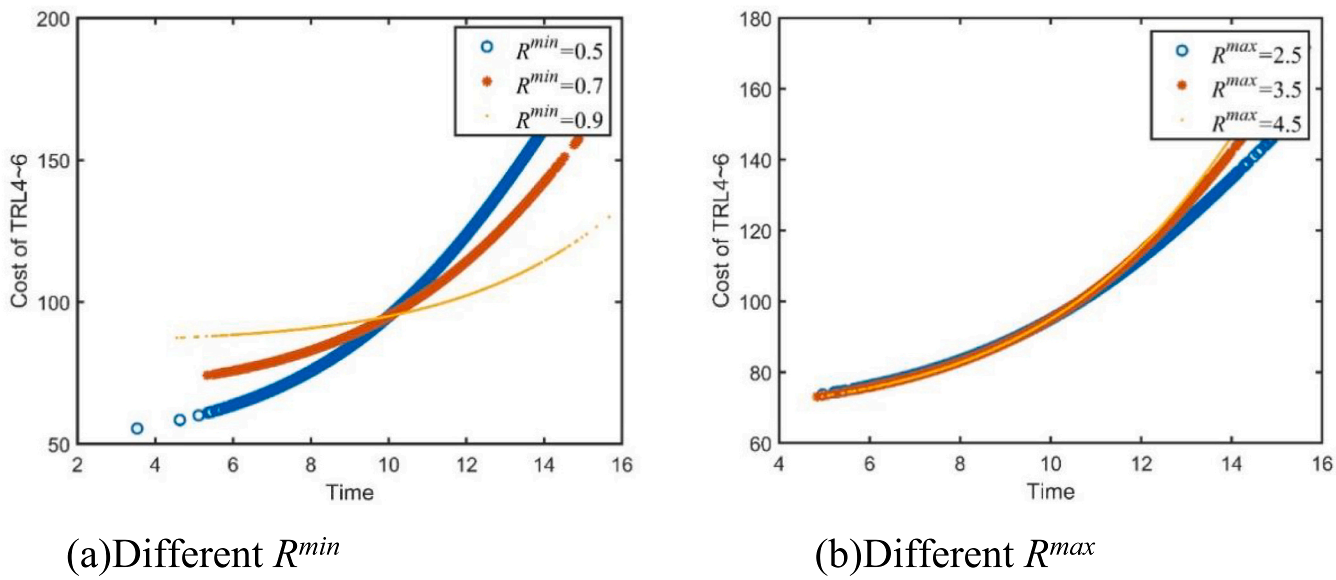


Fig. 8. The impact of different R^{max} and R^{min} on costs.

When $a = 0.3$ and $R^{max} = 3.5$ are fixed, let R^{min} be 0.5,0.7 and 0.9, respectively. The effects of different R^{min} are observed, as shown in Fig. 8 (a). And we fix $a = 0.3$ and $R^{min} = 0.7$, and let R^{max} be 2.5,3.5 and 4.5, we also observe the influence of different R^{max}, as shown in Fig. 8(b).

It can be seen in Fig. 8 that when R^{min} is smaller and R^{max} is larger, the cost dispersion is greater, and it is easier to exceed the budget when the construction period is extended, which means that when the proportion of fixed costs in the experimental R&D process is smaller and the expert-expected cost is larger, the advance or extension of the construction period has a greater impact on cost volatility, and the budget management in the experimental R&D process faces greater risks.

When we fix $a = 0.3$, $R^{max} = 3.5$, $R^{min} = 0.7$, given different T(1–5 years), and observe the maximum acceptable budget of different T, as shown in Fig.9(a). When T (allowed to exceed the upper limit of time) is 1 year, 2 years, 3 years, 4 years and 5 years respectively, the maximum acceptable budget is 10.358 billion yuan, 11.423 billion yuan, 12.712 billion yuan, 14.229 billion yuan and 15.953 billion yuan.

We fix $a = 0.3$, $R^{max} = 3.5$ and $R^{min} = 0.7$, give different cost upper limits C^{max}, and observe how long the construction period can be extended. It is observed that the maximum duration can be extended when exceeding 10% ~100% of the initial budget as the acceptable upper limit of cost, as shown in Fig. 9(b). When the maximum acceptable cost is 110%, 150% and 200% of the budget, the maximum extension period is about 1.09 years, 4.01 years and 6.59 years respectively.

4.3. Industrial demonstration result and analysis

Let $\beta = 0.7, \sigma = 0.1$, we make the residual cost path (shown in Fig. 10 (a)) and the total cost path change diagram (shown in Fig. 10(b)). When the total construction period is extended from the initial 8 years to the longest 13 years, the maximum total cost change of the ID stage is 58.087 billion yuan. It can also be seen in the Fig.10 that the impact of the extension of the construction period on ADANES will greatly exceed the initial budget of 32 billion yuan. The construction period is extended by 5 years, and the cost overrun reaches 182%. According to the data in Table 4, this is within a reasonable range.

