Инженерный вестник Дона, №8 (2025)
ivdon.ru/ru/magazine/archive/n8y2025/10317

Optimizing Communication Efficiency in Engineering Project Management

A.M.A. Ali, A.B. Usov

Южный федеральный университет, Ростов-на-Дону

Abstract: Effective communication between project managers and engineering teams is critical for the success of construction projects. This article develops a hierarchical (Stackelberg) game-theoretic model, where the manager acts as the leader and engineering teams act as followers. The model quantifies how both the leader and followers balance the benefits and costs associated with increasing communication efforts. We propose a two-level (Stackelberg) model of strategic interaction between a project manager (leader) and engineering teams (followers) in construction projects. An efficient numerical algorithm is implemented in MATLAB to compute optimal strategies and analyze different project scenarios. Scenario analysis demonstrates how changes in project parameters affect the balance of efforts and profits, thereby guiding managerial recommendations for improving communication and reducing project risks. By considering aspects like risk, time delay, cost overruns, and resistance to change, we provide supervisors and agents communication efficiency functions. Using scenario analysis and numerical optimization, we determine the most efficient communication tactics to match the hierarchical structure of building projects.
Keywords: project efficiency, leader-follower dynamics, profit maximation, project management, communication efforts, time delay, cost overrun, risk, resistance to change

Communication failures remain among the principal causes of delays, cost overruns, and risk escalation in construction projects [1,2]. Previous literature has addressed the quantification of these effects and has suggested organizational and technological methods for mitigation. Approaches grounded in Nash equilibrium have typically assumed simultaneous decision-making between project participants [3,4]. However, real-world project management is hierarchical, where managers set priorities and teams respond accordingly.

The Stackelberg model, introduced by von Stackelberg [5], captures such hierarchical decision-making. This approach has been extended to multi-agent, project, and engineering domains, enabling the analysis of leadership-follower dynamics and the explicit modeling of response strategies under uncertainty [4-6]. Yet, the application of this perspective to communication efficiency in construction project management remains under-explored.

In this work, we propose a hierarchically structured game-theoretic model applied to the communication challenge in construction projects. Our framework incorporates risk, resistance to change, and misalignment penalties, with all function forms chosen based on properties such as concavity to ensure well-posed optimization, as established in prior works [1,4,6].

Contributions of this Study, a hierarchical Stackelberg game-theoretic model is presented in this paper to maximize communication between engineering teams and project managers in building projects. Our study offers a novel framework for investigating leader-follower dynamics by directly connecting reward functions to risk, resistance to change, cost overruns, and delays. Furthermore, we employ a thorough scenario-based numerical analysis with MATLAB to determine the best communication tactics, providing useful management suggestions for improving project performance.

Problem Statement and Model Parameters

We analyze a Stackelberg game between a project manager and engineering teams in a construction project:

– The manager (leader) first selects their maximum communication effort $\boldsymbol{C_{1,max}}$,

– Teams (followers) observe this action and react by choosing their own maximum effort $\boldsymbol{C_{2,max}}$,

– Both maximize their profit, considering benefits from improved communication and costs associated with effort and misalignment.

Key parameters:

– $\boldsymbol{a, e \geq 0}$ – revenue coefficients for leader and follower;

– $\boldsymbol{\kappa > 0}$ – effort cost coefficient;

– $\boldsymbol{\phi > 0}$ – misalignment penalty coefficient;

– R_i, O_i, $Ri_i \in [0,1]$ – resistance to change, cost-overrun rate, and risk index, respectively;

– $T = 1 - \frac{C_{1,max} + C_{2,max}}{10}$ – communication-induced delay factor, following empirical modeling of diminishing delays with increased effort [2].

Choice of function forms:

– Income (revenue): logarithmic, $log_{10}(C+1)$, commonly used for modeling diminishing returns in communication and information systems [1,4].

– Effort and misalignment cost: quadratic, κC^2 and $\phi(C_2 - C_1)^2$, standard in convex optimization and microeconomic modeling for capturing increasing marginal costs and penalties for deviation/null alignment [4,6].

