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Conceptual Critical Success Factors Model on Infrastructure Sustainability Rating System for California Construction Projects

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California State University Transportation Consortium

CALIFORNIA STATE UNIVERSITY LONG BEACH

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16. Abstract

This report addresses the sensitivity and reliability of the sustainability rating systems by comparing each category's verified scores with its respective submitted scores to evaluate how points are awarded for infrastructure projects, examine which categories present the most challenges for verification, and identify the best category for verification in the sustainability rating system. The authors conducted three analyses using credit score data obtained from fourteen actual civil infrastructure projects certified under Envision. First, the Natural World category had the highest average score from the submitted and verified data. Pairwise comparisons using t-tests indicate that the mean value of one category does not differ statistically from that of other categories. Second, a one-way analysis of variance found no statistically significant differences among the five categories' scores. Two-sample t-tests for comparing the submitted credit scores and the verified credit scores demonstrated no statistically significant difference in all five categories. However, the results showed that the verified credit scores are 18.63% lower than the submitted credit scores for all five categories. Third, multiple comparisons (Hsu's MCB) showed that the Natural World category is the best category with 95% confidence. The results also indicated that the Quality of Life, Leadership, New World, and Climate and Risk categories have a higher possibility of being verified on a similar level, proving that those projects are close to the "best" category and present fewer challenges to be certified than the Resource Allocation category. The findings from this report will provide sustainability managers and project teams with insights into credit implementation in the pre-design stage of potential infrastructure projects that may pursue the certification process.

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Executive Summary

Various sustainability rating systems have been developed to address the significant demands oof global sustainability issues in civil infrastructure construction projects. Credit weighting rubrics in many sustainability rating systems are an important but controversial kind of rating system developed in an extensive collaborative effort. However, these systems leave room for allocation consideration because of the arbitrary decisions from various organizations' sustainability goals. Thus, this report aims to address the sensitivity and reliability of the credit weighting systems by identifying the best and easiest category to verify in the sustainability rating system. Moreover, by comparing each category's verified scores with its respective submitted scores, this report aims to evaluate how points are awarded for infrastructure projects and to examine which categories present the most challenges in the process of verification. To achieve this, the authors conducted three experiments using point-by-point data obtained from 14 civil infrastructure projects certified under Envision version 2, which is one of the most popular and widely used rating systems.

First, we computed the percentage mean of verified and submitted scores for the five categories and conducted *t*-tests to determine if the differences between verified and submitted scores were statistically significant. This way, the study could determine if the infrastructure project team wanted to achieve a certain level of credits but were unable to verify them. The Natural World category showed the highest average score from the submitted and verified data. However, the result showed that the mean value of one category did not differ statistically from that of other categories.

Second, a one-way analysis of variance (ANOVA) was conducted to compare all percentage means of verified credit scores to determine if there were any statistically significant differences among the five categories. Two-sample *t*-tests for comparing the submitted credit scores and the verified credit scores demonstrated no statistically significant differences in all five categories. However, the results showed that the verified credit scores were, on average, 18.63% lower than the submitted credit scores for the data.

Third, multiple comparisons (Hsu's MCB) were conducted to identify the best category that provided the easiest procedure to achieve the maximum possible score while allowing project designers to identify the category more likely to be verified and awarded. The results showed that the Natural World (N.W.) category is the best category with 95% confidence because a lower bound close to 0 indicates the category is close to the best category. The results from the MCB comparison also indicated that Quality of Life (Q.L.), Leadership (L.D.), New World (N.W.), and Climate and Risk (C.R.) categories have a higher possibility to be verified on a similar level, proving that those projects are close to the "best" category and present less challenges to be certified than the Resource Allocation category. The findings from this study will provide sustainability managers and project teams with insights into credit implementation in the pre-design stage of potential infrastructure projects that may pursue the certification process.

1. Introduction

The Federal Highway Administration (FHWA) defines sustainability in highways as giving equal weight to environmental, economic, and social values. Sustainable highways are being built to consider safety, mobility, environmental protection, livability, asset management, and effective cost management over their life cycle (FHWA 2018). Due to limited resources and the urgent need to repair aging infrastructure systems, the construction industry has become more interested in sustainable development (Reeder 2010). Black (2010) proposed four issues to be resolved to maintain sustainable development in transportation systems. These issues include consumption of limited resources, injuries caused by traffic congestion, heavy traffic congestion, and damage to the environment. Because of the profound impact that U.S. highways have on sustainable transportation efforts, it is essential to consider the perspective of the regulatory body governing highway projects. The United States Green Building Council's Leadership in Energy and Environmental (LEED) system mainly focuses on vertical building constructions (USGBC 2023); thus, the involvement of LEED into horizontal infrastructure projects is limited. Therefore, sustainability rating systems for horizontal infrastructure projects have been receiving more interest from public agencies for infrastructure projects, especially in the transportation sector. Simpson (2013, 2014) introduced the ten existing rating systems in the nation and developed a framework for several DOTs, excluding California. While the methods and criteria of these rating systems share some commonalities, they also differ from one another in certain ways (McCarthy and Kim 2022).