We analyze the total cost under different duration extensions shown in Fig. 11. When the expected duration is 9 years (1 year delay), 10 years (2 years delay), 11 years (3 years delay), 12 years (4 years delay) and 13 years (5 years delay), the total cost is 35.492 billion yuan, 39.487 billion

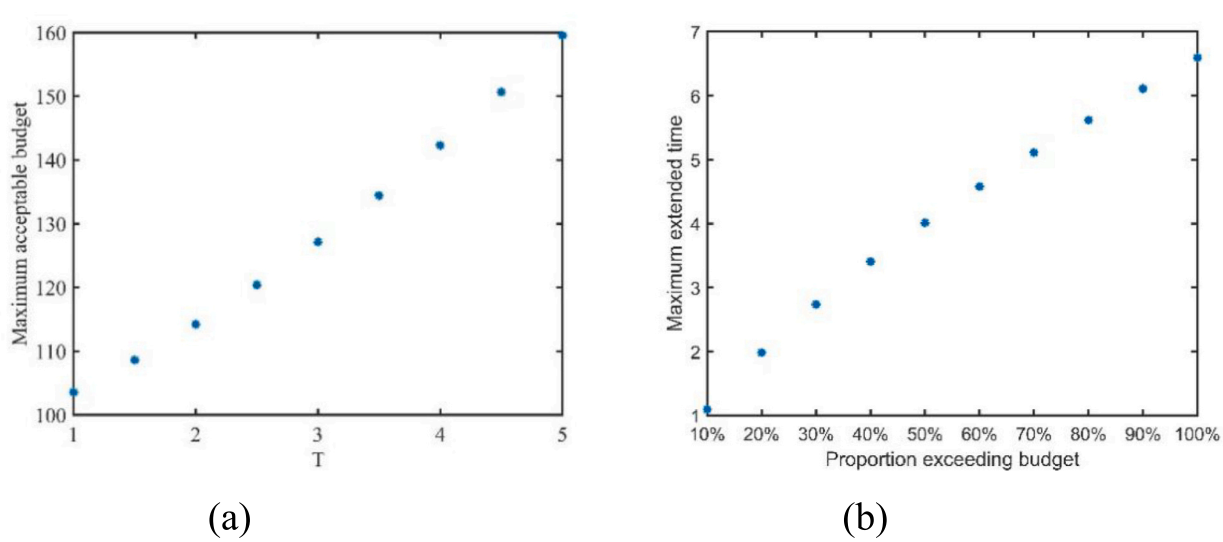
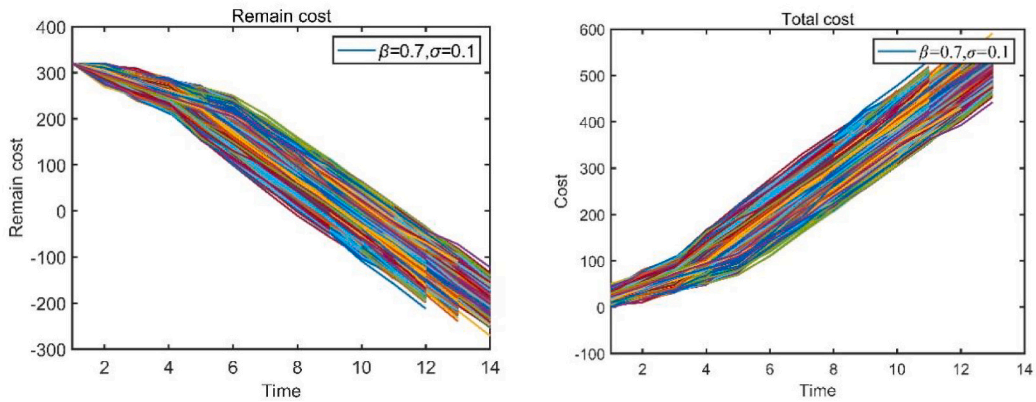


Fig. 9. The influence of different duration extension time and cost upper limit.



(a) Remaining costs (b) Total cost of industrial demonstration

Fig. 10. Paths of cost change in ID stage.

