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01-030 – Exploratory quantitative analysis to model hidden complexities in project management – Análisis cuantitativo exploratorio para modelar complejidades ocultas en gestión de proyectos

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English Spanish

In high-uncertainty environments, this proposal explores a preliminary approach to addressing projects as evolving complex systems. It introduces the development of a Multidimensional Performance Matrix and a Systemic Complexity Index (SCI), aimed at capturing nonlinear interactions and emerging dynamics among critical success factors. Unlike other management models, this methodology seeks to quantitatively identify early signals of cumulative complexity and provide strategic support for decision-making. Although initial applications have been carried out, the model is currently in the phase of comprehensive validation and assessment of its applicability in different contexts.

Keywords: *Project management; Critical factors; Nonlinear interactions; Project deviations; Risks; Strategic decision-making*

En entornos de alta incertidumbre, esta propuesta explora un enfoque preliminar para abordar proyectos como sistemas complejos en evolución. Se plantea el desarrollo de una Matriz de Desempeño Multidimensional y un Índice de Complejidad Sistémica (ICS), orientados a capturar interacciones no lineales y dinámicas emergentes entre factores críticos de éxito. A diferencia de otros enfoques en gestión, esta metodología busca identificar cuantitativamente señales tempranas de complejidad acumulativa y ofrecer soporte estratégico a la toma de decisiones. Aunque se han realizado aplicaciones iniciales, el modelo se encuentra en fase de validación integral y evaluación de su aplicabilidad en distintos contextos.

Palabras claves: *Gestión proyectos; Factores críticos; Interacciones no lineales; Desviación proyectos; Riesgos; Decisiones estratégicas*

1. Introduction

Today's project management requires controlling multiple critical success factors (CSFs), such as schedule, cost, quality, sustainability, risks, and stakeholder satisfaction (Ika, 2022). These CSFs interact in a complex, non-linear way, limiting the effectiveness of traditional approaches (PMBOK, PRINCE2, Agile frameworks), which tend to address them in isolation (Project Management Institute, 2021).

After a systematic literature review of 89 publications, the results revealed that methodological heterogeneity is a major driver of divergence in the identification of Critical Success Factors (CSFs) across project management research. Studies employing quantitative (40.9% of all studies) and mathematical methods (11.3%) report a greater number of CSFs than those using qualitative approaches (26.1%), regardless of sectoral differences. Based on these findings, there is a need for an adaptive and generalizable quantitative method that standardizes CSF identification while respecting project-specific contexts.

Advanced tools such as System Dynamics (Chang et al., 2022), agent-based models, or probabilistic analyses have attempted to tackle this complexity but often require static models, historical data, or lack real-time adaptability (Khodakarami 2014; Saaty, 2004). In this context, a complementary, systemic (Kapsali, 2011), and dynamic methodology is proposed that overcome these limitations.

This approach is based on a Multidimensional Performance Matrix (MPM), which combines Key Performance Indicators (KPIs), risk levels (NPR), and importance weights, feeding two key tools: Interaction Connection (IC), which quantifies cross-relationships between CSFs, and the Systemic Complexity Index (SCI), the main innovative contribution of this proposal, which measures accumulated non-linear complexity in real time. Unlike methods such as the Analytic Hierarchy Process (AHP) or the Design Structure Matrix (DSM), this proposal detects emerging dynamics and distortions among factors through matrix operations and multidimensional geometry. In essence, the SCI captures how deviations in one factor amplify or compensate for deviations in others, revealing systemic risks that might otherwise go unnoticed. This enables managers to better anticipate cascading effects across factors and make proactive decisions before issues escalate.

The SCI updates as the project progresses, alerting about potential systemic complexity. Validations in European Research projects showed a high correlation (dCor > 0.85) between SCI and actual deviations, confirming its analytical capability (Zhou, 2012). Overall, this methodology provides a hybrid, operational framework that enhances anticipation, resilience, and decision-making in environments of high uncertainty, closing gaps in both literature and professional practice (Reiff & Schlegel, 2022).

2. Objectives

Building on the previous evidence, the main objective of this study is to provide a quantitative method to measure, anticipate, and manage project deviations by considering the performance and risk of multiple factors and subfactors, capturing their cumulative non-linear interactions to detect hidden complexities at an early stage and make proactive decisions that improve integrated project management. The methodology presented aims to illuminate what was previously invisible in project dynamics (Calderón-Téllez, 2025).

3. Methodology

To apply the methodology and its mathematical basis, three types of data are required: project deviations with monthly detection to calculate KPIs per stage (scale 0–1); risks per stage, normalized through the Risk Priority Number (NPR = Severity × Occurrence × Detection); and weights (0–1) for five critical success factors (CSFs): cost, schedule, quality-execution, stakeholder satisfaction, and sustainability (Cooke-Davies, 2002). These weights were obtained after analyzing 89 publications and 9 studies with statistically comparable methodologies, obtaining variety on the values that reflects an evolution in how project success is conceptualized (Müller & Jugdev, 2012), assigning the following values to the research sector applied in this proposal: cost (0.19), schedule (0.12), execution (0.23), stakeholders (0.23), and sustainability (0.32). These weights are the result of calculating the average of the weight values (normalized in scale 0-1) obtained in the nine selected studies, after these factors were categorized within the same critical factor category and sector (Ayertey Nubuor, 2017; El Touny, 2021; Ipsilandis, 2008; Kiani Mavi, 2018; Niazi, 2016; Verburg, 2013; White, 2002; Young, 2013; Zou, 2014).