Sustainability evaluation in construction projects is required to examine the level of impact towards the environment in the short and long term. In the United States and other countries, various studies have been conducted to determine an adequate and suitable rating system to assess civil infrastructure projects and achieve global sustainable goals. Mattinzioli (2020) developed an up-to-date critical review on the most prominent rating systems currently in the global market, including CEEQUAL, Envision, BE2ST-in-Highways, Greenroads, GreenLITES, Invest, and GreenPave. They reviewed and analyzed each system based on environmental, social, and economic pillars of sustainability for a roadway project. CEEQUAL and Envision were found to be complete regarding macro-categories, three-pillar considerations, and life cycles, but they were comparatively much more complex and lacking specificity for pavement projects.

Kumar and Mehany (2022) determined how three sustainability rating systems—Envision, CEEQUAL and IS (AGIC)—covered the criteria found in the UN Sustainable Development Goals (SDGs). Their study proposed a sustainability and resilience monitoring scheme. Their evaluations indicated high alignment of the rating systems with the UN SDGs, with 94.12% coverage of the UN SDGs by Envision, 94.12% coverage by AGIC (94.12%), and 88.24% coverage by CEEQUAL. Moreover, Diaz-Sarachagaa et al. (2016) conducted an analysis of the mainstream sustainability rating frameworks for infrastructure projects—including CEEQUAL, Envision and IS Rating tool—to determine their effectiveness in construction applications for the least developed countries. This comparison revealed that the three rating tools are biased towards their geographical context in developed countries and need to be enhanced to be suitable systems for other countries with the least developed technologies.

Regarding highway civil infrastructure, Griffiths (2019) investigated four third-party verified infrastructure sustainability rating tools used by the highway and transportation industry, including CEEQUAL, Envision, Infrastructure Sustainability, and Greenroads. The study implemented a case study of a viaduct project in New Zealand to compare the results of each rating system. Results indicated that CEEQUAL awarded the most points to highway projects, followed by Envision. However, CEEQUAL is specifically adapted to highway projects, while Envision shows usefulness specifically as a reference for early project planning and consideration of broader questions of sustainability and community. Moreover, with highway and road projects, Szpotowicz and Toth (2020) utilized the TOPSIS method to rank the applicability of sustainability rating systems in the development of infrastructure road construction. The study found that the most suitable options for these types of projects are Envision, Greenroads, INVEST, GreenLITES, and I-LAST. Additionally, Envision was the system that satisfied most of the criteria, followed by Greenroads.

Some studies have compared rating systems for transportation infrastructure projects. For instance, Tran et al. (2020) assessed the significance of traffic-and-transportation-planning-related indicators (TTPIs) in sustainable transportation infrastructure rating system (STIRS) to determine how these projects in their planning phase can be improved by aiming for more sustainable practices. The rating system "Green Guides for Roads" allocates the highest percentage of total points (37%) to TTPIs, whereas the rating system "Infrastructure Voluntary Evaluation Sustainability Tool" allocates the lowest percentage of total points (20.9%) to TTPIs.

The Envision rating system is presented as one of the tools to address sustainability issues in civil infrastructure as it offers a framework to measure, assess and verify the level of sustainability and resilience of all types of projects regarding infrastructure construction. These systems cover five major categories of evaluation: Quality of Life (Q.L.), Leadership (L.D.), Resource Allocation (R.A.), Natural World (N.W.), and Climate and Risk (C.R.). Researchers have utilized Envision as a rating tool to measure the impact of sustainability on civil infrastructure case studies and projects. Huang (2014) implemented the Envision rating system to evaluate the design sustainability of a pedestrian bridge in the City of Long Beach California. The research proposed a comparative analysis of the original design of the bridge and an optimized design that sought to incorporate more sustainable practices and elements. The study concluded that the Envision checklist was biased towards high-level decisions related to the preliminary planning and site selection of the project, and decisions related to design and construction practices were not awarded evenly.

Trop (2018) also used a case study from a public bike sharing system to evaluate the parameters with Envision. The study revealed that, overall, the project scored highly as a sustainable infrastructure. However, it also mentioned that Envision focuses on the process rather than on the purpose of the project, neglecting many important considerations of social sustainability, often failing to evaluate sector-specific concepts, and disregarding locational and temporal context.