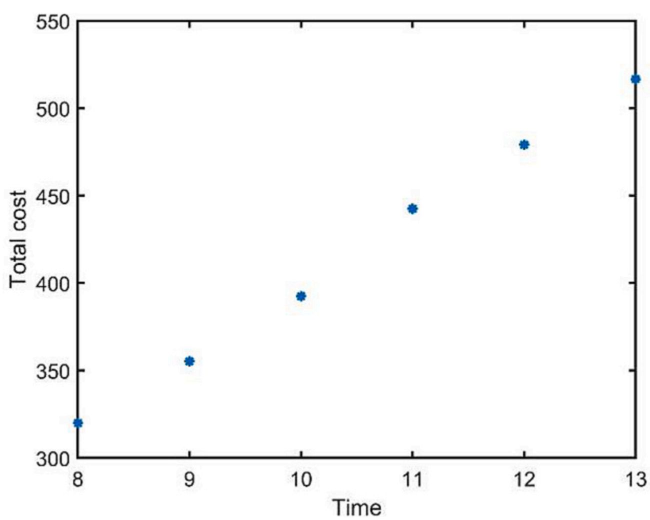


Fig. 11. The total cost under different duration extension time(The initial construction period is 8 years).

yuan, 44.259 billion yuan, 47.948 billion yuan and 51.639 billion yuan respectively.

5. Conclusion

This study introduces an innovative cost analysis approach tailored for advanced nuclear energy systems, designed to address heightened uncertainty, protracted construction periods, and significant cost overruns. Focused on the ADANES, the research analyzes two pivotal stages in the development of advanced nuclear energy systems: the ERD stage and the ID stage. In the ERD stage, employing the Logistic function, the study integrates expert-provided estimates for maximum and minimum costs to evaluate the ramifications of varying duration extensions on cost overruns. Two termination conditions are considered: (1) when the projected cost exceeds the acceptable cost threshold and (2) when the extension duration surpasses the acceptable time limit. Concerning the ID stage, this study incorporates SDE further to simulate the effects of project duration extension. When technical complexity increases, the experts' estimation of technical costs becomes more prominent, and the overall cost becomes more responsive to the extension of the construction duration. During the ERD phase, a five-year extension in the construction period results in a maximum acceptable budget of 15.953 billion yuan (initial budget: 9.5 billion yuan). The construction period can be extended by up to 6.59 years when the upper limit of the ERD stage budget cost is twice the initial budget. Additionally, the cost overrun in the ID phase is highly sensitive to the extension of the construction period. In the ID phase, a five-year extension leads to an ID stage cost of 51.639 billion yuan. Simultaneously, strategically extending the construction period and elevating the cost limit can enhance the success rate of ADANES.

The primary objective of this study is to formulate an extensive cost framework for evaluating ADANES that considers the duration extension and cost overruns. Regarding the extensive application of the TRL tool across diverse technical fields and its pertinence to emerging disruptive technologies such as ADANES, the Logistic function and SDE proposed in this study provide a mechanism for appraising costs in nuclear energy projects. Importantly, the proposed method can be customized to appraise costs across various projects by refining input parameters. The generalization of the model is delineated as follows:

(1) The critical time points can be segmented according to maturity, as distinct technologies exhibit varying TRLs.

(2) The R^{max} and R^{min} values can be determined through expert estimation and consideration of specific technological contexts.

(3) The coefficient a determines the inflection point in the Logistic function and can be calculated by substituting cost data from comparable technologies.

(4) The annual investment rate I in the SDE formula impacts cost scale, enabling the derivation of I according to cost particulars across diverse technologies, streamlining stage-specific cost assessments.

This study's conclusions rely on cost simulation analysis of ADANES. Subsequent endeavors can broaden the practical application range of the proposed method, affirming its efficacy. Moreover, the lack of prior successful instances for ADANES introduces specific discrepancies in the parameter estimation of the model delineated in this study. Specifically, the Logistic function's coefficient a has been determined by consulting alternative data on the costs of nuclear power technology, highlighting the need for future refinement. Additionally, in the SDE, the annual investment rate I is consistently iterated at a fixed value. The annual investment amount I remains variable and is not constant. Improving the precision of cost estimation can be accomplished by iteratively adjusting the initially estimated I to align with the actual time planning and project schedule, thus accommodating the fluctuating nature of the investment.

CRediT authorship contribution statement

Zhen Li: Writing – review & editing, Writing – original draft, Visualization, Methodology, Investigation, Data curation, Conceptualization. **Mingliang Qi:** Writing – review & editing, Validation, Supervision, Methodology. **Renlong Wang:** Methodology, Writing – review & editing. **Xuesong Yan:** Writing – review & editing, Supervision, Data curation, Conceptualization. **Yangyang Yang:** Writing – review & editing, Visualization, Supervision, Data curation, Conceptualization. **Mingang Gao:** Writing – review & editing, Validation, Supervision, Methodology.

Declaration of competing interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

Data availability

Data will be made available on request.

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