The KPIs and sub-KPIs linked to the CSFs were defined through a three-round Delphi method with 11 experts in European projects. Initially, 15 KPIs were proposed: deviation in deliverables, impact on public policies, fulfillment of technical objectives, market transfer, deviation in communication and dissemination, post-project international collaboration, gender and inclusion criteria, alignment with EC policies, partner participation, media impact, budget deviation, stakeholder participation, technological/methodological innovation, time deviation, and number of patents or licenses. In the first round, the KPIs with an average ≥ 3.5 (on a Likert scale of 1-5) were kept, eliminating three. In the second round, seven KPIs were prioritized, resulting in a preselection of eight indicators. In the third round, the five most relevant were agreed upon, defining their measurable sub-KPIs (see Table 1).

Table 1: Input data for the proposed methodology.

KPIs	Sub-KPIs	CSF** associated with the KPI
KP1: % Deviation in deliverables	subKPI1=[Deadline;Quality]	CSF2, CSF3
KPI2: % Fulfillment of technical objectives	subKPI2*= [WP2; WP3; WP4;WP5;WP6]	CSF3, CSF5
KPI3: % Time deviation	subKPI3=[Task;Work Package;Milestone]	CSF2
KPI4: % Budget deviation	subKPI4= [Costs, Effort/month]	CSF1
KPI5: % Deviation in Communication&Dissemination metrics	subKPI5= [Website visitors; Newsletter subscribers; Number of Sister Projects; Number of Publications]	CSF4, CSF5

*WP: Work Package; **Five main CSF categories from literature: CSF1: Cost; CSF2: Schedule; CSF3: Execution; CSF4: Stakeholders; CSF5: Sustainability

Having defined the KPIs and their sub-KPIs, the MPM (performance adjusted by risks), the IC (effects among factors), and the SCI (accumulated interactions over time) are calculated. This last calculated index detects those accumulated interactions before they become visible through traditional KPIs and compares behavior across stages and measure how much one factor “pulls” another.

3.1 Multidimensional Performance Matrix (MPM)

The project's multidimensional performance matrix (MPM) shows, in stage k, the performance metric relative to what was planned in that stage, measured in the KPIs associated with the five CSFs and their relationships.

$$MPM_{ij}^{k} = \begin{bmatrix} \mathrm{KPI}_1 & \Delta_{12} & \Delta_{13} & \dots & \Delta_{1n} \\ \Delta_{21} & \mathrm{KPI}_2 & \Delta_{23} & \dots & \Delta_{2n} \\ \Delta_{31} & \Delta_{32} & \mathrm{KPI}_3 & \dots & \Delta_{3n} \\ & & & \ddots & \\ \Delta_{n1} & \Delta_{n2} & \Delta_{n3} & \dots & \mathrm{KPI}_n \end{bmatrix} \tag{1}$$

In Matrix (1), the diagonal elements (MPM_{ii})—which reflect the % of execution with respect to the planned value in the analyzed stage $\mathrm{KPI}_i \in [0,1]$—would correspond to the following expression:

$$MPM_{ii} = \delta_{ij}\,(\mathrm{KPI}_i \cdot (1 - w_i \cdot \mathrm{NPR}_i))$$

The term $(1 - w_i \cdot \mathrm{NPR}_i)$ is a penalty factor that reduces execution proportionally to weight w_i and risk (NPR_i). This makes it possible to focus on a factor even when its performance is good if its associated risk is high.

Meanwhile, the off-diagonal elements ($MPM_{ij}, i \neq j$), which show the relationship of execution among the factors, also adjusted by importance weights and risks, would be as follows:

$$MPM_{ij} = \left(1 - \delta_{ij}\right)\ \underbrace{0.5\, w_i \cdot w_j}_{\substack{1 \\ \text{Factors weights}}} \cdot \underbrace{\sqrt{\mathrm{NPR}_i \cdot \mathrm{NPR}_j}}_{\substack{2 \\ \text{Risk Correlation}}} \cdot \underbrace{\left(\mathrm{KPI}_i - \mathrm{KPI}_j\right)}_{\substack{3 \\ \text{Execution Difference}}} \cdot \underbrace{\left(1 + \frac{\mathrm{NPR}_i + \mathrm{NPR}_j}{2}\right)}_{\substack{4 \\ \text{Average risk amplification}}}$$

