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Modeling the Drivers of Total Productive Maintenance Strategy through System Dynamics Simulation: A Case Study of the National Iranian South Oilfields Company

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A B S T R A C T

This study aimed to develop and simulate a system dynamics model of the drivers of Total Productive Maintenance (TPM) strategy in oil production and to evaluate alternative policy scenarios for improving long-term maintenance performance at the National Iranian South Oilfields Company. The study used an applied, quantitative, exploratory system dynamics design. The statistical population comprised 570 employees, managers, and experts working at the headquarters and affiliated companies of the National Iranian South Oilfields Company in Ahvaz, Iran, from whom 291 participants were selected through simple random sampling. Data were collected using a researcher-developed questionnaire covering the principal drivers of TPM strategy. Exploratory factor analysis was used to refine the indicators and identify the major latent dimensions. The resulting variables were incorporated into a system dynamics model developed in Vensim. The model included political factors, investment-policy factors, upstream capital-resource provision, technological factors, maintenance characteristics, and weakening factors. Model verification included structural assessment, parameter validation, extreme-condition testing, behavioral validation, stability testing, and the Vensim Check Model procedure. The baseline simulation showed that the TPM strategy index increased from 10.00 to a peak of approximately 128.94 around year 9.25, followed by a sustained decline to 68.73 at year 20. All nine intervention scenarios improved the final value relative to the baseline. The largest effects were observed for intermediate financing, which increased the final value to 197.59 (+128.85 units), debt-based financing to 177.07 (+108.33 units), and reserve-based financing to 138.31 (+69.58 units). Improvement in financing assessment increased the value to 121.55 (+52.82 units), while reduction of unfavorable monetary policies increased it to 106.41 (+37.68 units). Smaller improvements were observed for R&D policy, maintenance-resource diversification, technology-entry policy, and development of extraction and production structures. The findings indicate that TPM performance in oil production is generated by interacting financial, technological, organizational, political, and maintenance-related feedback mechanisms, with financing structures representing the strongest strategic leverage points for sustaining long-term improvement.

Keywords: *Total Productive Maintenance; System Dynamics; Oil and Gas Industry; Maintenance Strategy; Vensim; Financing; National Iranian South Oilfields Company.*

1. Introduction

The oil and gas industry operates through capital-intensive, technologically complex, and highly interdependent production systems in which continuity of operations depends heavily on the availability, reliability, and maintainability of physical assets. Production facilities, rotating equipment, pumps, compressors, pipelines, processing units, control systems, and auxiliary infrastructure are exposed to continuous operating loads, harsh environmental conditions, aging, corrosion, technological obsolescence, and fluctuating production requirements. Consequently, maintenance is not merely a technical support activity but a strategic function directly connected to production continuity, operational safety, cost control, asset utilization, environmental performance, and long-term organizational competitiveness. Equipment failures and prolonged downtime can interrupt production, create cascading operational disturbances, increase repair and replacement expenditures, and weaken the economic performance of an oil and gas company. This challenge becomes particularly significant when organizations must manage aging or obsolete rotating equipment, because obsolescence can magnify the probability of downtime, reduce access to compatible components, and complicate maintenance decision-making (Kolo, 2025). Oil and gas performance is also influenced by broader supply-chain conditions, because the timely provision of parts, technical services, materials, technologies, and logistical resources is closely linked to operational continuity and organizational performance (Ogbaini, 2025). Thus, contemporary oil and gas organizations require maintenance strategies capable of integrating equipment reliability with financial, technological, human, organizational, and external environmental considerations rather than approaching maintenance as a series of isolated corrective interventions.

Among the major approaches developed for improving asset reliability and operational effectiveness, Total Productive Maintenance (TPM) has evolved into a comprehensive management philosophy that seeks to maximize equipment effectiveness through the participation of employees, preventive and proactive maintenance, continuous improvement, and coordinated responsibility for productive assets. TPM moves maintenance beyond the traditional assumption that equipment care is exclusively the responsibility of maintenance departments. Instead, it promotes shared responsibility among operators, technicians, engineers, supervisors, and managers while connecting maintenance activities with quality, productivity, safety, and organizational performance. Studies of TPM implementation have shown that the approach can be applied across diverse organizational and technological settings. In aircraft-part manufacturing, TPM has been applied as a structured mechanism for enhancing the management of production equipment and maintenance activities (Adhiutama et al., 2020), while research in smaller manufacturing enterprises has similarly emphasized the practical requirements and organizational challenges associated with implementing TPM (Tian & Jeng Feng, 2021). The same stream of research on TPM implementation in manufacturing small and medium-sized enterprises further highlights the importance of adapting maintenance practices to organizational conditions and resource constraints (Xiang & Feng, 2021). These studies collectively indicate that TPM should be regarded not simply as a set of maintenance techniques but as an organizational system involving technology, work routines, management, and human participation.

The operational logic of TPM is closely associated with the pursuit of high overall equipment effectiveness and the reduction of losses arising from breakdowns, setup time, speed losses, quality defects, and other forms of equipment inefficiency. Examination of individual TPM pillars has demonstrated that different components of the TPM architecture may contribute differently to overall equipment effectiveness, suggesting that implementation quality and the interaction among pillars are as important as the formal adoption of the framework itself (Vital & Lima, 2020). Similarly, research on TPM performance evaluation has emphasized the usefulness of integrating maintenance indicators with broader managerial performance systems such as the balanced scorecard, thereby linking maintenance performance with organizational objectives rather than restricting assessment to engineering indicators alone (Hraiga et al., 2023). The relationship between TPM and organizational profitability has also received attention, with evidence and conceptual reviews suggesting that improvements in equipment utilization, downtime reduction, production stability, and maintenance efficiency can translate into stronger financial outcomes (Risonarta & Wardhani, 2023). Accordingly, TPM provides an important strategic bridge between equipment-level maintenance decisions and organization-level performance outcomes.

Successful TPM implementation, however, cannot be explained only by technical procedures. Human and organizational factors are central to the effectiveness and sustainability of maintenance programs. Employee involvement is especially important because TPM depends on operators and maintenance personnel identifying abnormalities, performing routine care, reporting equipment conditions, participating in improvement activities, and supporting preventive practices. A bottom-up perspective on TPM has emphasized employee participation as an important mechanism through which maintenance practices become embedded in everyday organizational routines (Yang & Yang, 2023). Motivation also influences the effectiveness of TPM because employees are more likely to participate consistently in preventive activities, improvement initiatives, and collaborative problem solving when they perceive value, support, recognition, and responsibility in the maintenance process (Guedes et al., 2021). The organizational success of TPM therefore depends on managerial commitment, communication, employee competence, training, participation, and cultural acceptance in addition to maintenance technology. Research examining critical success factors has further demonstrated the importance of systematically identifying and testing the organizational conditions that support TPM implementation and reliability (Kalpande & Toke, 2022). These findings reinforce the view that maintenance performance emerges from interactions among human, technical, managerial, and structural variables rather than from isolated interventions.

The implementation and continuous improvement of TPM also require attention to the maturity and adaptability of the maintenance system. Organizations may initially adopt selected TPM practices but fail to sustain their benefits when improvement mechanisms, learning processes, management commitment, and organizational routines are insufficiently institutionalized. The implementation and improvement of TPM therefore constitute an ongoing organizational process rather than a one-time maintenance project (Wolska, 2023). Empirical work in the pharmaceutical industry has similarly demonstrated the relevance of integrating TPM with lean manufacturing principles, emphasizing the complementary role of waste reduction, process discipline, equipment effectiveness, and continuous improvement (Saenagri, 2023). Lean-maintenance approaches that employ TPM also illustrate the potential for maintenance redesign to improve production-system efficiency by reducing unnecessary activities and structuring preventive interventions more effectively (Farihi, 2023). Even in educational laboratory environments, TPM concepts have been applied to equipment-intensive settings, demonstrating the adaptability of the approach to contexts in which asset availability, routine maintenance, and user involvement are important (Sivasankaran, 2022). The breadth of these applications suggests that the core principles of TPM are transferable, but their operational configuration must be tailored to the characteristics of the organization and production system.

Technological transformation has introduced an additional dimension to the evolution of maintenance strategy. Industry 4.0 technologies—including sensor networks, advanced data analytics, interconnected equipment, digital monitoring, predictive systems, and intelligent decision-support mechanisms—provide opportunities to strengthen traditional TPM by improving the visibility of equipment conditions and enabling earlier, more precise maintenance interventions. Research on the integration of Industry 4.0 technologies into TPM practices has shown that digital technologies can complement maintenance processes by increasing information availability and facilitating more advanced maintenance decisions (Tortorella et al., 2021). The integration of Industry 4.0 and TPM has also been discussed from a sustainability perspective, suggesting that digitally enabled maintenance can support broader objectives related to efficient resource utilization, productivity, and sustainable operations (Samadhiya et al., 2022). For the oil and gas industry, where production installations frequently consist of large networks of interdependent assets, these technological developments are particularly important. Nevertheless, technological modernization itself requires investment, access to specialized knowledge, adequate infrastructure, and supportive organizational policies, meaning that technological factors cannot be separated from financing, managerial capability, and strategic decision-making.