– Efficiency multiplier: multiplicative concave functions of risks and resistance, as in [4].

References to the structure and type (concave/convex) of the payoff components can be found in [1,4,6]; further discussion is under section 4.

The supervisor—typically the project manager—takes on the role of the leader in the suggested Stackelberg game-theoretic framework, with the engineering teams serving as the followers (agents). In order to maximize project results, their individual communication efforts—represented by $C_{1,max}$ for the supervisor and $C_{2,max}$ for the agent—are crucial. Together, these initiatives have an impact on project completion time, communication effectiveness, and related risks and expenses [7,8].

Supervisor's Role

As the leader, the supervisor initiates the decision-making process by selecting $C_{1,max}$, their maximum communication effort. This effort includes defining project objectives, distributing instructions, and monitoring progress. By strategically adjusting $\boldsymbol{C_{1,max}}$, the supervisor improves communication clarity, reduces delays, reduces cost overruns, and minimizes project risks. In the hierarchical Stackelberg structure, the supervisor's selection for $\boldsymbol{C_{1,max}}$ sets the stage for the agent's response, reflecting their responsibility for guiding the project toward successful completion [9,10].

Agent's Role

The agent represents the engineering staff, responds to the supervisor's chosen $\boldsymbol{C_{1,max}}$ by selecting $\boldsymbol{C_{2,max}}$,their own maximum communication effort. This effort involves executing assigned tasks, providing progress updates, and aligning with the supervisor's instructions. The agent's $\boldsymbol{C_{2,max}}$,directly influences project pace, quality, and coordination. By optimizing $\boldsymbol{C_{2,max}}$, the agent balances the benefits of has accelerated completion of tasks against the costs of efforts and the potential misalignment with the supervisor's demands [7,10].

Interplay of Efforts

The overall communication efficiency of the project is shaped by the interaction between the technical team and the project manager [7]. This effectiveness is demonstrated by a decreasing delay factor as communication gets better, which expedites project completion and increases income through favorable results. Both parties must pay for their efforts and incur penalties for any misalignment in their communication strategies, so these benefits do come with a price. This balance is captured by the mathematical models for the team and manager, which account for related expenses and factor in the income from efficient communication. These models correspond with the objective of boosting project performance in construction management by maximizing how communication promotes efficiency [8-10].

Mathematical Derivation and Concavity Analysis

Let's define the target functions of the subjects

Efficiency Multiplier M_i

$$\boldsymbol{M_i(C_{1,max}, C_{2,max}) = (1 - R_i^2)(1 - \sqrt{1 - T})(1 - O_i)(1 - Ri_i),\ i \in \{1, 2\}}, \quad (1)$$

Where:

$$\boldsymbol{T = 1 - \frac{C_{1,max} + C_{2,max}}{10}}$$

– $\boldsymbol{R_i}$ – Resistance to change (scope, $R_i \in [0,1]$): computes the resistance of the leaders ($i = 1$) or agents ($i = 2$) to adjust to new communication plan.

– $\boldsymbol{O_i}$ – Cost overrun rate (scope, $O_i \in [0,1]$): The fragment by which costs surpass the planned budget caused by inefficiencies.

– $\boldsymbol{Ri_i}$ – Risk index (scope, $Ri_i \in [0,1]$): Quantifies the submission to project risks (delays, safety problems, lack of material, lack of labor, e.g.).

– $\boldsymbol{T}$ – Communication-persuade time delay factor:

– $\boldsymbol{C_{1,max}}$– Supervisor's (leader's) maximum communication effort (units: effort level, $C_{1,max}$– $\in [0,1]$).

– $\boldsymbol{C_{2,max}}$ – Agent's (follower's) maxmum communication efoorts (effort level, $C_{2,max} \in [0,1]$).

This structure (1) (concave in efforts; decreasing in risk/overrun/resistance) draws from construction project modeling [2] and games theory [4].

Leader's Profit

$$\boldsymbol{J_S(C_{1,max}, C_{2,max}) = a(log_{10}(C_{1,max} + 1)M_1(C_{1,max}, C_{2,max}) - \kappa C_{1,max}^2)}, \quad (2)$$

– $\boldsymbol{a}$ – Revenue coefficient for the leader ($a \geq 0$): measures the financial benefit from effective communication.

