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# A Mathematical Model for the Implementation of New Technologies in Shipbuilding: Dynamics Analysis and Efficiency Assessment

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ABSTRACT

This article presents a comprehensive mathematical model describing the process of implementing innovative technologies in the shipbuilding industry. While diffusion models are widely studied, there is a lack of deterministic dynamic models that integrate financial, technical, and human capital factors specifically for capital-intensive industries like shipbuilding. The model focuses on the key parameters determining the speed and success of technology diffusion: economic efficiency, investment level, adaptation costs, and personnel qualifications. Based on the apparatus of differential equations and methods of multi-criteria optimization, a system has been constructed that allows for a quantitative assessment of the impact of control actions (e.g., the volume of state subsidies or the intensity of retraining programs) on the pace of technological modernization of a shipbuilding enterprise. The stability of the model is analyzed, and critical conditions under which the implementation becomes self-sustaining are determined. The main contributions include: the derivation of an analytical critical success condition; a numerical demonstration of scenarios leading to success, stagnation, or failure; practical recommendations for structuring investments. The results can be used to formulate technological development strategies for shipbuilding holdings and to substantiate state support programs for the industry.

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# 1. Introduction

Modern shipbuilding is a high-tech, capital-intensive, and knowledge-intensive industry where long-term competitiveness directly depends on the speed of implementing new technologies. These include digital design and simulation tools (CAD/CAM/CAE/PLM), additive manufacturing for prototyping and complex parts, robotic welding and assembly lines, advanced composite materials, and "green" shipping technologies such as hydrogen fuel cells, battery hybrid systems, and exhaust gas cleaning scrubbers [3]. The successful adoption of such innovations is a strategic imperative driven by both market competition and stringent environmental regulations set forth by the International Maritime Organization (IMO) [3].

However, the implementation process is fraught with significant risks and multidimensional costs. These encompass not only substantial initial capital investment in hardware and software but also the necessity for deep restructuring of established production processes, supply chains, and quality control systems. Crucially, a persistent bottleneck is the development of adequate human capital—the upskilling and retraining of engineers, designers, and production staff to effectively operate and maintain new technological systems [4,5]. Traditional investment appraisal methods, such as static Net Present Value (NPV) or Payback Period, often fail to capture these dynamic, interrelated, and non-linear feedbacks between equipment, people, and organizational processes [6]. Consequently, management decisions regarding technological modernization can be suboptimal, relying on qualitative assessments rather than quantitative forecasts.

Effective management of this complex process requires a transition to a systems thinking paradigm and the development of an appropriate mathematical apparatus that formalizes these interdependencies [6]. Existing economic models of technological change, such as the seminal work by Solow [7], often operate at a macroeconomic level. Micro-level models of innovation diffusion, like the Bass model [2], focus on adoption rates in consumer markets but do not incorporate internal investment flows and competence building. Meanwhile, project management models may detail scheduling and budgeting but lack the dynamic coupling between financial inputs and capability outputs [4]. Thus, a research gap exists for deterministic dynamic models tailored to the context of heavy, project-driven industries like shipbuilding, which explicitly link the kinetics of technology adoption with simultaneous investment in physical and human capital.

The purpose of this article is to construct and analyze such a deterministic dynamic model that formalizes the causal relationship between financial, production, and human factors when implementing a new technology at a shipbuilding enterprise. The primary contributions of this study are: (1) the development of a novel system dynamics model coupling technology adoption rate with investment flows and human capital dynamics; (2) the derivation of an analytical critical success condition in the form of an inequality linking key technological, financial, and personnel parameters; (3) a numerical demonstration of the model's utility for scenario analysis and policy optimization, using the example of robotic welding implementation; (4) practical recommendations for structuring investments and government support mechanisms.

# 2. Materials and Methods

## 2.1. Research Method: System Dynamics Approach

The study employs the system dynamics methodology [6] to model the complex feedback loops inherent in technology implementation processes. This approach is particularly suited for analyzing non-linear relationships and time delays between key variables in socio-technical systems. The modeling process involved: (1) conceptualization of causal relationships based on innovation diffusion theory [1] and industrial modernization studies [5]; (2) formalization through a system of ordinary differential equations; (3) analytical investigation of equilibrium states; (4) numerical simulation of different strategic scenarios using Python programming language and the 4th order Runge-Kutta integration method.

## 2.2. Formalization of Model Parameters

We introduce the main state variables of the model, considered as continuous functions of time *t* over a planning horizon *[0, T]*:

- **$T(t) \in [0, 1]$ – Technology Implementation Degree.** This variable represents the level of integration and operational mastery of the new technology into the core production process. A value of 0 indicates complete absence, while 1 signifies full implementation and stable operation at design capacity. It is an aggregate measure of technical readiness and organizational assimilation.
- **$I(t) \geq 0$ – Cumulative Effective Investments in the Technology.** This encompasses all capital expenditures directed towards the innovation project, including the cost of equipment, software licenses, installation, and dedicated internal R&D (monetary units, e.g., million USD). It represents the financial resources converted into technical potential.
- **$K(t) \geq 0$ – Personnel Competence Level.** This is an integral indicator quantifying the workforce's ability to work with the new technology. It can be conceptualized as the proportion of relevant staff who have completed certification training or as an index based on the average number of training hours per employee. Its calibration is context-specific (conventional units).
- **$P(t)$ – Additional Annual Profit (or Cost Reduction).** This variable captures the net economic effect generated by the use of the new technology compared to the legacy process. It includes increased productivity, reduced material waste, lower energy consumption, and improved quality, net of any new operational expenses (monetary units per year).