Rodriguez-Nikl and Mazari (2019) evaluated a transit tunnel to measure the sustainability of an underground transportation infrastructure (UTI) using the Envision rating system. The study found that Envision captured the advantages and disadvantages of UTI well; however, the areas in which the UTI scored better were also those that do not address well for that type of project—namely Natural World and Quality of Life, which are two of five major Envision categories. Saville et al. (2016) utilized the Envision sustainability rating system to assess water infrastructure projects designed to enhance resiliency of supply. They found that the water system performed efficiently in its evaluation. Nonetheless, Envision omits aquifer-wide monitoring programs, sustainable yield, groundwater regulations, and public awareness of water resource limitations. These omissions can be factors that could improve the score of a project. Boeles et al. (2017) used Envision to evaluate a case study that described three alternative solutions for the continued operation of "Rockaway," an aging and underutilized wastewater treatment plant (WWTP) susceptible to extreme weather events. The Quality of Life and Climate and Risk categories scored higher by considering the reduction of operational noise and energy consumption respectively. Consequently, Envision provided a highly applicable standard mechanism as a decision-making tool during project planning phases.

The current study is unique in that it determines the "best" desirable category based on the Envision-certified projects. Additionally, it compares the five Envision categories of each project to determine the level of accuracy that the project designer achieved based on the number of credit points that were submitted for evaluation and the resulting verified credit points after evaluation. First, we review existing studies on sustainability rating systems for civil infrastructure construction projects. Second, we describe the data collection on Envision projects and the limitations of the data sets. Third, we present statistical results on the Envision credit score data, followed by concluding remarks.

2. Literature Review

Several studies have been conducted over the last two decades to address the challenges arising from civil infrastructure construction projects that significantly impact global warming and climate change. Ni et al. (2015) addressed the difficulties presented by linear infrastructure projects in complex environments, especially in the Western United States. They reviewed the state-of-the-art assessments of infrastructure sustainability and aimed to incorporate resilience and sustainability principles into the decision-making process for linear infrastructure, whereas previous research frequently concentrated on financial elements or construction components. The impact of the complicated mountain environment on linear infrastructure projects in Western China is emphasized by the study background, which is noteworthy. This underscores the need for a tailored evaluation system that takes many elements into account. The Analytic Hierarchy Process (AHP), Decision Analysis (DEA), and Technique for Order of Preference by Similarity to Ideal Solution (TOPSIS) are among the methodologies that the study used, with a preference for AHP because it is appropriate for the system of evaluation. Pythagorean fuzzy sets improved the way in which uncertainty was handled, lowering subjectivity in weight scoring, and raising overall believability. This novel strategy fills the knowledge gap on certain infrastructure types in complex environments by providing insightful information for sustainable decision-making in difficult geographic contexts.

Thacker et al. (2019) evaluated the importance of integrated infrastructure planning in line with Sustainable Development Goals (SDGs) for long-term sustainable development. The study included pre-existing sustainability initiatives like the Paris Agreement, the Sendai Framework for Disaster Risk Reduction, and the New Urban Agenda. The study used methodical sustainability evaluations to examine each country's contribution under the Paris Agreement, focusing on policies and infrastructure investments that support the SDGs and minimize unforeseen consequences. A sustainable infrastructure plan is the result of scenario analysis, options appraisal, and stakeholder-led envisioning of future infrastructure performance. The study suggests continuous and adaptive application of this approach to manage trade-offs, involve the public, and incorporate sustainability into decision-making. The study also highlighted the need for increased capability for infrastructure planning and administration.

Yanamandra (2020) examined the shift in economic growth, particularly in infrastructure initiatives, from prioritizing social growth and political stability to a more comprehensive and sustainable development agenda. The United Nations SDGs have influenced this shift, focusing on social, economic, and environmental factors, as well as specific industries like transportation and sanitation. The study defined sustainable infrastructure projects, highlighting their focus on the SDGs, triple bottom line assessment, affordability, and financial sustainability. The study also emphasized the need for additional study on institutional systems and financial sustainability as they significantly influence financing and implementation of sustainable infrastructure projects.

Sadiq et al. (2020) argued a potential decline in infrastructure systems due to the COVID-19 pandemic and climate change, indicating a need for strategic planning and resource allocation. Infrastructure plays a crucial role in a nation’s development and faces challenges from population and economic expansion. Early planning is crucial to prevent costly consequences. Governments worldwide must take practical steps to address urban infrastructure issues, including encouraging electric vehicle charging stations, improving water systems, building energy-efficient dwellings, and implementing green building certification schemes. To create resilient infrastructure systems, corporate funding, community mobilization, and technology uptake are essential. Incorporating diverse stakeholders, such as governmental entities and local populations, is also crucial. Forums like "Sustainable Infrastructure" can promote communication between scientific communities and stakeholders, highlighting new issues, financial resources, technical developments, and best practices.