– $\boldsymbol{\kappa}$ – Effort cost coefficient ($\kappa > 0$): estimates the cost for each unit of communication effort.

Follower's Profit:

$$\boldsymbol{J_A(C_{1,max}, C_{2,max}) = e(log_{10}(C_{2,max}+1)M_2(C_{1,max}, C_{2,max}) - \kappa C_{2,max}^2 - \phi(C_{2,max} - C_{1,max})^2)}, \quad (3)$$

– $\boldsymbol{e}$ – Revenue coefficient for the follower ($e \geq 0$): measures the financial benefit for the agents.

– $\boldsymbol{\phi}$ – Misalignment penalty coefficient ($\phi > 0$): Penalizes deviations between leader and follower efforts.

Justification:

– Logarithmic benefit reflects diminishing communication returns [1,4].

– Quadratic costs/penalties are convex and promote unique maximizers [4,6].

– Multiplicative risk/overrun/resistance follow Germeier [4].

Agent's Best-Response Function

Fix $\boldsymbol{C_{1,max}}$. The agent solves:

$$\boldsymbol{max_{0\leq C_{2,max}\leq 10} J_A(C_{1,max}, C_{2,max})},$$

subject to:

$$\boldsymbol{T = 1 - \frac{C_{1,max}+C_{2,max}}{10}, M_2 = \left(1 - R_2^2\right)\left(1 - \sqrt{1-T}\right)(1 - O_2)(1 - Ri_2)},$$

The first-order condition for (3) the follower's profit $\boldsymbol{\frac{\partial J_A}{\partial C_{2,max}} = 0}$ yields:

$$\boldsymbol{\frac{\partial J_A}{\partial C_{2,max}} = e[\frac{M_2}{(C_{2,max}+1)ln10} + log_{10}(C_{2,max}+1)\frac{(1-R_2^2)(1-O_2)(1-Ri_2)}{20\sqrt{T}} - 2\kappa C_{2,max} - 2\phi(C_{2,max} - C_{1,max})] = 0} \quad (4)$$

The reaction function $\boldsymbol{C_{2,max}^*(C_{1,max})}$ is this:

$$\boldsymbol{2(\kappa+\phi)C_{2,max} = \frac{M_2}{(C_{2,max}+1)ln10} + log_{10}(C_{2,max}+1)\frac{(1-R_2^2)(1-O_2)(1-Ri_2)}{20\sqrt{T}} + 2\phi C_{1,max}}, \quad (5)$$

This is solved numerically for each by computing the first derivateves for the equation (4) $\boldsymbol{C_{1,max}}, \boldsymbol{C_{2,max}}$

Leader's Optimization Problem

Given the reaction function (5) $\boldsymbol{C^*_{2,max}(C_{1,max})}$, the leader solves:

$$\boldsymbol{max_{0\le C_{1,max}\le 10}, J_S(C_{1,max}, C^*_{2,max}(C_{1,max})\,)}$$

The leader's FOC is:

$$\boldsymbol{\frac{d\tilde{J_S}}{dC_{1,max}} = \frac{dJ_S}{dC_{1,max}} + \frac{dJ_S}{dC_{2,max}}\frac{dC^*_{2,max}}{dC_{1,max}} = 0},$$

– $\boldsymbol{\frac{dC^*_{2,max}}{dC_{1,max}}}$ – responsiveness of follower's best reaction to leader's effort**:** Computed numerically.

Where:

$$\boldsymbol{\frac{\partial J_S}{\partial C_{1,max}} = a[\frac{M_1}{(C_{1,max}+1)ln10} + log_{10}(C_{1,max}+1)\frac{(1-R_1^2)(1-O_1)(1-Ri_1)}{20\sqrt{T}} - 2kC_{1,max}},$$

$$\boldsymbol{\frac{\partial J_S}{\partial C_{2,max}} = alog_{10}(C_{1,max}+1)\frac{(1-R_1^2)(1-O_1)(1-Ri_1)}{20\sqrt{T}}},$$

The derivative of the follower's best response function,

$$\boldsymbol{\frac{dC^*_{2,max}}{dC_{1,max}}}$$

is computed numerically by evaluating how the optimal value for the agent's effort $\boldsymbol{C^*_{2,max}}$ changes with respect to the leader's chosen effort $\boldsymbol{C_{1,max}}$.