The sustainability dimension of maintenance is also becoming increasingly important. Traditional maintenance assessment has often prioritized equipment availability, production output, and maintenance cost, whereas contemporary approaches increasingly recognize the environmental and social implications of maintenance decisions. Sustainable Total Productive Maintenance extends the TPM philosophy by incorporating sustainability considerations into maintenance practices and examining how maintenance can simultaneously support economic, environmental, and social objectives (Hallioui et al., 2023). In oil and gas operations, this extension is particularly relevant because maintenance deficiencies can increase leakage, energy inefficiency, abnormal emissions, environmental risks, and operational incidents.

Environmental management decisions in oil and gas development also increasingly require systematic consideration of stakeholder and public inputs, indicating that operational strategies function within broader environmental and social governance systems (Sinambela, 2026). Moreover, evidence from green office facilities suggests that awareness among building occupants and users can influence the implementation of TPM-related practices, further emphasizing the role of human awareness and behavioral engagement in maintenance systems (Au-Yong et al., 2021). Therefore, an effective TPM strategy in oil and gas production should consider not only equipment reliability but also environmental responsibility, stakeholder expectations, organizational awareness, and sustainable resource utilization.

Despite the recognized benefits of TPM, its implementation in the oil and gas sector differs substantially from implementation in conventional manufacturing. Oil production systems consist of geographically distributed facilities, continuous-process operations, complex upstream and downstream linkages, sophisticated technologies, substantial capital requirements, and high consequences of equipment failure. Maintenance decisions in such systems are affected by production targets, investment priorities, technology acquisition, availability of spare parts, financing mechanisms, contractual arrangements, policy conditions, managerial capabilities, and macroeconomic pressures. These factors are interconnected. For example, insufficient investment can delay technological modernization, which may increase equipment obsolescence and maintenance requirements; rising equipment failures can increase operating costs and reduce production; reduced production can constrain financial resources; and financial constraints may subsequently limit maintenance investment. This circular causality means that static models that examine one-way relationships may be insufficient for understanding the long-term behavior of maintenance strategy. The growing literature on TPM shows that its effectiveness depends on interacting technical, managerial, organizational, and technological conditions rather than on a single isolated determinant (Kalpande & Toke, 2022; Tortorella et al., 2021; Wolska, 2023).

This requirement is particularly important in the Iranian oil and gas context. Iran's oil and gas industry operates under economic and institutional conditions in which external restrictions can influence investment, access to technologies, financing, procurement, and industrial development. Recent analysis of economic sanctions on Iran's oil and gas industry has emphasized the significance of external economic pressures for the performance and development of this sector (Dezhpasand et al., 2025). Such conditions can intensify maintenance challenges when imported technologies, specialized equipment, spare parts, financing channels, or external technical services become difficult or expensive to obtain. Under these circumstances, maintenance strategy becomes closely related to decisions concerning domestic capabilities, technology policies, resource diversification, investment mechanisms, financing structures, and organizational adaptation. The maintenance problem therefore has a strong systemic character: political-economic constraints may influence financing; financing affects technology and maintenance investment; technological capacity affects reliability and productivity; productivity affects profitability and available resources; and the resulting economic outcomes feed back into future maintenance decisions. The strategic significance of managing obsolete equipment and minimizing loss and downtime in oil and gas operations further reinforces the importance of treating these relationships as interconnected rather than independent (Kolo, 2025).

For organizations such as the National Iranian South Oilfields Company, these interdependencies are especially consequential because maintenance strategy is embedded within a large-scale oil-production system. Strategic maintenance decisions cannot be evaluated adequately merely by asking whether a single intervention produces an immediate improvement. Decision-makers also need to know whether the intervention remains effective over time, whether it creates unintended consequences in other parts of the system, and how it interacts with alternative policies. For instance, increasing access to maintenance resources may improve equipment support but may depend on financing arrangements; technology-entry policies may improve technological capability but may require complementary R&D and organizational capacity; and production-development policies may alter financial requirements and maintenance workloads. Research emphasizing integration between TPM and advanced technologies indicates that technological benefits are realized most effectively when they are embedded within broader organizational and managerial systems (Samadhiya et al., 2022; Tortorella et al., 2021). Likewise, evidence on profitability and performance evaluation suggests that maintenance policies should be considered in relation to financial and strategic performance rather than simply operational indicators (Hraiga et al., 2023; Risonarta & Wardhani, 2023).

System dynamics provides a particularly appropriate methodological foundation for examining such conditions because it focuses on how system structure produces behavior over time. Rather than considering a maintenance outcome as the linear result of separate independent variables, system dynamics represents causal relationships through feedback loops, state variables, rates, delays, and interconnected decision rules. This perspective is highly compatible with the conceptual nature of TPM, because TPM itself involves feedback among employee participation, managerial commitment, maintenance quality, equipment effectiveness, production outcomes, and organizational learning (Guedes et al., 2021; Wolska, 2023; Yang & Yang, 2023). In addition, the literature on critical success factors demonstrates that TPM outcomes depend on the combined and mutually reinforcing effect of multiple organizational conditions (Kalpande & Toke, 2022). A dynamic framework therefore offers a stronger analytical basis than isolated cross-sectional associations when the objective is to explore how policy changes accumulate, interact, and generate long-term consequences.

The need for dynamic modeling also arises from limitations in much of the existing TPM literature. Previous studies have generated valuable knowledge about implementation practices, employee participation, critical success factors, overall equipment effectiveness, lean integration, Industry 4.0, sustainability, motivation, and performance evaluation (Farihi, 2023; Guedes et al., 2021; Hallioui et al., 2023; Hraiga et al., 2023; Tortorella et al., 2021; Vital & Lima, 2020; Yang & Yang, 2023). Yet much of this research has focused on manufacturing or organizational contexts where the principal objective is to evaluate implementation factors, operational improvements, or relationships among selected variables. Research in the pharmaceutical sector has shown that the integration of TPM and lean manufacturing can improve operational outcomes (Saenagri, 2023), while studies in aircraft manufacturing and smaller manufacturing companies have illustrated the organizational feasibility and practical challenges of TPM implementation (Adhiutama et al., 2020; Tian & Jeng Feng, 2021). However, comparatively less attention has been given to modeling the longitudinal behavior of TPM strategy in a large oil-production organization where political, technological, financial, investment, and maintenance variables interact simultaneously.

Another gap concerns the integration of financial policy into TPM analysis. TPM studies traditionally emphasize maintenance pillars, equipment effectiveness, human participation, or technological implementation, but capital structure, financing assessment, resource diversification, and investment mechanisms can also shape maintenance capability, especially in industries characterized by high capital intensity. In oil and gas operations, supply-chain strategy, access to components, procurement reliability, and financial capability are all important for sustaining operational performance (Ogbaini, 2025). Similarly, the management of obsolete equipment requires strategic resource allocation to prevent escalating downtime and loss (Kolo, 2025). When such pressures are combined with economic sanctions and restrictions affecting Iran's oil and gas industry, financing and investment decisions can become central elements of maintenance strategy (Dezhpasand et al., 2025). A system dynamics framework is therefore valuable because it can explicitly model how financing conditions affect maintenance resources, technology, production, and profitability and how these outcomes subsequently feed back into the maintenance system.

The present study also reflects the increasing need to understand TPM as part of a sustainable and adaptive industrial strategy. Sustainable TPM emphasizes that maintenance performance should contribute to environmental, economic, and social outcomes simultaneously (Hallioui et al., 2023). This is consistent with the broader movement toward environmentally informed management in oil and gas development, where stakeholder inputs, environmental considerations, and operational planning must increasingly be integrated (Sinambela, 2026). At the organizational level, awareness and participation also shape how maintenance practices are adopted and sustained (Au-Yong et al., 2021; Yang & Yang, 2023). Accordingly, a comprehensive model of TPM drivers in the oil and gas industry should incorporate not only technical and financial factors but also political, social, managerial, and environmental dimensions capable of reinforcing or constraining maintenance performance over time.