Hellström et al. (2021) examined two infrastructure development scenarios: a new passenger and freight ferry between Vasa, Finland, and Umea, Sweden; and a shipbuilding project for short-sea operations in the Baltic Sea. The first scenario focused on sustainability objectives and introduces new technology, while the second scenario highlighted inefficiencies in short-sea shipping and environmental laws. The study conducted a cross-case analysis and summarized delivery model characteristics for both scenarios, highlighting the challenges and factors to consider in financing, delivery, and planning infrastructure within the framework of environmental and regional sustainability. Zuluaga et al. (2021) delved into the concept of “worth” in infrastructure development, highlighting its role in socio-economic advancements and the financial impact of these initiatives. The concept of worth categorizes value using a broad conceptual framework, highlighting the importance of environmental, social, and economic factors. Dimensions include direct preference, contribution to goals, prioritization, and embedded relations. The study emphasized the challenges of aggregating and comparing data and the need for integrating diverse value concepts for more complex and environmentally friendly infrastructure evaluations. Direct preference is a recurring issue in planning and operations evaluations.

Elzomor et al. (2022) evaluated the significance of incorporating sustainability into academic programs in architecture, engineering, and construction (AEC) to educate future professionals about fair and sustainable infrastructure. The Envision Academic Committee's observations suggest a comprehensive framework for integrating sustainability rating systems into higher education. The framework can be used in various formats, such as course modules and workshops. AEC students should pursue sustainability qualifications like the Envision Sustainability Professional (ENV SP) to understand social concerns about infrastructure and contribute to sustainable and equitable systems in their future jobs. Their study aimed to expand sustainability education in higher education and inspire students to seek sustainability credentials.

Laali et al. (2022) proposed a Building Information Modelling (BIM)-based methodology to automate sustainability evaluation and optimize infrastructure projects. The framework allows real-time assessment of sustainability implications throughout the design stage and the assessment has been proven to be effective through a prototype in a case study. The BIM-based method simplifies certification and documentation procedures, provides a single platform for project teams and sustainability assessment organizations, and removes barriers associated with initial and additional expenses. The method also reduces cognitive strain, resolves interoperability concerns, and enhances sustainability evaluation. The study emphasized the potential of BIM for automated sustainability assessment and optimization but acknowledged future expansions to systematically model various forms of infrastructure.

Abedi et al. (2023) presented a thorough synopsis of the multidisciplinary investigation of qanats, which are complex water system with a variety of ethnic and geographical characteristics. Their review indicated that many existing studies on qanats focused on technical issues (32%), but they also included other fields, including built environment, water management, social science, environment and sustainability, geography, biology, heritage-history, chemistry, rehabilitation, cultural science, archaeology, disaster risk, tourism, and philosophy, all of which have attracted an increasing amount of interest over time. Their study also tracked the changing patterns and observes the patterns in fields like sustainability, sustainable architecture, urban planning, and landscape architecture. There has been a noticeable shift in emphasis in recent years towards holistic viewpoints. The assessment emphasizes how closely Qanat is related to the natural, cultural, social, and economic spheres. It emphasizes the function of infrastructure in not only the provision of water, but also in influencing social networks, forming cultural and religious customs, and making substantial contributions to commercial values. The study highlights the diverse range of material and immaterial characteristics connected to Qanat in numerous scientific fields.

Dvorak and Barutha (2023) compared the environmental impacts of an offshore wind farm with a novel foundation design (Novel Design) to a conventional design using a steel monopile foundation (Conventional Design). The foundation of a wind farm is crucial for environmental sustainability, with the tower being the largest contributor. Their comparative life cycle assessment (LCA) focused on building, installation, and end-of-life phases. Their findings showed that the Novel Design had lower environmental impacts in half of the impact categories, whereas the Conventional Design had lower impacts in other categories. The study emphasized the influence of building and foundation decisions on sustainability results and provided insights into the overall environmental performance of various offshore wind farm designs.

3. Research Objective and Method

The objective of this study is to address the sensitivity and reliability of sustainability rating systems by comparing each category's verified scores with its respective submitted scores to evaluate how points are awarded for infrastructure projects, examine which categories present the most challenges for verification, and identify the best category for verification in the sustainability rating system.