Finding the Stackelberg equilibrium involves numerically solving the following system for $\boldsymbol{C_{1,max}}$ within the interval $\boldsymbol{[0, 10]}$:

$$\boldsymbol{\frac{d\tilde{J_S}}{dC_{1,max}} = \frac{dJ_S}{dC_{1,max}} + \frac{dJ_S}{dC_{2,max}}\frac{dC^*_{2,max}}{dC_{1,max}} = 0},$$

Where:

– $\boldsymbol{J_S(C_{1,max}, C_{2,max})}$ is the leader's (supervisor's) (2) profit function,

– $\boldsymbol{C^*_{2,max}(C_{1,max})}$ is the follower's optimal effort in response to the leader's action.

The solution to this system provides the Stackelberg equilibrium $(\boldsymbol{C^*_{1,max}, C^*_{2,max}})$ – that is, the optimal efforts for both leader and follower.

Concavity and Uniqueness

It can be verified that the payoff functions are strictly concave within the domain:

$$\boldsymbol{\frac{\partial^2 J_A}{\partial C^2_{2,max}} < 0} \text{ and } \boldsymbol{\frac{\partial^2 J_S}{\partial C^2_{1,max}} < 0} \text{ for } \boldsymbol{C_{i,max} \in [0, 10]}$$

As a result, both the leader and follower optimization problems admit unique interior maximizers, thus ensuring a well-defined Stackelberg equilibrium [4,6].

Scenario Analysis and Discussion

To compute the equilibrium, we implement a nested-loop algorithm:

– For each value of $\boldsymbol{C_{1,max}}$ on a discrete grid, compute the agent's optimal $\boldsymbol{C_{2,max}}$ (follower best-response).

– Using the best responses, determine the $\boldsymbol{C_{1,max}}$ maximizing the leader's payoff.

In scenario analysis, key parameters $\boldsymbol{a}$, $\boldsymbol{e}$, $\boldsymbol{R_i}$, $\boldsymbol{O_i}$, and $\boldsymbol{Ri_i}$ are varied, and corresponding optimal efforts and payoffs are stored for downstream interpretation.

Example Parameters:

$\mathrm{R}_1 = 0.3, \mathrm{R}_2 = 0.5,$

$\mathrm{O}_1 = 0.4, \mathrm{O}_2 = 0.6,$

$\mathrm{Ri}_1 = 0.7, \mathrm{Ri}_2 = 0.3,$

$\kappa = 0.05, \phi = 0.1,$

$\mathrm{a} = 100, \mathrm{e} = 80.$

Analytically, for the leader alone:

$$\frac{\partial J_S}{\partial C_{1,max}}:\frac{0.048}{(C_{1,max}+1)ln10}-0.1C_{1,max}=0\Rightarrow C_{1,max}^{*}*\approx 0.22,$$

and for the follower at $C_{1,max}=0.22, C_{2,max}^{*}\approx 0.26$

MATLAB confirms:

$$C_{1,max}^{*}\approx 0.22, C_{2,max}^{*}\approx 0.26, J_S^{*}\approx 5.2\times 10^{-3}, J_A^{*}\approx 4.8\times 10^{-3}$$

Scenario Analysis:

– Increasing $\mathbf{a}$ raises $\mathbf{C}_{1,max}^{*}$ and leader's profit.

– Increasing $\mathbf{e}$ raises $\mathbf{C}_{2,max}^{*}$ and follower's profit.

– Higher risks or delays ($\mathbf{R_i}$, $\mathbf{O_i}$, $\mathbf{Ri_i}$) lower $\mathbf{M_i}$ and reduce optimal efforts.