The present research therefore extends prior TPM scholarship in several respects. First, it conceptualizes TPM as a strategic system rather than merely an operational maintenance program. Second, it places financing and investment mechanisms alongside traditional technological and organizational maintenance factors, which is particularly relevant in capital-intensive upstream oil operations. Third, it recognizes that policy interventions can generate delayed and indirect effects through feedback structures. Fourth, it employs system dynamics simulation to evaluate the long-term behavior of maintenance strategy under alternative interventions rather than limiting the analysis to static relationships. This systems perspective complements previous evidence that TPM effectiveness depends on employee participation (Yang & Yang, 2023), motivation (Guedes et al., 2021), reliable critical success factors (Kalpande & Toke, 2022), continuous organizational improvement (Wolska, 2023), integration with lean management (Farihi, 2023; Saenagri, 2023), and digital transformation (Samadhiya et al., 2022; Tortorella et al., 2021). It also responds directly to oil-sector concerns related to equipment obsolescence (Kolo, 2025), supply-chain management (Ogbaini, 2025), environmental strategy (Sinambela, 2026), and sanctions affecting Iran's oil and gas industry (Dezhpasand et al., 2025).

Accordingly, the aim of this study was to develop and simulate a system dynamics model of the drivers of Total Productive Maintenance strategy in oil production at the National Iranian South Oilfields Company and to evaluate alternative policy scenarios for improving its long-term maintenance performance.

2. Methods and Materials

This study employed an applied, quantitative, exploratory-modeling design based on system dynamics to identify, structure, and simulate the principal drivers of Total Productive Maintenance (TPM) strategy in the oil and gas industry. The National Iranian South Oilfields Company (NISOC), headquartered in Ahvaz, Iran, and its affiliated companies constituted the organizational setting of the study. The research was applied in purpose because its findings were intended to provide a decision-support framework for improving maintenance strategy, equipment availability, operational reliability, productivity, and managerial decision-making within a large oil and gas organization. In terms of methodological orientation, the study was exploratory because the relationships among the underlying drivers of TPM were initially investigated empirically rather than being restricted to testing a predetermined causal structure. Exploratory analysis was particularly appropriate because the research sought not only to identify relevant variables but also to reveal their latent structure and subsequently transform the resulting relationships into a dynamic simulation model. System dynamics was selected as the principal modeling approach because maintenance performance in oil and gas operations is generated by interacting technical, organizational, human, managerial, and operational processes characterized by feedback, accumulation, delays, and nonlinear relationships. Accordingly, the research process proceeded from empirical identification and refinement of TPM-related factors to the conceptualization and computational simulation of their dynamic relationships.

The statistical population consisted of all eligible employees, managers, and professional experts employed at the headquarters and affiliated companies of the National Iranian South Oilfields Company. Individuals working in managerial, technical, operational, maintenance, engineering, planning, and related organizational positions were considered eligible because their occupational experience provided direct or indirect exposure to maintenance management, equipment performance, production processes, organizational decision-making, and TPM-related practices. According to the organizational population frame available for the study, the total population comprised 570 employees, managers, and experts. A sample of 291 participants was determined using Cochran's sample-size procedure and was selected from the population through simple random sampling. The use of probability sampling provided each eligible member of the defined population with an opportunity for selection and reduced systematic selection bias. Participation was voluntary, and respondents were informed that the information collected would be analyzed at the aggregate level and used exclusively for research purposes. The quantitative data obtained from these participants formed the empirical basis for identifying the dimensions and indicators entering the system dynamics model.

Data were collected primarily using a researcher-developed questionnaire designed to identify and measure the drivers of Total Productive Maintenance strategy in the organizational context of the oil and gas industry. The initial pool of indicators was developed on the basis of the conceptual foundations of TPM, maintenance management literature, characteristics of oil and gas production systems, organizational requirements of NISOC, and the variables required for system dynamics modeling. Particular attention was given to constructs capable of influencing maintenance effectiveness and its organizational consequences, including managerial support, employee participation, maintenance knowledge and skills, preventive and autonomous maintenance practices, equipment reliability, failure reduction, maintenance planning, training, interdepartmental coordination, safety considerations, availability of maintenance resources, continuous improvement, production continuity, and organizational performance. The questionnaire was structured so that respondents could indicate the extent to which each proposed indicator represented or influenced implementation and effectiveness of TPM within the organization. Items were assessed using a Likert-type response format, with higher scores representing a stronger perceived presence or influence of the corresponding TPM driver. Prior to the principal analysis, the questionnaire was reviewed for conceptual clarity, relevance to the study objectives, comprehensibility, and compatibility with the operational conditions of an oil and gas organization. Items exhibiting conceptual redundancy, ambiguity, or insufficient relevance to the intended constructs were refined before the instrument was administered to the final sample.

The measurement instrument also provided the input for exploratory factor analysis, through which the initial set of indicators was reduced to a smaller and theoretically interpretable collection of latent factors. This stage was necessary because a system dynamics model should contain variables that are substantively meaningful while avoiding unnecessary duplication among closely related indicators. Indicators demonstrating inadequate relationships with their respective factors, particularly those with weak factor loadings or poor conceptual correspondence with the extracted dimensions, were considered for elimination. The indicators retained after this refinement process were used to define the principal variables incorporated into the causal structure of the simulation model. In this manner, questionnaire measurement and exploratory factor analysis served as an empirical filtering mechanism connecting the field data to the subsequent system dynamics modeling phase.

A system dynamics modeling framework constituted the second principal research tool. System dynamics is grounded in feedback theory and integrates concepts derived from systems thinking, information theory, management science, decision theory, and feedback-control theory. Rather than treating organizational variables as isolated predictors and outcomes, the approach conceptualizes the organization as an interconnected system in which changes in one component may influence other components and eventually return to affect the original variable through reinforcing or balancing feedback loops. The structural configuration of the TPM system was therefore represented through variables, causal links, feedback mechanisms, stock-and-flow relationships, and relevant time delays. The conceptual model was subsequently translated into a computer-based simulation environment using Vensim software. Vensim was selected because it provides a dedicated environment for developing causal loop diagrams, stock-and-flow structures, mathematical relationships, simulation scenarios, sensitivity analyses, and temporal representations of complex organizational systems. Its use enabled the researchers to convert the empirically identified TPM factors into a formal dynamic structure and to examine the consequences of alternative managerial interventions over time.

Data analysis was performed in sequential stages comprising descriptive analysis, assessment of the suitability of the dataset for factor extraction, exploratory factor analysis, development of the system dynamics structure, model formulation, verification and validation, and simulation of alternative managerial scenarios. Initially, the collected questionnaires were screened for completeness and data quality, after which descriptive statistics were calculated to summarize participants' responses and the distribution of the TPM indicators. Exploratory factor analysis was subsequently conducted to determine the latent dimensions underlying the proposed indicators and to identify the variables most suitable for inclusion in the dynamic model. Before factor extraction, the adequacy of the correlation structure for factor analysis was assessed using appropriate indicators of sampling adequacy and intercorrelation among questionnaire items. Factors were then extracted and interpreted according to their empirical contribution and conceptual coherence. Factor loadings were examined to evaluate the relationship of individual indicators with the corresponding latent dimensions. Indicators with inadequate factor loadings, substantial ambiguity, or insufficient conceptual compatibility with their intended factor were excluded from subsequent modeling. The final set of factors and indicators was therefore obtained through the combined consideration of statistical evidence and theoretical interpretability rather than through statistical criteria alone.

Following the exploratory factor analysis, the retained TPM drivers were entered into the system dynamics modeling process. The first stage of model development involved defining the system boundary, identifying the principal endogenous and exogenous variables, and determining the major relationships through which the TPM drivers could affect maintenance and organizational performance. Causal loop diagrams were constructed to represent the direction and polarity of relationships among the variables. Positive causal links indicated that, all other conditions being equal, an increase in one variable was expected to produce an increase in the connected variable, whereas negative links represented relationships in which an increase in one variable was expected to reduce the other. These causal relationships were organized into reinforcing and balancing feedback loops. Reinforcing loops represented mechanisms capable of amplifying change over time, such as the possibility that greater maintenance training could improve employee competence, increase maintenance quality, decrease equipment failures, and provide further organizational support for training and TPM activities. Balancing loops represented regulatory mechanisms through which increasing failures, maintenance costs, equipment downtime, or production losses could stimulate corrective or preventive actions that subsequently reduced the initial problem.

After development of the causal structure, the conceptual model was converted into a stock-and-flow model in Vensim. Stocks represented variables accumulating or changing over time, whereas flows represented the rates responsible for increasing or decreasing those stocks. Auxiliary variables and parameters were incorporated where required to represent intermediate relationships and managerial decision rules. Mathematical equations describing relationships among the model variables were formulated according to the empirical findings, theoretical expectations, organizational evidence, and logical assumptions of the proposed TPM system. Appropriate simulation time intervals and initial conditions were then defined. Because dynamic behavior depends not only on the magnitude of causal effects but also on the temporal sequence through which these effects propagate across a system, explicit consideration was given to delays between managerial actions and observable maintenance outcomes. For example, investments in employee training or preventive maintenance may not immediately influence equipment availability or production efficiency; therefore, such delayed relationships were represented where conceptually appropriate.