The methodology for the analysis of data follows three steps. First, we present the percentage mean of verified and submitted scores for the five categories and compare them with *t*-tests to determine if there are statistical differences between verified and submitted scores. In doing so, the study could determine if the infrastructure project team wanted to achieve a certain level of credits but were unable to verify them. Second, a one-way ANOVA was conducted to compare all percentage means of verified credit scores to determine if there were any statistically significant differences between the five categories' scores. Third, multiple comparisons (Hsu's MCB) were conducted to identify the best category that provided the easiest procedure to achieve the maximum possible score and that allowed project designers to identify the category more likely to be verified and awarded. The outcomes from this analysis will help identify which categories present the more challenging process of verification compared to the submitted credit scores in all five categories.

4. Data Collection

The project team collected credit score data from state transportation agencies for infrastructure construction projects that were certified under Envision v2, which was one of the most widely used rating systems at the time of this study. Data were collected from May to December 2023 in California. We collected 21 credit score cards for completed California infrastructure construction projects certified under Envision v2. However, during data screening, only 14 credit score cards (66.7%) were considered complete datasets. Therefore, only 14 of the infrastructure construction projects were used for the statistical data analysis. Note that the number of infrastructure construction projects was limited due to the limited availability of credit score cards which are not released to the public due to confidentiality. In addition, there have been only a small number of California infrastructure construction projects that pursued Envision certification during the study period.

5. Analysis and Findings

This section describes three analyses: (1) mean percentages of verified and submitted scores for the five categories and *t*-tests between verified and submitted scores; (2) the completely randomized design and one-way ANOVA used to compare the mean submitted credit points and the mean verified credit points among five categories; and (3) multiple comparisons (Hsu's MCB) to determine the most desirable "best" category.

5.1 Mean Credit Scores from Five Major Sustainability Categories

The mean credit scores of five major categories were compared between the submitted and verified credit scores. Table 1 tabulates the descriptive statistics for the five categories. The Natural World category has the highest average score from the submitted and verified data. Table 2 shows the statistical results on Anderson-Darling tests for the normality. For Anderson-Darling tests of normality, the null and alternative hypotheses are H_0: Data follow a normal distribution and H_1: Data do not follow a normal distribution, respectively. Since the *p*-values for all five major sustainable categories are greater than the significance level of 0.05, we do not reject the null hypothesis that the data follow a normal distribution. The result suggests that parametric tests such as ANOVA tests can be used to analyze the data. Indeed, Bartlett's tests of homogeneity of variances method is used because this method is accurate for normal distribution to examine the equal variance among five major sustainable categories. For Bartlett's tests for the equal variance, the null and alternative hypotheses are H_0: All variances are equal and H_1: At least one variance is different, respectively. Bartlett's tests yield test statistics of 8.30 and 7.98 having the *p*-values of 0.081 and 0.092 for both submitted score data and verified score data, respectively. Since the p-values for all five major sustainable categories are greater than the significance level of 0.05, we failed to reject the null hypothesis that all the variances among the data are equal. The result means that equal variance assumptions are met for parametric tests such as ANOVA tests to analyze the data.

Based on a 95% confidence interval, the null hypothesis is that the mean credit scores for each category are equal for both the verified and submitted scores. Table 3 tabulates the ANOVA results for all five major sustainability categories. The one-way ANOVAs yielded *p*-values of 0.207 and 0.092 for both submitted and verified credit scores, which are less than $\alpha = 0.05$; therefore, we do not have significant evidence to reject the null hypothesis. The result means that the mean value of one category does not differ statistically from that of other categories.

Table 1. Descriptive Statistics for Submitted and Verified Credit Scores

Category	N	Mean Score	Standard Deviation	Standard Error Mean
(a) Submitted				
Quality of Life	14	77.57	9.90	37.04
Leadership	14	61.79	6.14	22.98
Resource Allocation	14	60.10	10.30	38.50
Natural World	14	81.60	11.00	41.30
Climate and Risk	14	57.57	5.91	22.10
(b) Verified				
Quality of Life	14	68.00	9.48	35.46
Leadership	14	50.86	7.12	26.64
Resource Allocation	14	46.07	8.66	32.42
Natural World	14	71.80	11.90	44.70
Climate and Risk	14	44.43	5.59	20.91

Table 2. Results of Normality and Equal Variances

Test	Anderson Darling - Submitted			Anderson Darling - Verified		
Category	Test Statistics	P-Value	Normality	Test Statistics	P-Value	Normality
Quality of Life	0.244	0.713	Yes	0.235	0.745	Yes
Leadership	0.308	0.518	Yes	0.294	0.548	Yes
Resource Allocation	0.206	0.837	Yes	0.255	0.671	Yes
Natural World	0.484	0.191	Yes	0.325	0.484	Yes
Climate and Risk	0.345	0.431	Yes	0.693	0.054	Yes

