

GAME-THEORETIC APPROACHES TO ENVIRONMENTAL PROTECTION AROUND CONSTRUCTION AND INDUSTRIAL DEVELOPMENT SITES: PROBLEMS, EXISTING SOLUTIONS, AND FUTURE DIRECTIONS

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Анотація

Будівництво та промисловий розвиток істотно сприяють економічному зростанню, проте часто породжують екологічні проблеми, які впливають на прилеглі екосистеми та місцеві громади. Ефективне управління довкіллям вимагає досягнення балансу між економічними цілями та екологічною стійкістю з урахуванням стратегічних взаємодій між численними зацікавленими сторонами. У зв'язку з цим здійснено огляд основних екологічних проблем, пов'язаних із будівельними майданчиками та об'єктами промислового розвитку. Досліджено можливості застосування теоретико-ігрових підходів до прийняття екологічно орієнтованих рішень. Особливу увагу приділено моделям дилеми в'язня, повторюваним дилемним іграм, іграм із суспільними благами, моделям Stag Hunt, динамічним іграм та безшумним дуелям. Проаналізовані літературні джерела свідчать, що результати екологічної діяльності значною мірою залежать від систем стимулювання, механізмів співпраці, репутаційних ефектів і своєчасності втручання. Якщо традиційні методи оцінювання впливу на довкілля зосереджуються переважно на технічних та економічних аспектах, то теоретико-ігрові підходи безпосередньо враховують конфлікти інтересів і адаптивну поведінку зацікавлених сторін. Проведений аналіз дає підстави вважати, що інтеграція еволюційної теорії ігор, повторюваних ігор, моделей часових рішень на основі безшумних дуелей та багатоагентного імітаційного моделювання здатна забезпечити перспективні інструменти підтримки прийняття рішень для сталого міського та промислового розвитку.

Ключові слова: охорона довкілля, сталий розвиток, промисловий розвиток, теорія ігор.

Abstract

Construction and industrial development contribute substantially to economic growth but often generate environmental challenges affecting nearby ecosystems and communities. Effective environmental management requires balancing economic objectives with ecological sustainability while accounting for the strategic interactions among multiple stakeholders. So, major environmental problems associated with construction and industrial development sites are reviewed. The applicability of game-theoretic approaches to environmental decision making is examined. Particular attention is paid to Prisoner's Dilemma models, iterated dilemma games, public goods games, Stag Hunt models, dynamic games, and silent duel models. The reviewed literature indicates that environmental outcomes are strongly influenced by incentives, cooperation mechanisms, reputation effects, and the timing of interventions. While traditional environmental assessment methods focus primarily on technical and economic aspects, game-theoretic frameworks explicitly incorporate conflicts of interest and adaptive stakeholder behavior. The analysis suggests that integrating evolutionary game theory, repeated games, silent-duel timing models, and multi-agent simulation must provide promising decision-support tools for sustainable urban and industrial development.

Keywords: environmental protection, sustainable development, industrial development, game theory.

Introduction

Urbanization and industrial development are among the main drivers of economic growth in modern societies. The construction of high-rise residential buildings, shopping malls, industrial facilities, warehouses, and transportation infrastructure creates employment opportunities, improves public services, and contributes to regional development. However, these benefits are often accompanied by significant environmental impacts affecting nearby ecosystems and local communities [1, 2].

The environmental consequences of construction and industrial expansion may persist long after project completion. In many cases, the interests of developers, investors, local authorities, environmental agencies, and residents are not fully aligned and satisfied. Developers typically seek to minimize costs and complete projects as efficiently as possible, whereas environmental organizations and local communities may prioritize ecological preservation and public health. As a result, environmental management frequently

becomes a problem of strategic interaction among multiple stakeholders [3, 4].

This situation makes game theory a natural analytical framework. Rather than assuming that all participants pursue a common objective, game-theoretic models explicitly account for conflicts of interest, cooperation opportunities, competition, uncertainty, and long-term strategic behavior [5–10]. Therefore, the purpose of this paper is to review major modern environmental challenges associated with construction and industrial development and to discuss how various state-of-the-art game-theoretic approaches can be applied to support environmentally sustainable decision making [11–15].

Methods

The present study presents a conceptual-review approach. First, major environmental problems associated with construction and industrial development are identified. Second, existing environmental management approaches are briefly discussed. Finally, these problems are mapped to game-theoretic models capable of representing interactions among stakeholders.

Environmental problems near development sites

Construction and industrial activities influence both natural ecosystems and human populations. The most frequently reported environmental concerns include [1, 16, 17]:

- 1) deterioration of air quality due to dust and emissions;
- 2) increased noise levels from machinery and transportation;
- 3) contamination of soil and groundwater;
- 4) loss of vegetation and green spaces;
- 5) habitat fragmentation and biodiversity reduction;
- 6) increased waste generation;
- 7) traffic congestion and associated emissions;
- 8) long-term modification of landscapes and local ecosystems.

These effects rarely originate from a single source. Instead, they emerge from the combined actions of multiple stakeholders whose objectives only partially overlap.

Existing environmental management approaches

A variety of methods have been developed to assess and mitigate environmental impacts. The most common approaches include [1, 2, 18, 19]:

- 1) Environmental Impact Assessment (EIA) [1];
- 2) sustainability assessment frameworks;
- 3) life-cycle assessment;
- 4) environmental risk analysis;
- 5) multi-criteria decision-making methods;
- 6) cost-benefit analysis.