Model verification and validation were undertaken before the model was used for scenario analysis. Structural verification examined whether equations, feedback relationships, variable definitions, dimensional consistency, and model boundaries accurately represented the conceptual assumptions of the study. Extreme-condition and behavioral examinations were used, where applicable, to determine whether the model generated logically plausible responses when selected parameters were assigned unusually high or low values. The simulated patterns were also assessed for consistency with theoretically expected maintenance behavior and the operational characteristics of the organization. Sensitivity analysis was performed by varying influential parameters within plausible ranges and observing resulting changes in the principal outcome variables. This procedure was particularly important for identifying those drivers whose modification produced the greatest changes in TPM performance and for evaluating whether the overall conclusions of the model remained stable under alternative parameter assumptions.

Finally, alternative simulation scenarios were constructed in Vensim to evaluate the effects of managerial interventions on the development and effectiveness of TPM strategy over time. Baseline simulation represented continuation of the existing or reference conditions, while intervention scenarios represented changes in selected strategic drivers identified through the exploratory and dynamic analyses. The trajectories generated under these scenarios were compared in terms of maintenance-related and organizational outcomes, including equipment reliability, failure frequency, downtime, preventive maintenance effectiveness, maintenance performance, productivity, and other relevant outputs represented in the final model. Comparison of simulated scenarios enabled the identification of leverage points within the TPM system and provided a basis for assessing how different managerial policies could influence the long-term behavior of maintenance strategy in the National Iranian South Oilfields Company. Thus, the analytical procedure integrated exploratory statistical analysis with feedback-based simulation, allowing the study to move beyond static identification of determinants toward an assessment of how interactions among TPM drivers may generate organizational outcomes dynamically over time.

3. Findings and Results

Following identification of the problem and specification of an appropriate simulation horizon, a dynamic hypothesis was formulated to explain the behavior of the Total Productive Maintenance strategy within the oil-production system. The system dynamics model indicated that maintenance strategy was not governed by a single organizational or technical mechanism; rather, its long-term behavior emerged from several interacting feedback structures. Six principal dynamic domains were identified: dynamics arising from political factors, investment-policy factors, upstream capital-resource provision, technological factors, maintenance characteristics, and weakening or constraining factors. These domains were incorporated into the causal structure of the model and subsequently translated into reinforcing and balancing mechanisms in Vensim. The principal feedback structures identified in the model are summarized in Table 1.

Table 1

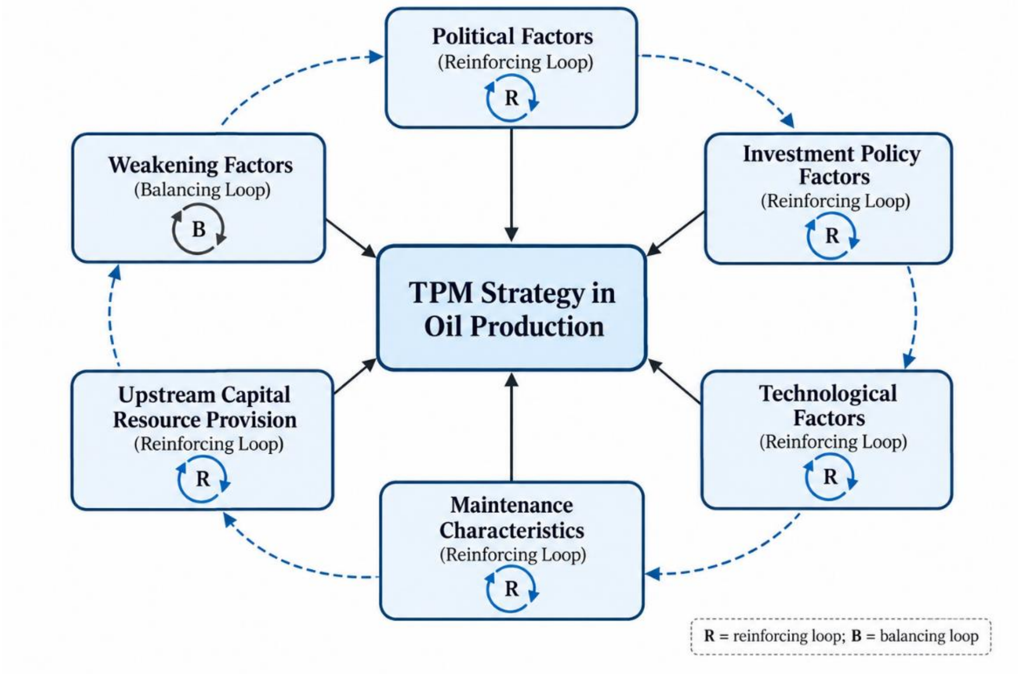
Principal Feedback Loops of the System Dynamics Model

Dynamic domain	Main causal mechanism	Loop type
Political factors	Improved maintenance policies reduce negative perceptions toward external maintenance, improve the attitudes of political and economic decision-makers, reduce political monopolies and rent-seeking, decrease bureaucratic complexity in oil-production policies, and subsequently strengthen maintenance policy.	Reinforcing
Investment-policy factors	Oil-industry R&D policies strengthen policies for introducing petroleum technologies, which support external maintenance policies, diversification of maintenance resources, and development of extraction and production structures. These structural improvements subsequently reinforce R&D policy.	Reinforcing
Technological factors	Productivity and optimization of oil production increase the attractiveness of the oil industry for maintenance investment and improve profitability from optimized production. The qualitative dimension of maintenance further reinforces attractiveness and profitability.	Reinforcing
Maintenance characteristics	Maintenance characteristics operate as a state variable and are strengthened through new petroleum-contract maintenance arrangements and efforts toward economic management, which reinforce the relevant maintenance variables.	Reinforcing
Upstream capital-resource provision	Debt-based financing strengthens intermediate financing, which contributes to equity-based financing. Reserve-based financing also supports equity financing and financing through production-related repayment mechanisms.	Reinforcing
Weakening factors	Potential risks influence monetary policy, financing evaluation, and maintenance management. Adverse investment-management and sociocultural mechanisms contribute to environmental neglect and restrictions on production capacity, ultimately weakening maintenance policy.	Balancing/weakening

The political feedback loop showed that improvements in maintenance policy could progressively reduce unfavorable perceptions regarding the use of external maintenance resources. A more favorable perception, in turn, could reduce resistance among political and economic decision-makers, weaken monopolistic arrangements and political rents, and diminish administrative bureaucracy affecting oil-production policies. Because reduced bureaucracy facilitates implementation of maintenance decisions, the loop ultimately returns to strengthen the original maintenance-policy variable. The investment-policy loop similarly demonstrated a self-reinforcing process in which R&D policy encourages the introduction of petroleum technologies and diversified maintenance arrangements, while improved production and extraction structures further stimulate R&D investment. In the technological loop, productivity, optimized production, the qualitative dimension of maintenance, industry attractiveness, and profitability were mutually reinforcing. The maintenance-characteristics loop showed that implementation of maintenance through new petroleum contracts and stronger economic management could reinforce maintenance capability. The upstream-financing loop emphasized interaction among debt-based, intermediate, equity-based, reserve-based, and production-repayment financing mechanisms. In contrast to these reinforcing structures, the weakening loop represented the adverse effects of risk, unfavorable monetary conditions, weak financing assessment, sociocultural constraints, environmental neglect, and restrictions on production capacity.

Figure 1

System Dynamics Model of Total Productive Maintenance Strategy in Oil Production under the Baseline Condition



The complete system dynamics structure was executed under baseline assumptions to determine the endogenous behavior of the maintenance-strategy state variable over a 20-year simulation horizon. Under the reference condition, the strategy variable started at 10.00 and increased rapidly during the initial years. It reached approximately 115.45 by year 4 and continued to increase more gradually until reaching a peak of approximately 128.94 around year 9.25. Thereafter, the simulated trajectory reversed, and a sustained decline emerged. By the end of year 20, the strategy value had declined to approximately 68.73. Thus, the reference trajectory exhibited three distinct behavioral phases: rapid growth during approximately the first four years, a relatively stable or slowly increasing phase in the subsequent period, and a persistent downward trend over the later simulation horizon. The key reference values are presented in Table 2.