Table 3. Results for Differences of Means using one-way ANOVAs

Source	DF	Adj SS	Adj MS	F-Value	P-Value
(a) Submitted					
Factor	4	6783	1696.000	1.520	0.207
Error	65	72568	1116.000		
Total	69	79352			
(b) Verified					
Factor	4	9126	2281.000	2.090	0.092
Error	65	70870	1090.000		
Total	69	79996			

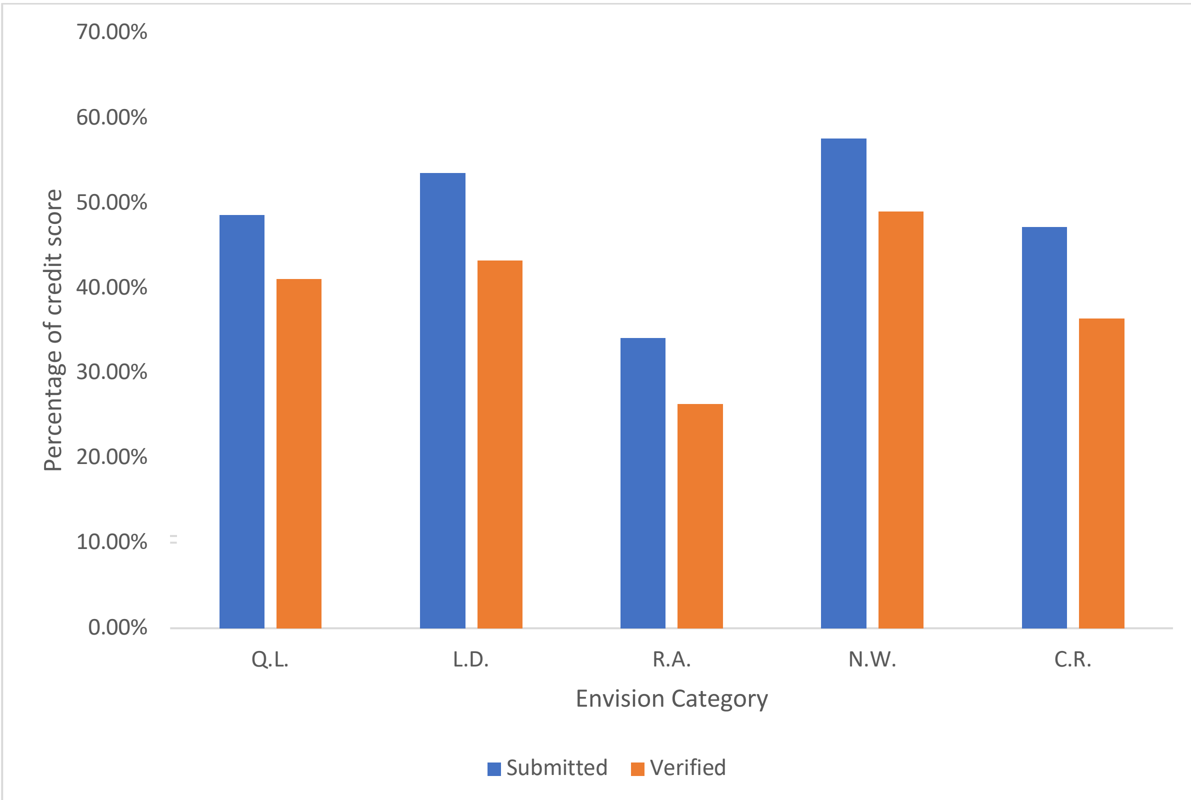
5.2 Completely Randomized Design and Analysis

The completely randomized design is used to further examine to what extent, if any, the differences exist between the submitted credit scores and the verified credit scores. The completely randomized design is widely used because it is the simplest experimental design for comparing more than two population means. The analysis of variance (ANOVA) is used to determine whether or not a factor affects the response variable. If the factor is significant, the mean response differs for the various treatments (Kuehl 2000). Pairwise comparisons using the Tukey procedure are employed to compare each performance measure means with each of the other measure means. The parameters of interest are all pairwise differences among the performance measure means. The pairwise comparison aims to detect significant inequalities for all performance measure means (Kim 2010).