These approaches provide valuable information regarding environmental consequences and possible mitigation measures. Nevertheless, they often treat stakeholder behavior as fixed or externally determined. In reality, stakeholders continuously adapt their actions in response to the decisions of others. This limitation motivates the use of game-theoretic models.

Why game theory?

Game theory is particularly suitable because environmental protection often involves strategic choices. For example, a developer may decide whether to invest in pollution-control technologies, while regulators determine inspection intensity and local communities decide whether to support or oppose a project. The resulting outcomes depend not only on individual decisions but also on how those decisions interact. Consequently, environmental management can often be interpreted as a game involving cooperation, competition, negotiation, or timing decisions.

Prisoner's Dilemma and environmental compliance

One of the most widely used game-theoretic models in environmental studies is the Prisoner's Dilemma

[4, 5, 7, 20–26]. The model captures situations in which all participants would benefit from environmental protection, yet each participant has an incentive to avoid the associated costs. For example, neighboring industrial facilities may collectively benefit from reducing emissions. However, each facility may prefer that others bear the costs of environmental improvements while it continues to operate without additional expenditures [12, 13]. Research based on Prisoner’s Dilemma models frequently demonstrates that:

- 1) short-term incentives encourage environmentally harmful behavior;
- 2) collective welfare is maximized through cooperation;
- 3) voluntary cooperation is often difficult to sustain;
- 4) institutional incentives can improve environmental outcomes.

Iterated Dilemma games and long-term sustainability

Many environmental interactions are not isolated events but repeated encounters occurring over years or even decades. Examples include recurring environmental inspections, repeated construction projects, and long-term industrial operations. Iterated dilemma games extend the analysis by allowing participants to learn from previous interactions [20, 23, 24, 27]. Studies based on repeated games indicate that:

- 1) reputation becomes important;
- 2) cooperative behavior becomes more attractive;
- 3) trust may gradually emerge;
- 4) long-term environmental performance improves.

These findings are particularly relevant for urban regions where developers, regulators, and contractors repeatedly interact across multiple projects. The approach of optimizing their interrelationships is a hardly realizable because even formalization of such a problem is difficult.

Public goods games and shared environmental resources

Environmental quality is often a shared resource. Clean air, green spaces, rivers, and groundwater systems benefit all stakeholders regardless of who finances their protection. Public goods games have therefore been extensively applied to environmental problems involving [4, 28]:

- 1) pollution reduction;
- 2) urban greening initiatives;
- 3) watershed protection;
- 4) biodiversity conservation.

A recurring challenge identified in these studies is free-riding, where some stakeholders benefit from environmental improvements without contributing to their costs.

Stag Hunt models and collective environmental action

Some environmental initiatives produce substantial benefits only if many stakeholders participate simultaneously. Examples include regional recycling programs, coordinated ecosystem restoration, and large-scale pollution-control projects. Stag Hunt models [29] demonstrate that environmental cooperation may be beneficial for everyone but remains difficult to achieve because participants fear that others may not cooperate.

Dynamic games and environmental evolution

Environmental systems evolve continuously over time. Pollution accumulates, ecosystems recover gradually, and environmental interventions may produce delayed effects. Dynamic and differential game models [30] are particularly useful for studying:

- 1) air pollution trajectories;
- 2) groundwater contamination;
- 3) ecosystem restoration processes;
- 4) long-term sustainability policies.

Such models help identify strategies that remain effective over extended planning horizons.

Silent duel models and timing of environmental actions

Among less frequently applied approaches, silent duel models [8, 31–36] offer interesting opportunities

for environmental analysis. Many environmental decisions involve uncertainty regarding the timing of interventions. Stakeholders often face questions such as:

1. When should pollution-control equipment be installed?
2. When should ecological restoration begin?
3. When should regulators intervene?
4. When should environmental monitoring be intensified?

Silent duel models explicitly incorporate timing decisions and the risks associated with acting too early or too late. This feature makes them particularly attractive for studying environmental management around large construction and industrial projects.

Discussion

The reviewed approaches demonstrate that environmental protection is not merely a technical problem but also a strategic one. Many environmental difficulties arise because individually rational actions do not necessarily lead to socially desirable outcomes.

Several common patterns emerge from the literature. First, environmental cooperation generally produces better long-term outcomes than purely self-interested behavior. Second, repeated interactions tend to strengthen cooperation through reputation and reciprocity mechanisms. Third, incentive structures often play a more important role than punitive measures alone. Finally, the timing of environmental actions may significantly influence both economic and ecological outcomes.

Among the reviewed models, Prisoner's Dilemma and public goods games remain the most established frameworks. However, emerging opportunities exist for integrating these traditional approaches with silent-duel models and evolutionary game theory [5]. A promising future direction is the development of integrated simulation environments combining:

- 1) repeated dilemma games;
- 2) evolutionary adaptation;
- 3) silent-duel timing decisions;
- 4) multi-agent stakeholder interactions;
- 5) environmental impact models.

Such systems could support planners and policymakers in evaluating alternative development scenarios before project implementation.

Conclusions

Construction and industrial development generate substantial environmental challenges that require balancing economic objectives with ecological sustainability. Traditional environmental assessment methods provide valuable information but often overlook the strategic behavior of stakeholders. Game-theoretic approaches offer a complementary perspective by explicitly modeling cooperation, competition, incentives, and timing decisions. Existing research demonstrates the usefulness of Prisoner's Dilemma models, public goods games, Stag Hunt games, and dynamic environmental games for understanding environmental conflicts. Particularly promising is the application of silent-duel models to environmental management problems involving uncertain intervention timing. By combining timing analysis with traditional cooperation models, future research may provide more realistic decision-support tools for sustainable urban and industrial development.

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