Table 2

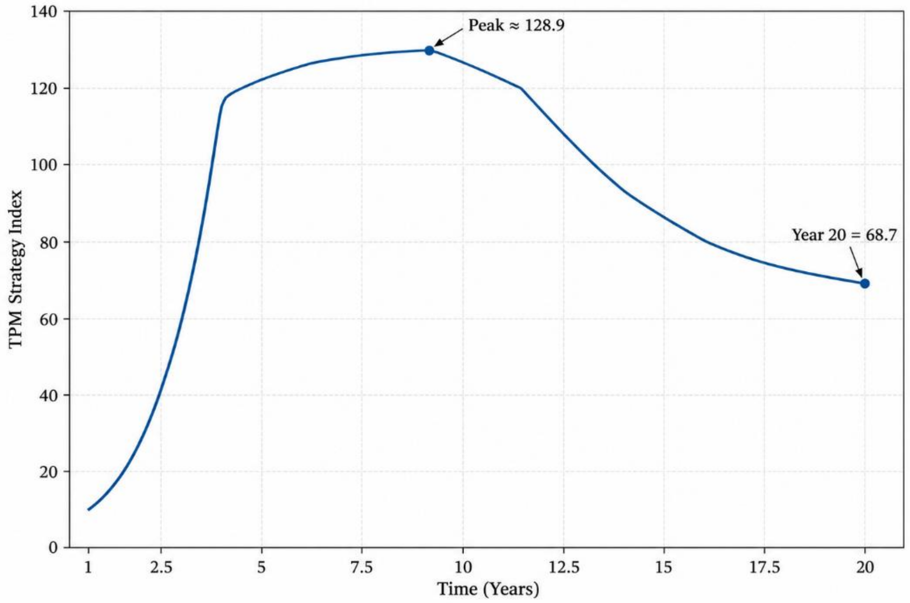
Selected Baseline Simulation Results for Total Productive Maintenance Strategy

Simulation year	Baseline value
1.00	10.000
2.00	23.038
3.00	51.851
4.00	115.450
5.00	121.582
6.00	125.608
7.00	127.219
8.00	128.268
9.00	128.939
Approximate peak	128.939
10.00	125.608
12.00	109.344
15.00	85.257
18.00	75.174
20.00	68.732

The baseline trajectory demonstrated that maintenance strategy could initially improve considerably even without additional policy intervention; however, the improvement was not sustainable over the entire planning horizon. Although the simulation increased from an initial value of 10.00 to 68.7324 at the end of the 20-year horizon, the downward behavior following the mid-simulation peak indicated that the reference system would not sustain the level of improvement required for long-term development of oil-production maintenance. This pattern suggested that additional policy interventions would be necessary to prevent deterioration in the later years and to produce a more favorable long-term maintenance trajectory.

Figure 2

Baseline Behavior of the System Dynamics Model for Total Productive Maintenance Strategy over the 20-Year Simulation Horizon



Nine intervention scenarios were subsequently simulated. In Scenario 1, unfavorable monetary-policy conditions were reduced from 0.55 to 0.35. The intervention increased the final maintenance-strategy value from the baseline value of 68.7324 to 106.408, corresponding to an improvement of approximately 37.676 units. In addition to improving the principal state variable, this intervention strengthened the qualitative dimension of maintenance and increased the profit generated by optimized oil production. The scenario trajectory also remained above the baseline trajectory throughout much of the later simulation period, demonstrating that reducing unfavorable monetary conditions could mitigate deterioration in maintenance performance.

Scenario 2 examined improvement in financing assessment by reducing the corresponding adverse parameter from 0.72 to 0.43. This intervention produced a stronger effect than Scenario 1. The final maintenance-strategy value increased to approximately 121.553, representing an improvement of approximately 52.820 units relative to the reference condition. The intervention particularly improved the qualitative dimension of maintenance and efforts toward economic management. The results therefore showed that better financing assessment could improve not only financial decision-making but also organizational conditions supporting maintenance quality and economically oriented maintenance management.

Scenario 3 assessed diversification of maintenance resources by increasing the relevant parameter from 0.42 to 0.62. The simulated value at the end of the horizon increased from 68.7324 under the reference condition to approximately 89.119, corresponding to an improvement of about 20.386 units. The principal secondary effects occurred in intermediate financing and equity-based financing, indicating that diversification of maintenance resources generated financial-system effects beyond its immediate operational influence. Selected results for the first three scenarios are summarized in Table 3.

Table 3

Results of Scenarios 1–3

Scenario	Parameter change	Baseline final value	Scenario final value	Improvement	Principal secondary effects
Reduction of unfavorable monetary policies	0.55 → 0.35	68.732	106.408	+37.676	Maintenance quality; profit from optimized production
Improvement in financing assessment	0.72 → 0.43	68.732	121.553	+52.820	Maintenance quality; economic-management effort
Diversification of maintenance resources	0.42 → 0.62	68.732	89.119	+20.386	Intermediate financing; equity-based financing

Scenario 4 investigated structural development of oil extraction and production by increasing the relevant model parameter from 0.38 to 0.58. This change increased the final maintenance-strategy value to approximately 78.736, an improvement of about 10.003 units compared with the reference condition. Although the direct effect on the main maintenance variable was modest relative to several other scenarios, the intervention positively affected intermediate and equity-based financing mechanisms. This result suggested that structural development of extraction and production could support maintenance indirectly through an improved financing environment.

Scenario 5 evaluated improvement in oil-industry research and development policies. The relevant parameter was increased from 0.39 to 0.41. The intervention increased the maintenance-strategy outcome to approximately 100.537, representing an improvement of approximately 31.804 units relative to the baseline condition. The model further showed that strengthening R&D policy reduced several adverse systemic influences, particularly constraints related to production capacity, financing assessment problems, sociocultural factors, and potential risks. Thus, the R&D intervention operated through a wider set of pathways than its direct technological effect.

Scenario 6 examined reserve-based financing by increasing financing based on underground reserves from 0.34 to 0.54. This intervention produced one of the strongest improvements among the nine simulated policies. The final maintenance-strategy value increased from 68.7324 to approximately 138.313, yielding an improvement of approximately 69.580 units. The intervention also influenced production-capacity conditions associated with investment management, potential risks, financing assessment, and maintenance management through new petroleum-contract arrangements. The results of Scenarios 4–6 are reported in Table 4.

Table 4

Results of Scenarios 4–6

Scenario	Parameter change	Baseline final value	Scenario final value	Improvement	Principal secondary effects
Development of extraction and production structures	0.38 → 0.58	68.732	78.736	+10.003	Intermediate financing; equity-based financing
Improvement in oil-industry R&D policies	0.39 → 0.41	68.732	100.537	+31.804	Production ceiling, financing assessment, sociocultural factors, and potential risks
Reserve-based financing	0.34 → 0.54	68.732	138.313	+69.580	Production capacity, potential risks, financing assessment, new petroleum-contract maintenance

Scenario 7 simulated an improvement in debt-based financing by increasing its value from 0.58 to 0.78. The intervention generated a pronounced improvement in the maintenance-strategy trajectory. The final simulated value reached approximately 177.066 compared with 68.7324 in the reference condition, corresponding to an increase of about 108.333 units. The scenario also had substantial effects on intermediate financing, maintenance management through new petroleum contracts, profit generated through optimized production, and equity-based financing. The time-series behavior was distinctive: after the initial growth period, the intervention generated values substantially exceeding the reference trajectory, reaching a maximum of approximately 252.98 before gradually declining to 177.07 by year 20. Despite this later decline, the final value remained substantially above the baseline.

Scenario 8 examined improvement in intermediate financing by increasing its value from 0.39 to 0.59. Among all simulated interventions, this scenario produced the greatest improvement in the principal maintenance variable. The trajectory increased rapidly and reached a maximum of approximately 306.32 during the middle portion of the simulation before gradually declining. Nevertheless, at year 20, the simulated value remained approximately 197.587, compared with 68.7324 under the reference condition. The overall improvement was therefore approximately 128.854 units. In addition to its effect on the main state variable, improvement in intermediate financing strongly influenced sociocultural factors, investment management, financing assessment, and the qualitative dimension of maintenance.

Scenario 9 investigated improvement in policies governing the introduction of petroleum technologies by increasing the relevant parameter from 0.43 to 0.63. This intervention increased the final maintenance-strategy value to approximately 81.462, corresponding to an improvement of about 12.729 units relative to the baseline. Its most important secondary effects occurred through external maintenance policies and the development of oil extraction and production structures. Compared with the major financing interventions, however, its direct long-term influence on the main maintenance-strategy variable was considerably smaller. Table 5 summarizes Scenarios 7–9.