The two parameters of interest for the comparison are: (1) mean percentage of submitted credit score data, which is calculated as the percentage of submitted credits over the total of applicable credits for each of five Envision categories; and (2) mean percentage of verified credit score data, which is calculated as the percentage of verified credits over the total of applicable credits for each of five Envision categories. Figure 1 shows the comparison results. The Quality of Life (Q.L.) category shows 48.56% of all applicable credits that were submitted and 41.07% that were verified. The graph shows the Leadership (L.D.) category in which 53.52% of credits were submitted and 43.24% were verified, the Resource Allocation (R.A.) category in which 34.13% of credits were submitted and 26.35% were verified, the Natural World (N.W.) category in which 57.60% of credits were submitted and 49.03% were verified, and the Climate and Risk (C.R.) category in which 47.19% of credits were submitted and 36.42% were verified. The results showed that the verified credit scores are 18.63% lower than the submitted credit scores for the data. 18.63% was obtained by the difference between the average percentage of submitted credit scores and verified credit scores and divided by the average percentage of submitted credit scores (48.20% - 39.22%) / 48.20% x 100.

A two-sample *t*-test is a method to statistically determine whether the population means of two independent groups differ (Minitab 2023). Thus, the authors of this report conducted two-sample t-tests for hypothesis testing. The hypothesis being tested is whether the submitted credit scores ($\mu1$) exceed the verified credit scores ($\mu2$). The mathematical form of the hypothesis is that Ho: $\mu1 - \mu2 = 0$ and Ha: $\mu1 - \mu2 > 0$. Table 4 shows the statistical results. All results indicate a *p*-value greater than the $\alpha = 0.05$, which demonstrates that there is not enough evidence to reject null hypothesis, meaning that verified and submitted are not statically different within each category.

Figure 1. Comparison of Average Scores between Submitted and Verified Credits



Moreover, a one-way ANOVA was conducted utilizing Minitab® 23 to determine whether the mean percentages of *submitted* credit scores of five Envision categories differ from each other. The null and alternative hypotheses are Ho: μQLsub = μLDsub = μRAsub = μNWsub = μCRsub and Ha: at least two mean percentages differ. The resulting test statistics are F=2.43, with a p-value of 0. Additionally, a second one-way ANOVA analysis was performed in order to determine whether the mean percentage of *verified* credit scores of the five Envision categories differ from each other. The null and alternative hypotheses are Ho: μQLver = μLDver = μRver = μNWver = μCRver and Ha: at least two mean percentages differ. The resulting test statistics are F=2.25, with a p-value of 0. The p-value is the probability of obtaining a test statistic as large as F value, assuming Ho is true. Since p-value is less than α = 0.05, the null hypothesis is rejected. The Tukey 95% simultaneous confidence intervals for all pair-wise comparisons among five categories show that the null hypothesis is rejected because the observed significance level or p-value of 0.00 is less than α = 0.05. The results confirm that the numbers of points under each category are well allocated to address the most important environmental impacts and human benefits by giving the greatest weight. These results indicate that the mean percentage differs among the five categories for both submitted and verified data, indicating that each category follows a different process of verification and approval for a project that is submitted for evaluation. Also, the number of credit points allocated in each of the five categories are efficiently distributed to measure the impact and benefits of sustainability in civil infrastructure projects.

Table 4. Comparison Results between Verified and Submitted Scores for Each Category

Category	Comparison	T-test	P-value
Quality of Life (Q.L.)	Verified vs. Submitted	0.9	0.375
Leadership (L.D.)	Verified vs. Submitted	1.26	0.218
Resource Allocation (R.A.)	Verified vs. Submitted	1.03	0.314
Natural World (N.W.)	Verified vs. Submitted	0.92	0.367
Climate and Risk (C.R.)	Verified vs. Submitted	1.62	0.119