The product $\left(w_i \cdot w_j\right)$ places greater emphasis on interactions between critical factors, increasing their impact on overall performance. The square root of the product of risks $\sqrt{NPR_i \cdot NPR_j}$ smooths extreme values and captures the non-linear correlation between risks, preventing a single high value from dominating the result. Additionally, a term reflecting the performance difference between the factors involved is incorporated. Finally, the average risk $\frac{NPR_i + NPR_j}{2}$, increased by one ensures a minimum effect even under low-risk conditions, while under high-risk scenarios it amplifies the interaction, thus representing systemic risk when both factors exhibit significant vulnerabilities. Matrix (1) in index form would look like shown in equation (2), which structurally adopts the logic of the Design Structure Matrix (Browning, 2001), used to model and analyze dependencies among a system's elements:

$$\begin{aligned} MPM_{ij}^{k} &= \delta_{ij}\left(KPI_i \cdot (1 - w_i \cdot NPR_i)\right) \\ &+ \left(1 - \delta_{ij}\right)\left(\frac{w_i \cdot w_j}{2} \cdot \sqrt{NPR_i \cdot NPR_j} \cdot \left(\mathrm{KPI}_i - \mathrm{KPI}_j\right) \cdot \left(1 + \frac{NPR_i + NPR_j}{2}\right)\right) = MPM_{ii}^{k} + MPM_{ij}^{k} \end{aligned} \tag{2}$$

To calculate IC and SCI, performance is compared between stages. The final matrix (3) shows the percentage of variation, highlighting the need to mitigate critical risks and manage interdependencies.

$$\Delta MPM_{ij} = MPM_{ij}^{k} - MPM_{ij}^{k-1} \tag{3}$$

From the difference matrix, the manager can select pairs of factors and their KPIs/sub-KPIs to analyze cross-interactions and detect complex relationships that would go unnoticed using individual KPIs penalized by risk. This cross-multifactor analysis assesses systemic complexity between stages, considering KPI and sub-KPI vectors according to combinations chosen by the manager from the information in (1).

The following notation describes these cross-relationships, linking CSF pairs (i,j) with sub-KPIs (k,l) and their interaction with a third sub-KPI (m).

3.2 Interaction Connection (IC)

The Interaction Connection (4) values measure how the performance of one factor directly impacts another, capturing its "local" short-term sensitivity. This facilitates identifying possible project imbalances. The equation (4) shares a conceptual framework analogous to affine connections in differential geometry (Sandhu et al., 2016).

It helps to understand how changes in a factor's sub-KPIs affect relationships between pairs. However, it does not consider cumulative interdependencies, making it a preliminary step to the Systemic Complexity Index (SCI).

$$IC_{jk}^{i} = \left[\frac{1}{2}\sum_{m=1}^{n} MPM^{im}\left(\frac{MPM_{mk}(x_j+\Delta x_j)-MPM_{mk}(x_j)}{\Delta x_j} + \frac{MPM_{mj}(x_k+\Delta x_k)-MPM_{mj}(x_k)}{\Delta x_k} - \frac{MPM_{jk}(x_m+\Delta x_m)-MPM_{jk}(x_m)}{\Delta x_m}\right)\right]\left(1+\frac{\gamma}{\sqrt{1+\gamma^2}}\right) = [\frac{1}{2}\cdot \sum_{m=1}^{n} MPM^{im}\left(\Delta_j \mathrm{MPM}_{mk} + \Delta_k \mathrm{MPM}_{mj} - \Delta_m \mathrm{MPM}_{jk}\right)]\left(1+\frac{\gamma}{\sqrt{1+\gamma^2}}\right) \tag{4}$$

Expressed in simplified form:

$$IC_{jk}^{i} \approx [\frac{1}{2}\cdot (\text{Overall adjustment})\cdot (\frac{\text{Relationship change } i-j}{Stage\ change})] \cdot (\text{Persistence Factor}) \tag{5}$$

The factor $\frac{1}{2}$ acts as a scale adjustment to prevent calculated changes from being overly sensitive to project data. The matrix, the inverse of the MPM, functions as a mathematical filter that corrects the measurement by considering the influence of other project relationships on the interaction between pairs of factors, thus avoiding isolated interpretations. The term $\Delta_j MPM_{km}$ represents the matrix change from one stage to another, capturing how performance between factors evolves. The parameter γ ($0 < \gamma < 1$) is a persistence factor that regulates the influence of previous distortions via a sigmoidal function limiting their effect: when γ is high, the term $\frac{\gamma}{\sqrt{1+\gamma^2}}$ grows more slowly than , preventing disproportionate increases in the multiplier $\left(1+\frac{\gamma}{\sqrt{1+\gamma^2}}\right)$. The specific persistence of each sub-KPI is calculated as the number of deviations of that sub-KPI in previous stages divided by the total project deviations. Finally, Δx represents the time difference between stages (in months), scaling the impact of changes so that interactions adequately reflect the duration between phases.

3.3 Systemic Complexity Index (SCI)

The Systemic Complexity Index (SCI) is the main innovative contribution of this proposal, as it captures non-linear, cumulative interactions among factors that affect the project globally. It acts like a complexity thermometer, revealing hidden impacts.

The sign of the SCI indicates whether there is amplification (SCI > 0) or compensation (SCI < 0) of complexity. Its magnitude reflects intensity: values near zero imply linear interactions; high values, greater non-linear interdependence.