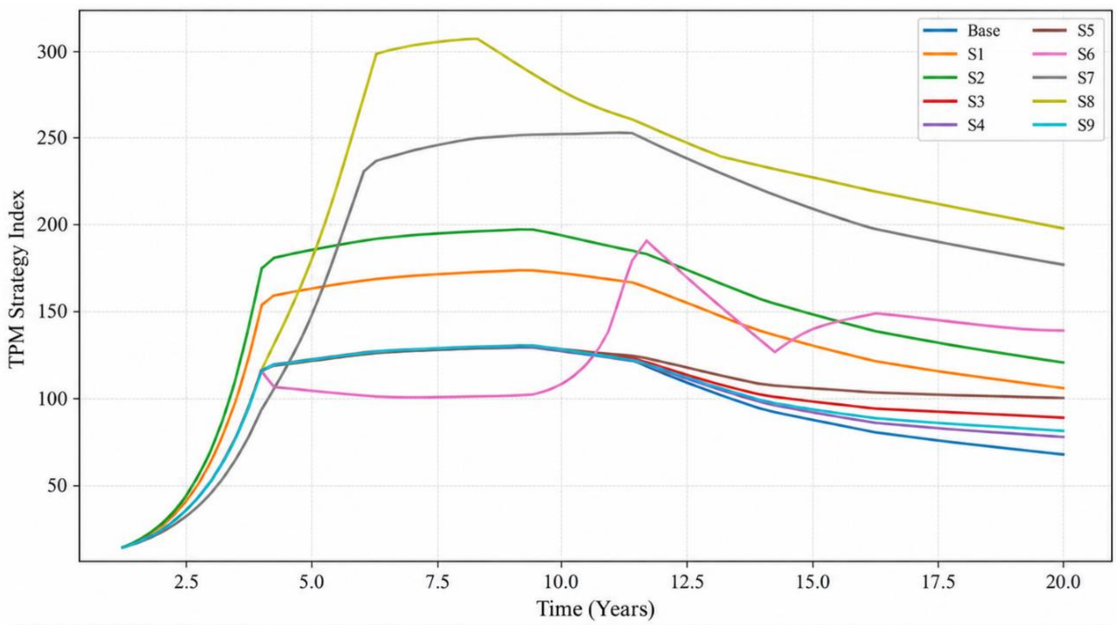
Table 5

Results of Scenarios 7–9

Scenario	Parameter change	Baseline final value	Scenario final value	Improvement	Principal secondary effects
Debt-based financing	0.58 → 0.78	68.732	177.066	+108.333	Intermediate financing; new petroleum-contract maintenance; optimized-production profit; equity financing
Intermediate financing	0.39 → 0.59	68.732	197.587	+128.854	Sociocultural factors; investment management; financing assessment; maintenance quality
Policies for introduction of petroleum technologies	0.43 → 0.63	68.732	81.462	+12.729	External maintenance policy; development of extraction and production structures

Figure 3

Comparative System Dynamics Behavior of the Baseline and Alternative Maintenance-Policy Scenarios



The comparative simulation results showed substantial heterogeneity in policy effectiveness. Interventions directed toward financing mechanisms generally produced larger changes in the long-term maintenance-strategy trajectory than interventions directed solely toward technological or structural variables. In particular, intermediate financing, debt-based financing, and reserve-based financing produced the strongest final-state improvements. Improvements in financing assessment and reductions in unfavorable monetary policies also generated substantial gains, whereas diversification of maintenance resources, R&D policy, introduction of petroleum technologies, and development of extraction and production structures produced positive but comparatively smaller changes. The complete comparison of the nine scenarios is presented in Table 6.

Table 6

Comparative Results of the Nine System Dynamics Scenarios

Scenario	Policy intervention	Reference value	Scenario value	Change
1	Reduction of unfavorable monetary policies	68.7324	106.408	+37.6756
2	Improvement in financing assessment	68.7324	121.553	+52.820
3	Diversification of maintenance resources	68.7324	89.118	+20.386
4	Development of extraction and production structures	68.7324	78.736	+10.003
5	Improvement in oil-industry R&D policies	68.7324	100.537	+31.804
6	Reserve-based financing	68.7324	138.313	+69.580
7	Debt-based financing	68.7324	177.066	+108.333
8	Intermediate financing	68.7324	197.587	+128.854
9	Improvement in petroleum-technology introduction policies	68.7324	81.462	+12.729

The simulation model was subjected to a series of verification and validation procedures before the policy results were interpreted. Model adequacy was first examined by determining whether the principal variables required to reproduce system behavior had been included. The variables had been identified through theoretical review and content analysis, providing support for adequacy of the system boundary. Structural verification was then conducted to determine whether the model structure and interactions were consistent with knowledge of the actual oil-production and maintenance system. The model components and their relationships were initially extracted from the theoretical foundations and were subsequently reconsidered through focused consultation with experts before preparation of the final system structure.

A second structural criterion concerned the ability of the model to reproduce the actual behavior of the system and remain compatible with historical patterns. Comparison of the simulated behavior with observed temporal behavior of oil production suggested that the model reproduced the general behavior expected from the real system. Parameter verification was also undertaken. The model parameters and the effects attributed to exogenous variables were assessed through focused expert sessions involving specialists familiar with management and oil-industry processes. Linguistic assessments and expert judgments were used to determine plausible values and directions for the relevant model relationships.

Equation consistency was examined by considering whether the model equations appropriately represented the intended real-world relationships. Expert review of the final model provided support for consistency between the equations, system components, and expected organizational mechanisms. Extreme-condition testing was also performed by introducing substantial parameter changes and examining whether the resulting system behavior remained logically plausible. In particular, an extreme change in the principal state variable from 1 to 100 was introduced to inspect the response of the maintenance system. Despite these large parameter perturbations, the resulting behavior remained logical and consistent with the structural assumptions of the model.

The usefulness and purpose-oriented validity of the model were examined according to its ability to explain the maintenance problem and provide policy alternatives capable of addressing it. Because the model was specifically constructed to analyze maintenance in oil production and its feedback loops were linked to mechanisms capable of improving or constraining system performance, it was judged to have adequate practical validity for the stated research purpose. Structural validity was supported by agreement between the feedback-loop components, causal relationships, equations, expert judgments, and theoretical foundations. Behavioral validity was supported by the model's ability to produce stable data without abnormal or implausible outputs and to respond logically to changes in policy parameters. Behavioral validity was additionally evaluated over an extended 100-year simulation horizon. Stability testing was undertaken by simulating model components separately and subsequently in combination. No logically inconsistent or anomalous behavior was observed at either level. Finally, the model was examined through the **Check Model** function in Vensim, and no critical structural inconsistency that would invalidate the simulation was identified. These validation procedures are summarized in Table 7.

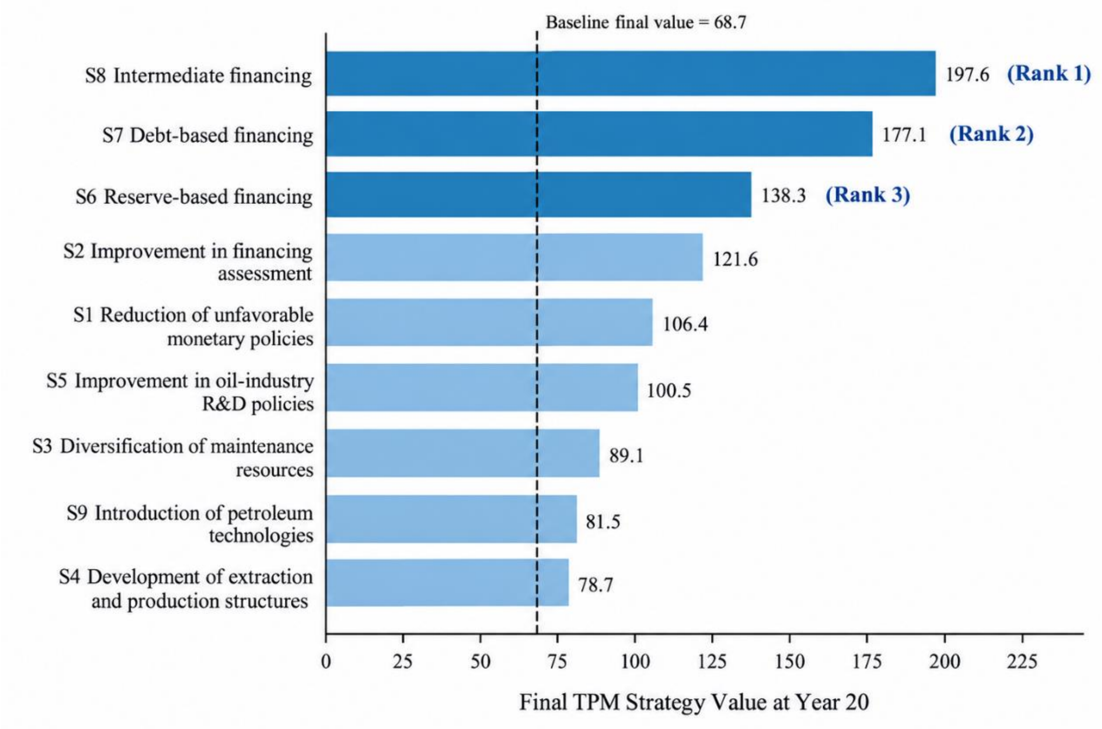
Table 7

Model Verification, Validation, and Stability Assessment

Validation test	Evaluation criterion	Result
Model adequacy	Inclusion of the principal variables required to reproduce system behavior	Principal variables identified through theoretical review and content analysis were incorporated
Structural verification	Consistency of model structure with theoretical and organizational knowledge	Relationships were derived theoretically and refined through expert consultation
Historical/behavioral correspondence	Ability to reproduce patterns consistent with observed system behavior	Simulated behavior was compatible with the general observed behavior of oil-production systems
Parameter verification	Plausibility of parameters and exogenous effects	Parameters were assessed through focused expert consultation
Equation consistency	Correspondence between model equations and the intended real-world system	Expert assessment supported consistency
Extreme-condition test	Logical behavior following very large parameter changes	System behavior remained logically plausible
Structural validity	Agreement among loops, equations, theory, and expert knowledge	Supported
Behavioral validity	Stable output and logical responses to policy changes	Supported, including evaluation over a 100-year horizon
Stability test	Absence of anomalous behavior when components were simulated separately and jointly	No anomalous behavior observed
Vensim model check	Software-based inspection of model consistency	Model successfully examined using the Check Model function