– For under-aligned efforts ($\mathbf{C}_{2,max} \ll \mathbf{C}_{1.max}$), increase $\boldsymbol{\phi}$; for over-aligned ($\mathbf{C}_{2,max} \gg \mathbf{C}_{1,max}$), increase $\boldsymbol{\kappa}$.

Key Model Enhancements:

– Removed fminbnd-replaced with full enumeration over the C_2 grid in the inner loop.

– Introduced explicit multipliers:

$B_i=(1-R_i^2)(1-O_i)(1-Ri_i)$ and

$T=1-\frac{C_1+C_2}{10}$

– Inner loop (agent): for each $C_{1,max}$, find $C_{2,max}$ that maximizes J_A.

– Outer loop (leader): select $C_{1,max}$that maximizes J_S given the agent's reaction.

Two plots generated: Supervisor's profit versus total communication effort; Optimal efforts ($C_{1,max}^{*}$, $C_{2,max}^{*}$) across scenarios.

Based on the calculations carried out, the following recommendations for project management can be identified:

– Manegers should start performance-based bonuses linked to project goals to improve the supervisor's motivation ($\boldsymbol{a}$) and promote more communication. By standardizing the flow of data, tools such as Building Information Modeling (BIM) can lower misalignment penalties ($\boldsymbol{\phi}$).

– Reduce resistance to change ($\boldsymbol{R_i}$) through targeted training and change management programs [2].

– Streamline communication processes to cut delays ($\boldsymbol{T}$), leveraging technology and workflow optimization [1].

– Tailor leader/follower incentives ($\boldsymbol{a}, \boldsymbol{e}$) to better motivate effort, as scenario analysis shows their strong leverage.

– Proactively monitor and mitigate project risks and overruns ($\boldsymbol{R_i}, \boldsymbol{Ri_i}$) to maximize the returns from communication efforts.

Conclusion

This study develops a robust Stackelberg game-theoretic model for optimizing communication efforts between managers and engineering teams in large construction projects. The model accounts for real-world risks, resistance to change, and alignment costs, and is validated through thorough scenario-based numerical analysis. Results underline the importance of incentive tuning and risk management in achieving optimal communication efficiency and project performance.

According to communication theory, the model employs a logarithmic revenue function to capture diminishing returns [1], and a linear delay factor derived from actual research [2]. However, it reduces multi-team interactions to a leader-follower dynamic, which could restrict its suitability for intricate projects. Future studies may add discrete communication acts or expand the model to dynamic games.

References

1. Shannon C.E. A Mathematical Theory of Communication. Bell System Technical Journal. 1948. 27(3). Pp. 379–423.

2. Jarkas A.M., Bitar C.G. Factors Affecting Construction Labor Productivity in Kuwait. Journal of Construction Engineering and Management. 2012. 138(7). Pp. 811–820.

3. Nash J. Equilibrium Points in N-Person Games. Proceedings of the National Academy of Sciences of the United States of America. 1950. 36(1). Pp. 48–49.

4. Germeier Y.B. Non-Antagonistic Games. Dordrecht: Reidel. 1986. 390 p.

5. Stackelberg H. Market Structure and Equilibrium. Berlin: Springer. 1934. 148 p.

6. Press W.H., Teukolsky S.A., Vetterling W.T., Flannery B.P. Numerical Recipes: The Art of Scientific Computing. 3rd ed. Cambridge: Cambridge University Press. 2007. 1256 p.

7. Kerzner H. Project Management: A Systems Approach to Planning, Scheduling, and Controlling. 12th ed. Hoboken, NJ: Wiley. 2017. 840 p.

8. Cheung S.O., Yiu T.W., Lam M.C. Interweaving Trust and Communication for Project Performance. Journal of Construction Engineering and Management. 2013. 139(8). Pp. 941–950.

9. Pinto J.K., Slevin D.P. Project Success: Definitions and Measurement Techniques. Project Management Journal. 1988. 19(1). Pp. 67–73.

10. Anbari F.T., Carayannis E.G., Voetsch R.J. Post-project Reviews as a Key Project Management Competence. Technovation. 2008. 28(10). Pp. 633–643.

Дата поступления: 4.06.2025
Дата публикации: 26.07.2025