A high SCI does not imply poor performance but rather significant changes in the relationship between factors, which may require attention. Comparing SCI between stages enables early detection of complex interdependencies, facilitating proactive decisions with a systemic view of the project, beyond isolated tasks.

$$SCI_{ijkl} = \frac{IC^{i}_{jk}(x_l + \Delta x_l) - IC^{i}_{jk}(x_l)}{\Delta x_l} - \frac{IC^{i}_{jl}(x_k + \Delta x_k) - IC^{i}_{jl}(x_k)}{\Delta x_k} + \sum_{m=1}^{n} \left(\mathrm{IC}^{i}_{km} \cdot \mathrm{IC}^{m}_{jl} - \mathrm{IC}^{i}_{lm} \cdot \mathrm{IC}^{m}_{jk}\right) = \Delta_k \mathrm{IC}^{i}_{jl} - \Delta_l \mathrm{IC}^{i}_{jk} + \mathrm{IC}^{m}_{jl} \cdot \mathrm{IC}^{i}_{mk} - \mathrm{IC}^{m}_{jk} \cdot \mathrm{IC}^{i}_{ml} \quad (6)$$

Expressed in simplified form:

$$SCI_{ijkl} = \text{(Influence of k on i-j) -(Comparison of influence of k on i of l)} + \text{Synergies - Conflicts} \quad (7)$$

The equation (6) reflects the structure of the Riemann curvature tensor (reinterpreted and adapted for project management), where interaction products capture cumulative nonlinear effects (Sandhu et al., 2016). The term $\Delta_k IC^{i}_{jl}$ represents the change in the influence of subfactor k of factor i on the relationship between factors i and j, measuring how that sub-KPI alters this interaction. Meanwhile, $-\Delta_l IC^{i}_{jk}$ compares the effect of this same subfactor k of i on a second relationship—this time between i and subfactor l of j, —thus capturing its impact on different links. The term $IC^{m}_{jl} \cdot IC^{i}_{mk}$ indicates a positive interaction mediated by a third subfactor m, i.e., an indirect connection between k of i and l of j through m. In contrast, $-IC^{m}_{jk} \cdot IC^{i}_{ml}$ represents a negative interaction, suggesting that subfactor k of i could generate an adverse effect on another subfactor m belonging to j.

With this terminology grouped in formulation SCI_{ijkl} (6), the interaction between sub-KPIs k (of i) and l (of j), considering other associated CSFs, is resolved.

4. Results

The procedure described in “Methodology” was applied to two European research projects under the Horizon Europe framework. The results and their interpretation are presented below. To preserve confidentiality, the projects are mentioned anonymously, and the specific deviations used to calculate the execution KPIs are not detailed.

4.1 Project 1 Results

After collecting deviations per stage (duration, budget, communication, etc.), they are assigned to a KPI and its sub-KPI vector according to their description (see Table 1). Each KPI is calculated as the geometric mean of the execution values of its sub-KPIs and is linked to the corresponding CSFs.

If a KPI is associated with n CSFs, the share of the KPI allocated to each CSF is calculated as:

$$\alpha_i = \frac{\text{NPR}_i}{\sum_{k=1}^{n} \text{NPR}_k} \qquad (8)$$

Where α_i: Weighting of KPI for CSF i, NPR_i: Risk level of CSF i and $\sum \text{NPR}_k$: Sum of NPRs of all CSFs linked to the KPI.

The sum of the α_i weightings is 1, preventing overestimations. The NPR (S × O × D) reflects multiplicative relationships among risks, aligning with the geometric mean used in KPIs. Assigning the KPI impact according to NPR highlights criticality: CSFs with higher risk have greater influence and respond more strongly to changes in perception.

Risks are assessed per stage (“low,” “moderate,” “high”), taking into account progress, deviations, and the S, O, and D factors. Each level is converted into values between 1 and 10, and the NPR is normalized with respect to the stage’s maximum.

Using these data, a final KPIs table is built for each CSF and stage, forming the basis for the Multidimensional Performance Matrix (MPM). Its application to Project 1 and the conclusions are detailed below.

Table 2: Project 1 input data.

CSF	w_i	NPR (Stage 1)	KPI (Stage 1)	NPR (Stage 2)	KPI (Stage 2)
Cost (1)	0.19	0.064	1.0	1.0	0.871
Schedule (2)	0.12	0.844	0.423	0.844	0.659
Execution (3)	0.23	0.832	0.417	0.832	0.459
Stakeholders (4)	0.23	0.719	1.0	0.813	0.340
Sustainability (5)	0.32	1.0	1.0	1.0	0.410

With the input data, the MPM matrix is computed for stage 1 and stage 2; their difference reveals how execution performance has changed between these stages:

$$\Delta MPM_{2-1} = \begin{bmatrix} -0.2823 & 0.0021 & 0.0114 & 0.0199 & 0.028 \\ -0.0021 & 0.2120 & 0.0042 & 0.0178 & 0.0280 \\ -0.0114 & -0.0042 & 0.0339 & 0.0259 & 0.0407 \\ -0.0199 & -0.0178 & -0.0259 & -0.5582 & -0.0044 \\ -0.028 & -0.0280 & -0.0407 & 0.0044 & -0.4012 \end{bmatrix}$$

The CSFs are interpreted as follows: CSF1 (Cost) decreases by 28.5% (from 0.9878 to 0.7055) and its NPR increases from 8 to 125, indicating higher risk. CSF2 (Schedule) improves by 21.2%, CSF3 (Execution) rises by 3.4%, while CSF4 (Stakeholders) drops by 55.8% and CSF5 (Sustainability) decreases by 40.1%.