Figure 4

Comparative Effects of the Nine Policy Scenarios on Total Productive Maintenance Strategy in Oil Production



The final comparison identified three interventions with the largest increases in the maintenance-strategy state variable. Improvement in intermediate financing produced the largest simulated change, increasing the final state by 128.854 units. Improvement in debt-based financing produced an increase of 108.333 units, while reserve-based financing generated an increase of 69.580 units. Financing assessment improvement was the next strongest intervention, with an increase of approximately 52.820 units, followed by reduction of unfavorable monetary policies, improvement in R&D policies, diversification of maintenance resources, policies for petroleum-technology introduction, and development of extraction and production structures.

Accordingly, within the simulated structure, intermediate financing emerged as the strongest policy leverage point, followed by debt-based financing and financing based on underground reserves. The results further demonstrated that these interventions did not operate exclusively through financial channels. Intermediate financing also affected sociocultural conditions, investment management, financing assessment, and maintenance quality; debt-based financing affected intermediate and equity-based financing, new petroleum-contract maintenance, and profitability; and reserve-based financing influenced production capacity, risks, financing assessment, and maintenance through new petroleum contractual mechanisms. Therefore, the model indicated that the financing subsystem occupied a central position in the feedback architecture of Total Productive Maintenance strategy and had the capacity to transmit policy effects simultaneously to maintenance, production, investment, and organizational variables.

Overall, the findings demonstrated that the baseline maintenance system generated strong improvement during the early years but was unable to sustain that improvement over the 20-year horizon. The baseline trajectory peaked at approximately 128.94 and subsequently declined to 68.73. Every policy scenario improved the final maintenance-strategy value relative to the reference condition, but the magnitude of improvement varied considerably. The greatest simulated gains were associated with intermediate financing, debt-based financing, and reserve-based financing, whereas development of extraction and production structures and petroleum-technology introduction policies produced comparatively modest improvements. The model-verification procedures, including structural assessment, parameter checking, equation-consistency evaluation, extreme-condition testing, long-horizon behavioral assessment, stability analysis, and the Vensim Check Model procedure, indicated that the developed system dynamics model was sufficiently stable and internally coherent for evaluating alternative maintenance-policy scenarios in the National Iranian South Oilfields Company.

4. Discussion and Conclusion

The present study developed and simulated a system dynamics model to explain the drivers of Total Productive Maintenance strategy in oil production at the National Iranian South Oilfields Company and to evaluate the long-term effects of alternative policy interventions. The results demonstrated that the behavior of the maintenance system was generated through the interaction of six broad dynamic domains: political factors, investment-policy factors, upstream capital-resource provision, technological factors, maintenance characteristics, and weakening factors. Most of these domains operated through reinforcing feedback loops, whereas the weakening domain created balancing pressures that reduced the sustainability of maintenance improvement over time. The baseline simulation was particularly informative because the TPM strategy index increased rapidly from an initial value of 10, reached approximately 128.94 around the ninth year, and then entered a sustained decline, reaching approximately 68.73 by the twentieth year. This finding suggests that existing conditions may be sufficient to generate short- and medium-term improvement but not to preserve that improvement over a longer strategic horizon. Such a result is consistent with the argument that TPM is not a one-time technical intervention but an organizational system requiring continuous reinforcement, managerial support, institutionalization, and iterative improvement (Wolska, 2023). It also supports the view that TPM performance depends on the coordinated functioning of multiple pillars rather than the isolated implementation of individual maintenance practices (Vital & Lima, 2020).

The feedback-loop structure further indicated that political, financial, technological, managerial, and maintenance-related forces were mutually dependent. In the political loop, improvement in maintenance policy reduced unfavorable perceptions of external maintenance, weakened political and administrative barriers, and ultimately strengthened maintenance policy itself. In the investment-policy loop, research and development policies stimulated technology-entry policies, maintenance-resource diversification, and development of extraction and production structures, which subsequently reinforced further investment and R&D activity. These results support the broader conception of TPM as a management philosophy whose effectiveness depends on organizational context, strategic commitment, and institutional conditions. Research has emphasized that implementation and improvement of TPM require sustained managerial and organizational effort rather than a narrow engineering focus (Wolska, 2023). Likewise, the importance of employee participation and bottom-up involvement identified by Yang and Yang suggests that organizational behavior and internal support mechanisms can reinforce or weaken maintenance practices over time (Yang & Yang, 2023). Although the present study focused on system-level policy rather than individual employee behavior, both perspectives emphasize that TPM performance emerges from interacting organizational mechanisms rather than purely technical maintenance interventions.

The technological feedback structure also showed that productivity and optimization of oil production increased both the attractiveness of maintenance investment and the profit generated from optimized production, while the qualitative dimension of maintenance further reinforced these relationships. This finding is compatible with prior research linking TPM with equipment effectiveness, profitability, and operational performance. Risonarta and Wardhani argued that TPM can contribute to improved profitability through increased equipment efficiency, reduced losses, and improved production performance (Risonarta & Wardhani, 2023). Similarly, the effect of individual TPM pillars on overall equipment effectiveness demonstrates that maintenance quality can create cumulative gains in asset performance (Vital & Lima, 2020). The technological dimension is increasingly important because contemporary TPM is being integrated with Industry 4.0 technologies, enabling better condition monitoring, information visibility, predictive capabilities, and maintenance decision-making (Tortorella et al., 2021). Samadhiya et al. likewise emphasized the value of integrating Industry 4.0 with TPM to support both operational effectiveness and sustainability (Samadhiya et al., 2022). Therefore, the reinforcing technological loop identified in the current model is theoretically consistent with a growing body of evidence showing that technological capability can amplify the benefits of maintenance strategy when it is embedded in an appropriate organizational and financial environment.

The scenario analysis provided a clearer understanding of the relative leverage of individual policy variables. Reduction of unfavorable monetary policies increased the final TPM strategy value from approximately 68.73 to 106.41, representing an improvement of about 37.68 units. Improvement in financing assessment produced a larger increase to approximately 121.55, corresponding to an improvement of about 52.82 units. These findings indicate that maintenance strategy in a capital-intensive oil-production system is sensitive not only to technical decisions but also to the quality of financial conditions and financial evaluation. In oil and gas operations, maintenance requires continuous access to capital for spare parts, specialized services, equipment replacement, technology modernization, and preventive interventions. This is especially important under conditions in which macroeconomic constraints affect access to resources. Dezhpasand et al. have emphasized the effects of economic sanctions on Iran's oil and gas industry, particularly through restrictions affecting investment, technology, financing, and operational development (Dezhpasand et al., 2025). The present findings extend this argument by showing dynamically that unfavorable monetary and financing conditions can influence maintenance performance over the long term rather than merely increasing short-term operational costs.

The third scenario, diversification of maintenance resources, increased the final value to approximately 89.12, while development of extraction and production structures increased it to approximately 78.74. Although both interventions were beneficial, their effects were smaller than those associated with major financing interventions. The influence of maintenance-resource diversification was transmitted particularly through intermediate and equity-based financing, whereas structural development of extraction and production similarly affected financial channels. This suggests that resource and infrastructure policies may have limited long-term effects unless they are accompanied by financing structures capable of sustaining their implementation. The importance of resource availability is compatible with studies emphasizing supply-chain management as a determinant of oil and gas company performance (Ogbaini, 2025). It also aligns with evidence that obsolescence management is essential in oil and gas rotating equipment because aging assets, unavailable parts, and technological discontinuity can increase downtime and financial loss (Kolo, 2025). Thus, diversification of maintenance resources and development of production structures may improve performance, but their effectiveness appears to depend on whether the organization possesses sufficient financial capacity to maintain those improvements over time.