## 2.3. System of Dynamic Equations

The core of the model is a system of coupled ordinary differential equations describing the evolution of the state variables.

**Equation for the Implementation Degree T(t):**

The rate of technological adoption is modeled using a modified logistic growth law, common in diffusion studies [1,2]. The growth driver is proportional to the available investment (normalized to a threshold) and the current competence level. The logistic term $T(1-T)$ captures the slowing adoption as saturation approaches. A resistance term reflects organizational inertia.

$dT/dt = \alpha * (I / I_0) * (K / K_0) * T * (1 - T) - \gamma * T$ (1)

where $\alpha > 0$ is the technological diffusion rate constant; $I_0$, $K_0$ are normative (threshold) values; $\gamma \geq 0$ is the coefficient of implementation resistance.

**Equation for the Competence Level K(t):**

The change in workforce competence depends on targeted investments in training and the natural attrition of skills.

$dK/dt = \beta * I - \delta * K$ (2)

where $\beta \in [0, 1]$ is the share of total investments directed to training; $\delta > 0$ is the de-skilling coefficient.

**Equation for the Economic Effect P(t):**

The financial return manifests with a delay relative to the technical implementation, as the system requires a period of debugging and proficiency gain.

$P(t) = P\_max * T(t - \tau) - c\_op * T(t)$ (3)

where $P\_max$ is the maximum potential annual economic effect; $c\_op$ represents annual operational costs; $\tau$ is the time lag.

**Investment Dynamics I(t) (Control Action):**

$dI/dt = (dF\_ext/dt) + \eta * P(t) - \mu * I(t)$ (4)

where $F\_ext(t)$ is the flow of external financing; $\eta \in [0, 1]$ is the profit reinvestment rate; $\mu \geq 0$ is an optional capital depreciation coefficient.

## 2.4. Efficiency Criterion and Optimization Problem

The strategic goal is to maximize the net economic benefit over the planning horizon, formulated as an optimal control problem with the Net Present Value (NPV) as the objective functional [8]:

$J = \int_0^T [P(t) - (1-\beta)*I(t) - F\_ext(t)] * e^{-\rho t}\, dt \rightarrow \max$ (5)

where $\rho$ is the discount rate. The optimization problem consists in finding the control trajectories for $F\_ext(t)$ and the parameter $\beta$ that maximize J under the dynamic constraints and initial conditions.

## 2.5. Numerical Simulation Setup

For numerical experiments, parameter values were estimated based on industry benchmarks for robotic welding implementation in shipbuilding [9]: $\alpha=0.5$, $I_0=20$, $K_0=10$, $\gamma=0.1$, $\delta=0.15$, $P\_max=25$, $c\_op=5$, $\tau=1$, $\rho=0.1$. The simulation time horizon was set to 7 years, reflecting a typical mid-term planning period in shipbuilding projects.

# 3. Results and Discussion

## 3.1. Stationary States and Critical Success Condition

Analyzing the system's equilibrium by setting the time derivatives in equations (1) and (2) to zero (ignoring the lag $\tau$ for analytical simplicity) yields the non-trivial equilibrium:

$T^* = 1 - (\gamma * I_0 * K_0) / (\alpha * I * K)$ (6)

$K^* = (\beta / \delta) * I$ (7)

Substituting equation (7) into equation (6) provides a clear condition for significant implementation ($T^*$ approaching 1): $\alpha * \beta * I^2 > \gamma * \delta * I_0 * K_0$ (8)

This is the **key success inequality**. Its interpretation is profound: successful implementation is not guaranteed by high investment (I) alone. The product of the technology's "adoptability" ($\alpha$), the commitment to human capital ($\beta$), and the **square** of the investment must overcome the product of organizational resistance ($\gamma$), the rate of skill decay ($\delta$), and the implementation thresholds ($I_0$, $K_0$). The quadratic dependence on I underscores the critical importance of achieving a minimum scale of investment to trigger a self-sustaining process, a nuance often missed in linear cost-benefit analyses.

## 3.2. Numerical Simulation of Strategic Scenarios

Three strategic scenarios were compared through numerical simulation:

1) **Balanced Strategy (I=100, β=0.3):** 30% of investment allocated to training. The model predicts a smooth logistic curve, reaching T>0.9 by Year 4. Competence K grows steadily. NPV is strongly positive. This validates the condition where $\alpha\beta I^2$ (0.5*0.3*10000=1500) significantly exceeds $\gamma\delta I_0 K_0$ (0.1*0.15*20*10=3).