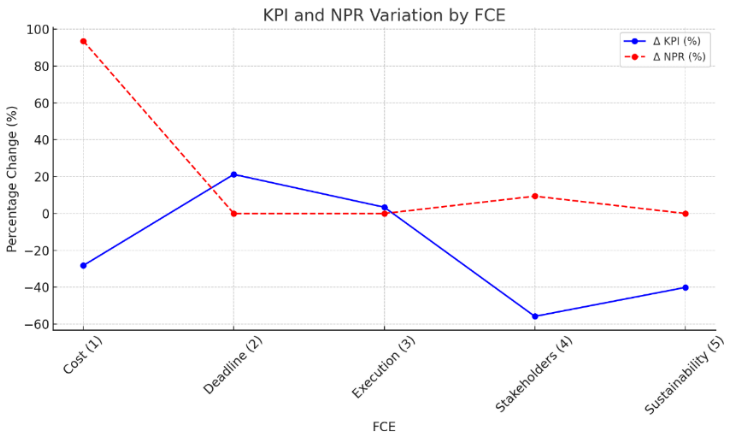
A dashboard (Table 3) or chart (Figure 1) helps the manager spot critical variations and their relation to risk. This reading guides the selection of factor pairs for calculating the Systemic Complexity Index (SCI).

Table 3: MPM Dashboard results in Project 1 (stage 2-1).

CSF	Δ KPI (%)	Δ NPR (%)	Trend
Cost (1)	-28.23	93.6	↗ ⚠
Schedule (2)	21.22	0.0	→
Execution (3)	3.4	0.0	→

Stakeholders (4)	-55.8	9.39	↗ ⚠
Sustainability (5)	-40.1	0.0	→

Figure 1: Chart of KPI and NPR variation by CSF in Project 1.



Following the same procedure, MPM matrices were calculated for stages 3-2 and 4-3. Based on the results, pairs of factors (and one sub-KPI per factor) are selected to analyze their relationships. Below are the results of the analysis between CSF1 and CSF2 in stage 2-1, using the difference matrix whose rows and columns correspond to these selected factors:

$$MPM_{2-1} = \begin{bmatrix} -0.2823 & 0.0021 \\ -0.0021 & 0.2120 \end{bmatrix}$$

The sub-KPIs chosen for this case were: CSF1 (Cost): "Effort/month" (Stage 1 = 1, Stage 2 = 0.73); CSF2 (Schedule): "Task" (Stage 1 = 1, Stage 2 = 0.81).

The time difference for this case is $\Delta x = 11$ months and the Persistence Factor: γ = 0.23.

Calculation of the Extended Metric $MPM_{extended}$ adjusted by sub-KPI differences:

$$MPM_{\text{extended}} = \frac{MDM_{1-2}}{\Delta_{\text{sub-KPIs}}}, \quad \Delta_{\text{sub-KPIs}} = (1 \cdot 1) - (0.73 \cdot 0.81) = 0.4087$$

$$MPM_{ij} = \frac{MPM_{1-2}}{0.4087} \approx \begin{bmatrix} -0.6907 & 0.0051 \\ -0.0051 & 0.5186 \end{bmatrix}$$

Inverse of the Metric MPM^{ij} and the time difference between stages:

$$\det(\mathrm{MPM}) = (-0.6907)(0.5186) - (0.0051)(-0.0051) \approx -0.3581$$

$$MPM^{ij} = \frac{1}{\det(MPM)} \begin{bmatrix} MPM_{22} & -MPM_{12} \\ -MPM_{21} & MPM_{11} \end{bmatrix} \approx \begin{bmatrix} -1.4484 & 0.0142 \\ -0.0142 & 1.9289 \end{bmatrix}$$

$$\frac{MPM_{1-2}}{\Delta x} = \frac{1}{11} \begin{bmatrix} -0.2823 & 0.0021 \\ -0.0021 & 0.2120 \end{bmatrix} \approx \begin{bmatrix} -0.0257 & 0.00019 \\ -0.00019 & 0.01927 \end{bmatrix}$$

After these preliminary steps, the Interaction Connection (IC) values are computed according to (4): $IC_{11}^{1} \approx 0.0146$, $IC_{12}^{1} = IC_{21}^{1} \approx -0.000363$, $IC_{22}^{1} \approx -0.0119$, $IC_{11}^{2} \approx 0.000121$, $IC_{12}^{2} =$

$IC_{21}^{2} \approx 0.0054$ and $IC_{22}^{2} \approx 0.01839$ and then the non-zero terms of SCI (6): $SCI_{212}^{1} \approx 0.00048$, $SCI_{112}^{2} \approx -0.00012$.