Improvement in oil-industry R&D policy generated an increase from the baseline value of approximately 68.73 to 100.54, an improvement of approximately 31.80 units. The scenario also reduced adverse influences associated with production constraints, financing assessment, sociocultural factors, and potential risks. This result indicates that R&D policy operates as more than a technological input; it can have system-wide effects by improving the organization's capacity to identify, absorb, adapt, and manage new maintenance technologies. This is consistent with studies on TPM and technological integration. Tortorella et al. showed that Industry 4.0 technologies can be integrated with TPM practices to improve production and maintenance systems (Tortorella et al., 2021), while Samadhiya et al. emphasized the strategic integration of Industry 4.0 and TPM for sustainability and competitive performance (Samadhiya et al., 2022). The findings are also compatible with lean-maintenance research showing that the redesign of maintenance systems through TPM can increase process efficiency and reduce operational waste (Farihi, 2023). Therefore, R&D policy may serve as an enabling mechanism through which maintenance knowledge, technology adoption, and managerial learning are strengthened simultaneously.

The most important result of the study concerned the three strongest financial scenarios. Reserve-based financing increased the final TPM strategy value to approximately 138.31, representing an improvement of about 69.58 units. Debt-based financing increased the value to approximately 177.07, or about 108.33 units above the baseline. The strongest intervention was intermediate financing, which raised the final value to approximately 197.59 and generated an improvement of approximately 128.85 units. These three scenarios substantially outperformed the remaining interventions. The result demonstrates that the financing architecture occupies a central position in the dynamic maintenance system. Intermediate financing not only improved the principal TPM state variable but also influenced sociocultural conditions, investment management, financing assessment, and maintenance quality. Debt-based financing affected intermediate financing, equity financing, profitability from optimized production, and maintenance management under new petroleum contracts. Reserve-based financing affected production capacity, risk, financing assessment, and maintenance-contract mechanisms. These results indicate that financial instruments function as system-wide leverage points capable of transmitting effects across multiple feedback loops.

The prominence of financing is particularly plausible in the oil and gas sector because maintenance activities frequently involve expensive equipment, imported components, specialized technical services, large infrastructure, and long investment cycles. Unlike smaller manufacturing environments, where TPM may be implemented primarily through employee participation, autonomous maintenance, and incremental process improvement, oil-production maintenance often requires substantial capital commitments. Nevertheless, the present results should not be interpreted as reducing TPM to a financial issue. Rather, financing appears to enable the human, technological, and organizational components of TPM to operate effectively. Research has shown that motivation significantly influences TPM outcomes because maintenance practices depend on sustained employee involvement and organizational engagement (Guedes et al., 2021). The critical-success-factor literature likewise emphasizes that TPM performance depends on a combination of organizational, managerial, technical, and human conditions (Kalpande & Toke, 2022). Accordingly, financing may be understood as a facilitating resource that strengthens the ability of an organization to support training, technology, contracts, spare parts, preventive activities, and continuous improvement.

The comparatively smaller effect of technology-entry policy was also noteworthy. Increasing the technology-entry policy parameter from 0.43 to 0.63 raised the final TPM value only to approximately 81.46, an improvement of about 12.73 units. Although this scenario positively affected external maintenance policies and development of extraction and production structures, its long-term effect remained considerably below that of the financing interventions. This finding suggests that access to new technology alone is insufficient to transform maintenance performance unless the organization possesses the financing, human capability, managerial infrastructure, and institutional support required to absorb and exploit that technology. This interpretation agrees with research showing that the adoption of Industry 4.0 technologies into TPM is dependent on organizational readiness and complementary management practices (Tortorella et al., 2021). Similarly, TPM implementation in manufacturing SMEs has been shown to require adaptation to organizational resources and implementation capability rather than simple adoption of maintenance tools (Tian & Jeng Feng, 2021; Xiang & Feng, 2021). Thus, technology should be regarded as one component of a broader socio-technical and financial maintenance system.

The findings also reinforce the importance of evaluating TPM through multidimensional performance mechanisms. The model showed that changes in maintenance strategy affected not only equipment-related outcomes but also profitability, production capacity, investment management, financial assessment, organizational conditions, and sociocultural variables. Hraiga et al. similarly emphasized the value of using a balanced-scorecard perspective when evaluating TPM performance because maintenance affects multiple dimensions of organizational performance (Hraiga et al., 2023). Moreover, sustainable TPM research argues that maintenance should be connected to economic, social, and environmental outcomes rather than assessed only through equipment availability (Hallioui et al., 2023). The weakening loop identified in the present research also included environmental neglect as a mechanism that could ultimately contribute to reduced production capacity. This is consistent with the broader movement toward integrating environmental considerations into oil and gas strategy and with recent work emphasizing structured environmental-management decision-making in oil and gas development (Sinambela, 2026). In addition, the importance of awareness and behavioral participation in maintenance-oriented environments has been observed in green-building applications of TPM (Au-Yong et al., 2021), further supporting the notion that sustainability and maintenance performance depend on both technical and human systems.

The validation results provide additional support for interpretation of the scenario findings. Structural adequacy was evaluated through theoretical review, expert consultation, assessment of equations and parameters, comparison of simulated behavior with expected real-world behavior, extreme-condition testing, long-horizon behavioral examination, and stability testing. The model generated logical responses under substantial parameter changes and did not exhibit abnormal behavior when its components were simulated separately or jointly. Such validation is important because system dynamics models are designed primarily to represent causal structures and behavioral tendencies rather than to produce isolated statistical predictions. The stability of the model over an extended simulation horizon and its logical reaction to policy interventions indicate that the identified feedback architecture provides a meaningful representation of the maintenance system. Overall, the results support the central conclusion that long-term TPM performance in oil production depends on the interaction of financing, technology, investment policy, maintenance quality, organizational conditions, and external constraints, with financing mechanisms emerging as the most powerful leverage points in the simulated system.

The study has several limitations. First, the model was developed within the organizational context of the National Iranian South Oilfields Company; therefore, the causal structure and parameter values may reflect characteristics of this specific oil-production environment and may not be directly transferable to other national oil companies, private operators, downstream organizations, or industries. Second, several model parameters were based partly on expert judgment and organizational assessments, which may introduce subjectivity despite the validation procedures applied. Third, system dynamics necessarily simplifies reality by representing selected variables and causal relationships, and some potentially relevant factors may have remained outside the model boundary. Fourth, the 20-year simulation horizon provides insight into long-term behavior but is sensitive to assumptions concerning parameter stability, policy continuity, and external economic conditions. Finally, the study concentrated primarily on strategic maintenance-system behavior and did not directly incorporate detailed equipment-level indicators such as individual failure distributions, mean time between failures, mean time to repair, or asset-specific lifecycle costs.

Future research could validate the model in other oil and gas companies and compare results across upstream, midstream, and downstream operations. Researchers could also integrate system dynamics with discrete-event simulation, agent-based modeling, reliability engineering, or optimization techniques to represent both strategic and equipment-level behavior. Future models should incorporate real-time operational data, predictive-maintenance indicators, sensor information, and digital-twin outputs to improve parameter calibration and behavioral validation. Additional scenarios could examine combinations of policies rather than changing one intervention at a time, particularly combinations of financing reform, technology modernization, workforce development, and preventive-maintenance expansion. Further studies could also examine uncertainty through Monte Carlo simulation and sensitivity analysis and evaluate economic outcomes such as lifecycle cost, return on maintenance investment, production losses avoided, and risk-adjusted profitability.

From a practical perspective, managers should treat TPM as a strategic production-management system rather than a maintenance-department program. The simulation results indicate that financial architecture deserves particular managerial attention, especially intermediate financing, debt-based financing, and financing linked to underground reserves. However, these mechanisms should be coordinated with stronger financing evaluation, R&D investment, resource diversification, technology acquisition, and development of extraction and production structures. Management should establish integrated maintenance-investment planning, protect preventive-maintenance budgets from short-term financial pressures, improve access to critical spare parts and technical resources, strengthen maintenance-quality monitoring, and ensure that new technologies are supported by workforce capability and organizational processes. Regular scenario simulation should also be incorporated into strategic planning so that decision-makers can evaluate the long-term consequences of maintenance and investment policies before implementation.

Authors' Contributions

Authors contributed equally to this article.

Declaration

In order to correct and improve the academic writing of our paper, we have used the language model ChatGPT.

Transparency Statement

Data are available for research purposes upon reasonable request to the corresponding author.

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Declaration of Interest

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In this research, ethical standards including obtaining informed consent, ensuring privacy and confidentiality were considered.

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