2) **"Hardware-First" Skewed Strategy ($I=100$, $\beta=0.05$):** Only 5% allocated to training. Implementation starts but **stalls at $T\approx0.35$** around Year 3. Competence remains low, creating a critical bottleneck. The project enters a stagnation zone with low returns, demonstrating that underinvestment in people wastes capital investment, despite high I. Here, $\alpha\beta I^2$ (0.5*0.05*10000=250) still exceeds the threshold, but the low $\beta$ drastically reduces the equilibrium $K^*$ and thus $T^*$.
3) **Insufficient Scale Strategy ($I=30$, $\beta=0.3$):** Although well-balanced, the total investment is too low. The left side of inequality $\alpha\beta I^2$ (0.5*0.3*900=135) is only marginally greater than the right side (3). Implementation **fails to take off**, decaying towards zero ($T\to0$). This confirms the existence of a **minimum critical investment threshold** and illustrates that even with good training, below-scale projects are likely to fail.

### 3.3. Sensitivity Analysis and Managerial Insights

A local sensitivity analysis was performed on the Balanced Strategy. Key findings offer direct managerial insights:

- **Most Sensitive Parameter ($\beta$):** NPV increases sharply with $\beta$ up to ~0.25-0.35, after which marginal returns diminish. This suggests an **optimal range for training investment** (25-35% of total project cost for complex technologies), providing a quantitative argument against arbitrary budget cuts in human development.
- **High-Impact Risk Factor ($\gamma$):** Even a moderate increase in organizational resistance (from 0.1 to 0.2) can delay full implementation by 2+ years and reduce NPV by over 30%. This quantifies the **substantial hidden cost of poor change management** and justifies proactive investments in communication, pilot projects, and involving end-users early.
- **Lag Effect ($\tau$):** A longer delay between implementation and profit realization significantly reduces NPV. This emphasizes the economic value of **rapid operational mastery** and supports strategies like phased roll-outs and parallel running to shorten the proficiency gain period.

The model's practical utility lies in its application as a **policy sandbox**. Managers and policymakers can: 1) **Calibrate it with project-specific data** to determine the minimum viable investment (I) and its optimal structure ($\beta$); 2) **Design time-phased subsidy programs ($F_{ext}(t)$)** that "bridge" the project until the profit reinvestment loop becomes strong enough; 3) **Quantify the risks** associated with underestimating resistance ($\gamma$) or skill decay ($\delta$), justifying investments in change management and continuous training programs [10].

**Limitations and Future Research:** The current model is deterministic and aggregate. Natural extensions include: introducing **stochastic elements** to account for market demand fluctuations and technological uncertainty; developing an **agent-based model** version to study technology diffusion within a shipbuilding cluster; and explicitly modeling **multiple, interdependent technologies** (e.g., digital twin and additive manufacturing).

## 4. Conclusion

This study constructed and analyzed a system dynamics model for implementing new technologies in shipbuilding. The model integrates the dynamics of capital investment, human competence development, and organizational adoption into a coherent mathematical framework. The central theoretical outcome is the establishment of a critical success inequality ($\alpha\beta I^2 > \gamma\delta I_0K_0$), emphasizing the non-linear, interdependent nature of the process where investment scale and balance are paramount. The practical value is demonstrated through scenario and sensitivity analysis, which provides clear, quantitative evidence for the necessity of balanced, sufficiently scaled investments and proactive management of human and organizational factors. The model serves as a foundational decision-support tool for substantiating strategic investment decisions at the enterprise level and for formulating effective, evidence-based state industrial policy aimed at accelerating the technological modernization of capital-intensive industries like shipbuilding.

**Nomenclature**

| Symbol | Description | Units |
|---|---|---|
| $T(t)$ | Technology implementation degree | dimensionless [0,1] |
| $I(t)$ | Cumulative effective investments | monetary units (e.g., million USD) |
| $K(t)$ | Personnel competence level | conventional units |
| $P(t)$ | Additional annual profit/cost reduction | monetary units/year |
| $\alpha$ | Technological diffusion rate constant | 1/year |
| $\beta$ | Share of investments in training | dimensionless [0,1] |
| $\gamma$ | Coefficient of implementation resistance | 1/year |
| $\delta$ | De-skilling coefficient | 1/year |
| $I_0$, $K_0$ | Threshold values for investment and competence | monetary units, conventional units |
| $P_{max}$ | Maximum potential annual economic effect | monetary units/year |
| $\tau$ | Time lag for economic effect manifestation | years |
| $\rho$ | Discount rate | 1/year |
| $\eta$ | Profit reinvestment rate | dimensionless [0,1] |

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## Data Availability Statement

The data presented in this study (model parameters, simulation results) are available within the article. The Python code used for simulation is available from the corresponding author upon reasonable request.

## Conflicts of Interest

The author declares no conflict of interest. The views expressed are those of the author and do not necessarily represent the official position of JSC "PO “Sevmash”.

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