Table 4 presents the SCI results for the pairs of factors analyzed throughout the project stages where deviations were identified. Because the SCI reflects complex interactions, its magnitude is not directly interpretable, so comparing it between stages highlights where decisions could trigger unexpected effects. To scale the SCI value according to the intensity and directionality of the project's actual deviations, and to enhance its interpretability, the SCI–actual deviations comparison is presented below:

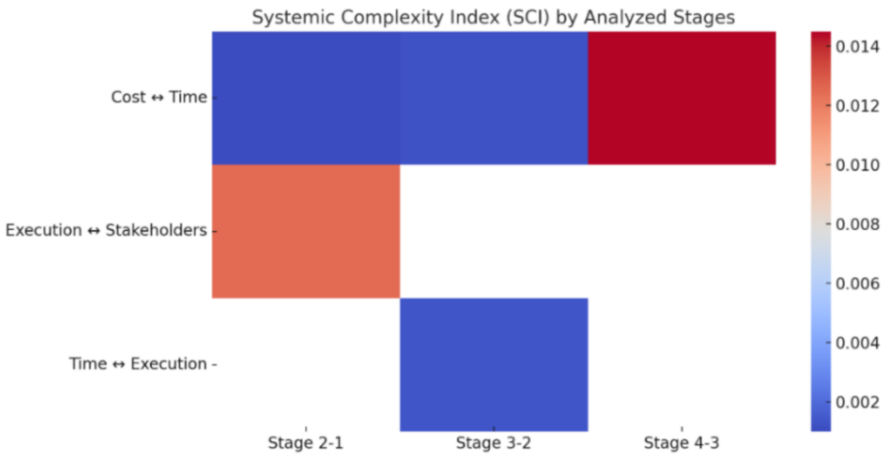
For the Cost-Schedule pair, the positive SCI value progressed from 0.00048 up to 0.0149 (stages 2-4), which aligns with an actual 3-month delay in WP3 and Task 3.2, coupled with a 27% personnel cost over cost in WP2. In addition, during the last stages, the SCI correlated with a cost risk increase (NPR=729) and a 32% drop in cost KPI.

The Schedule-Execution analysis showed the SCI increased by 67% compared to the previous stage, reflecting actual accumulated delays in WP1, WP5 and WP6 (up to 4 months). The rising SCI captures the growing interdependency between prolonged timelines and technical execution challenges, as extended deliverables deadlines intensified pressure on task completion.

Table 4: Comparative SCI results for Project 1.

CSF Pair	Stage 2-1	Stage 3-2	Stage 4-3	Trend
Cost ↔ Schedule	0.00048	0.00085	0.0149	▲ +300% Risk
Execution ↔ Stakeholders	0.0133	-	-	● Stagnated
Schedule ↔ Execution	-	0.00085	-	● Slight increase

Figure 2: Heat map of SCI results between factor pairs and stages in Project 1.



The heat map (Figure 2) facilitates visualization of the SCI. Horizontal analysis reveals the evolution of complexity and risks over time; vertical analysis shows which factor pairs are more or less complex per stage. Also, integrating SCI, KPIs, and NPRs helps detect patterns: a low NPR with a high SCI suggests reviewing the manager's assessment; a high SCI with high KPIs may indicate hidden complexity; if both decrease, one can infer stability and low complexity.

4.2 Project 2 Results

In Project 2, five different stages of deviation identification are considered. For simplicity, the SCI results are shown directly:

Table 5: Comparative SCI results for Project 2.

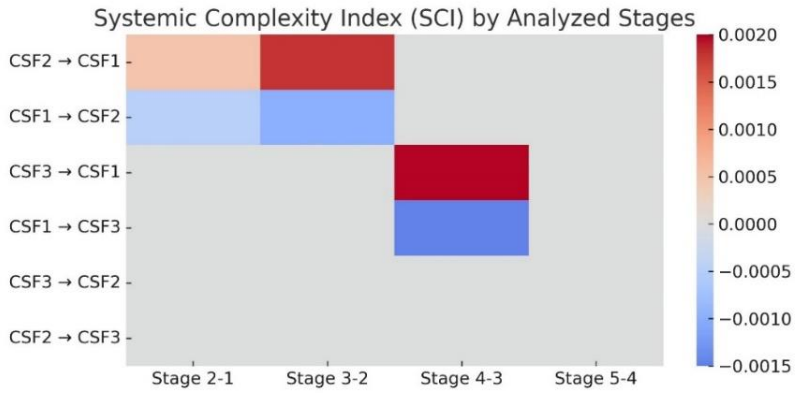
Stage 2-1	Relationship	SCI	Sub-KPIs	Time Difference Δx (months)	Persistence Factor γ
	CSF2 → CSF1	$+0.00052$	Effort/month	3	0.42
	CSF1 → CSF2	-0.00018	Deadline deliverables		
Stage 3-2	**Relationship**	**SCI**	**Sub-KPIs**	**Time Difference Δx (months)**	**Persistence Factor γ**
	CSF2 → CSF1	$+0.0018$	Effort/month	7	0.67
	CSF1 → CSF2	-0.0010	Deliverable quality		
Stage 4-3	**Relationship**	**SCI**	**Sub-KPIs**	**Time Difference Δx (months)**	**Persistence Factor γ**
	CSF3 → CSF1	$+0.0021$	Effort/month	4	0.5
	CSF1 → CSF3	-0.0015	Deliverable quality		
Stage 5-4	**Relationship**	**SCI**	**Sub-KPIs**	**Time Difference Δx (months)**	**Persistence Factor γ**
	CSF3 → CSF2	$+0.00008$	Deadline deliverables	4	0.17
	CSF2 → CSF3	-0.00005	Deliverable quality		

The relationships CSF2 → CSF1 y CSF1 → CSF2 increase significantly between stages 2-1 and 3-2. The relationship CSF3 → CSF1 is more critical in stage 4-3 and should be prioritized. In stages 5-4, the interactions are mild, with minimal changes in schedule and quality.

For the Cost-Schedule pair, the positive SCI in Stage 2-1 aligns with actual deviations where a partner reported in Stage 2 37.3% personnel overrun in WP5, and another partner noted a 0.9% over-allocation of Effort-Month. These discrepancies reflect schedule pressures (delayed deliverables in Stage 1) amplifying labor costs, as teams required additional effort to meet revised timelines. Stage 3-2 for the same factors shows an increase in SCI of 47% compared to Stage 2-1, correlating with actual accumulated delays reported in WP1, WP5 and WP6 (up to 4 months). This reflects escalating interdependencies between schedule adherence and execution efficiency, as evidenced by one Partner´s 69.8% efforts/month deviations in WP2 and another Partner's 6.6% resource misalignment.

Stage 4-3 (Execution-Cost) reflects escalating systemic complexity driven by five partners´ over allocation in WP2, compounded by a deliverable delay. These deviations intensified execution-cost interdependencies, mirroring the SCI's capture of non-linear strain from technical rework and resource misalignments. Finally, stage 5-4 aligns with stabilized operations: only one execution delay per stage with 96% and 97% of KPI compliance respectively.

Figure 3: Heat map of SCI results between factor pairs and stages in Project 1.



4.3 Validation of Results with Distance Correlation (dcor)

To validate that the Systemic Complexity Index (SCI) captures non-linear, cumulative interactions between project stages, Distance Correlation (dCor) is used, which detects both linear and non-linear dependencies (Zhou, 2012).

In each project, the correlation between SCI and deviations by CSF and sub-KPIs is analyzed. The process includes: 1) data normalization; 2) construction of distance matrices and double-centering; 3) calculation of dCov, dVar, and dCor; 4) statistical validation (permutation test); and 5) interpretation of results.

For simplicity, only the process for Project 1, stage 2-1, is detailed; in the other stages of Project 1 and in Project 2, only the results are presented (Table 6, Table 7, Table 8, and Table 9).

1. Preprocessing: Data Normalization:

Standard (Z-score) normalization is applied to vectors (SCI) and (FCE Deviations):

$$X_{\text{norm}} = \frac{X - \mu_X}{\sigma_X}, \quad Y_{\text{norm}} = \frac{Y - \mu_Y}{\sigma_Y}.$$

Where the SCI Vector (X): $[0.00048, -0.00012, 0.0133]$, $\mu_X = 0.00455$, $\sigma_X = 0.0072$, $X_{\text{norm}} = \left[\frac{0.00048-0.00455}{0.0072}, \frac{-0.00012-0.00455}{0.0072}, \frac{0.0133-0.00455}{0.0072}\right] = [-0.56, -0.65, 1.21]$

And the Deviation Vector (Y): $[-0.2823, 0.212, -0.5582]$, $\mu_Y = -0.2095$, $\sigma_Y = 0.385$, $Y_{\text{norm}} = \left[\frac{-0.2823+0.2095}{0.385}, \frac{0.212+0.2095}{0.385}, \frac{-0.5582+0.2095}{0.385}\right] = [-0.19, 1.10, -0.91]$

2. Distance Matrices and double-centering:

For each normalized vector, distance matrices A (for X) and B (for Y) are built, where:

$$A_{ij} = | X_i - X_j | = \begin{bmatrix} 0 & 0.09 & 1.77 \\ 0.09 & 0 & 1.86 \\ 1.77 & 1.86 & 0 \end{bmatrix}, \quad B_{ij} = | Y_i - Y_j | = \begin{bmatrix} 0 & 1.29 & 0.72 \\ 1.29 & 0 & 2.01 \\ 0.72 & 2.01 & 0 \end{bmatrix}$$

For each matrix A y B, double-centering is performed: $\tilde{A}_{ij} = A_{ij} - \bar{A}_{i.} - \bar{A}_{.j} + \bar{A}_{..}$, where $\bar{A}_{i.}$ Is the average of row i, $\bar{A}_{.j}$ is the average of column j, and $\bar{A}_{..}$ is the overall average.

3. Distance Covariance (dCov), Distance Variance (dVar) and Distance Correlation (dCor):

Distance covariance is calculated as:

$$\text{dCov}^2(X,Y) = \frac{1}{n^2}\sum_{i,j}\tilde{A}_{ij}\,\tilde{B}_{ij} = 0.85;\ \text{dVar}(X) = \sqrt{\frac{1}{n^2}\sum_{i,j}\tilde{A}_{ij}^2} = 0.78;\quad \text{dVar}(Y) = \sqrt{\frac{1}{n^2}\sum_{i,j}\tilde{B}_{ij}^2} = 0.91;\ \text{dCor}(X,Y) = \frac{\text{dCov}(X,Y)}{\sqrt{\text{dVar}(X)\cdot\text{dVar}(Y)}} = 0.92$$

4. Statistical Validation (Permutation Tests), by generating 1000 random permutations of Y, calculating $\text{dCor}_{\text{perm}}$ for each permutation and obtaining the value p: the proportion of permutations where $\text{dCor}_{\text{perm}} \geq \text{dCor}_{\text{obs}}$.

The SCI-FCE Deviation Correlation Results by Analyzed Stages in Project 1 are shown in Table 6:

Table 6: SCI-FCE Correlation Results in Project 1.

Stage	SCI Components (X)	CSF Deviations (Y)	dCor	p Value	Interpretation
2-1 (Cost-Schedule)	$[0.00048, -0.00012]$	$[-0.2823, 0.212]$	0.91	$p < 0.001$	Very strong, significant correlation.
2-1 (Execution-Stakeholders)	$[0.0133, -0.0073]$	$[0.0339, -0.5582]$	0.88	$p = 0.002$	Strong, significant correlation.
3-2 (Schedule-Execution)	$[0.00085, -0.00028]$	$[-0.0391, 0.2392]$	0.82	$p = 0.005$	High, significant correlation.
4-3 (Cost-Schedule)	$[0.0149, -0.0081]$	$[-0.323, 0.149]$	0.94	$p = 0.001$	Almost perfect, significant correlation.

dCor values above 0.8 in Project 1 show significant non-linear correlations between SCI interactions and actual deviations. This enables identifying key factors and designing proactive strategies based on non-linear dependencies, reducing subjectivity with robust mathematical methods. Applying the same approach, but now comparing SCI values with sub-KPI variations between stages, yields the results in Table 7:

Table 7: SCI-sub-KPI Correlation Results in Project 1.

Stage	SCI Components (X)	Sub-KPI Deviations (Y)	dCor	p Value	Interpretation
2-1 (Efforts-Task)	$[0.00048, -0.00012]$	$[-0.4975, 0.2941]$	0.85	$p < 0.001$	Strong, significant correlation.
2-1 (Deadline deliverables - web visitors)	$[0.0133, -0.0073]$	$[0.81, -0.0833]$	0.79	$p = 0.003$	Moderate, significant correlation.
3-2 (WP-Deadline)	$[0.00085, -0.00028]$	$[0.1432, 0]$	0.68	$p = 0.012$	Medium, significant correlation.

4-3 (Efforts-WP)	$[0.0149, -0.0081]$	$[0.3543, -0.0833]$	0.89	$p < 0.001$	Very strong, significant correlation.

If the correlation is then calculated jointly by concatenating the results of all project stages, both for the CSFs and sub-KPIs, a global analysis is obtained (Table 8):

Table 8: Concatenated Correlation Results for All Stages in Project 1.

	Concatenated SCI Vector (X)	Concatenated Deviations Vector (Y)	dCor	p Value	Interpretation
CSF	$[0.00048, -0.00012, 0.0133, \dots, 0.0149]$	$[-0.2823, 0.212, 0.0339, \dots,$	0.87	$p < 0.001$	Very strong, significant correlation.
sub-KPIs	$[0.00048, -0.00012, 0.0133, \dots, 0.0149$	$[-0.4975, 0.2941, 0.1432, ..$	0.81	$p = 0.001$	Strong, significant correlation.

The results show that the SCI interactions explain 87% of the global deviations (dCor = 0.87) associated with the CSFs. At the sub-KPI level, the overall correlation (dCor = 0.81) indicates that 81% of the deviations are related to the interactions captured by the SCI.

In Project 2 (see Table 9), the results are similar: SCI explains 87% of the global deviations and 79% at the sub-KPI level.

Table 9: Concatenated Correlation Results for All Stages in Project 2.

Deviation Type	dCor	Value (1000 permutations)	Interpretation
CSF	0.87	$p < 0.001$	Very strong, significant correlation.
sub-KPIs	0.79	$p = 0.002$	Strong, significant correlation.

Both cases support that the SCI model identifies relevant non-linear interactions. While a high dCor does not imply causality, it does reflect a strong relationship, validating the usefulness of this approach, which still requires further validation in more projects.

5. Conclusions

The proposed methodology measures non-linear interactions among critical success factors and their cumulative effect on performance, surpassing other approaches by treating the project as a complex, systemic, and quantifiable entity. It incorporates tools such as the MPM and the Systemic Complexity Index (SCI), integrating risk and performance to identify distortions and hidden risks, thereby facilitating strategic decisions in various phases of the project.

The SCI is the main innovative contribution, as it condenses systemic complexity into a single value, revealing non-obvious interactions with a global impact. Unlike conventional models, it does not define success as a final state but as a dynamic process aligned with strategic objectives, operationalizing a systemic approach to project monitoring and facilitating decision-making in project management (Tzeng & Huang, 2011).

Validation in two real cases showed a correlation between SCI and observed deviations, confirming its ability to detect hidden risks. Complementary to other management tools, its application requires complex mathematical processing, so it is recommended that interfaces be developed to hide these calculations and simplify interpretation, enhancing its practical value for project management.

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Use of Generative Artificial Intelligence

For the preparation of this work, no generative artificial intelligence was used, except for its support in translation.

Communication Aligned with the Sustainable Development Goals