5.3 Advanced Analysis using Multiple Comparisons with the Best

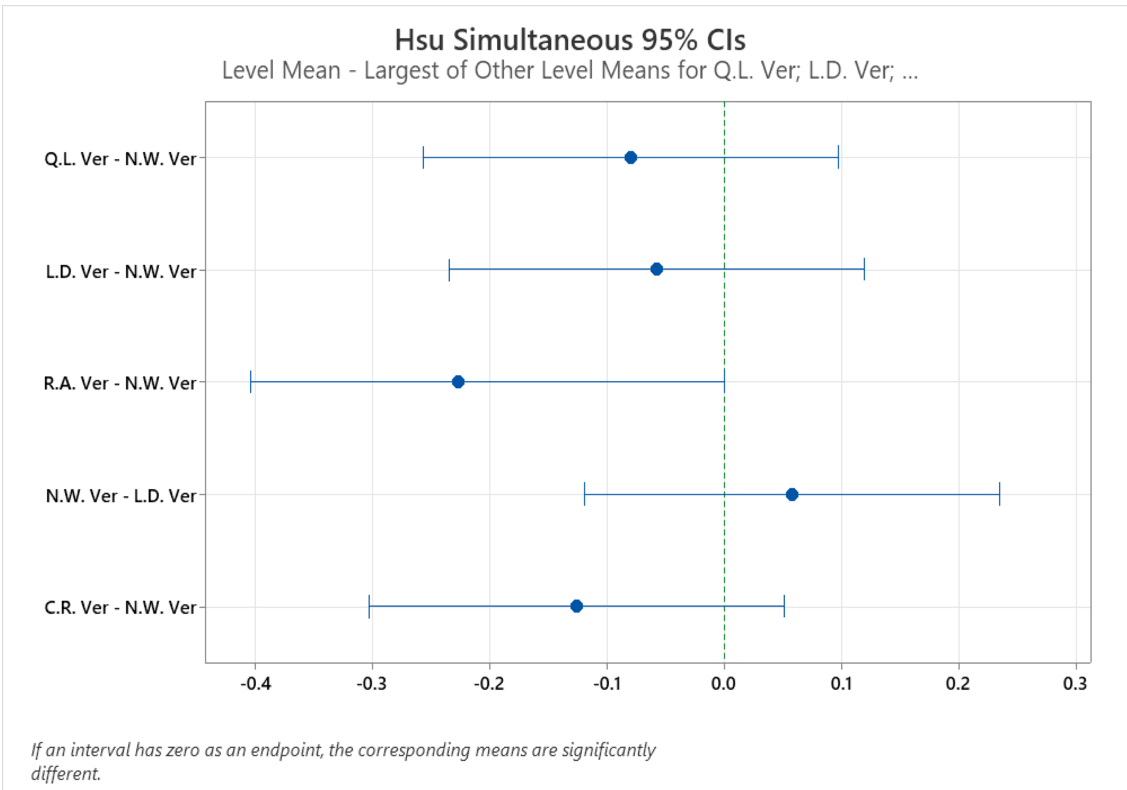
The five categories of the rating system are interconnected as they are all major aspects of sustainability that influence environmental impacts. The categories also focus on some specific areas of interest to the Envision project teams who will pursue Envision certification. The objective of this advanced analysis is to select the set of categories or single category that provides the highest percentage of approval (verified) to the Envision project teams. This will determine the category in which designers are likely to implement more sustainable practices in civil infrastructure projects, as they focus on submitting more points to consideration on one category than the others. At the same time, it will show the category that benefits the most to civil infrastructure projects to receive an Envision award. The multiple comparisons with the best (MCB) procedure from Hsu (1984) was implemented to enable the Envision project developers and designer to select the categories into a subset such that the "best" category is included in the subset with a given level of confidence. The best category can be interpreted as the most desirable category to be achieved easily.

Table 5 tabulates the data analysis procedure using MCB with the analysis results. Figure 2 presents the Confidence Interval at 95% of confidence. In MCB, the 100(1- α)% simultaneous constrained confidence intervals (SCI) is constructed as follows: (1) calculate the difference, Di, between each category mean and the largest category mean of the remaining categories; (2) compute the quantity M, M, $M = d_{\alpha,k,v}\sqrt{\frac{2s^2}{r}}$, where $d_{\alpha,k,v}$ the tabled statistic for one-sided comparisons and can be obtained using Minitab for Hsu's multiple comparisons with the best (MCB) from Kuehl (2000) for an experimental error rate of α_e, $k = t - 1$ comparisons, and v degrees of freedom for the experimental variance, $s^2 = MSE$, r = replications; and (3) compute the lower and upper confidence bounds for the difference of each category. We calculated the 95% confidence interval for a comparison of credit scores of the Resource Allocation (R.A.) category with the best of the other categories to illustrate the MCB procedure. The mean for the Resource Allocation (R.A.) category is 26.35% (0.2635) and Natural World (N.W.) category has the largest mean among all the remaining categories, so that $max\ \bar{y}_j$ (where, j ≠ 2) = 49.03% (0.4903). Then D2 = 0.4903 – 0.2635 = -0.2268. The value for $d_{\alpha,k,v}$ for the equation above is found approximately to be 0.013 with k = 5, α_e = 0.05, and v = 252 degrees of freedom for MSE = 0.000723. Thus, M is equal to 0.013 with r = 14 projects. The required quantities are -0.4035 for the lower bounds, respectively.

Table 5. Results for MCB Simultaneous Tests for Mean Scores

Difference of Levels	$\overline{y_i}$	max $\overline{y_i}$ (where j≠i)	Di	95% CI	T-value	Adjusted p-value
Q.L. - N.W.	0.41068	0.49030	-0.0796	(-0.2564; 0.0971)	-0.99	0.379
L.D. - N.W.	0.43242	0.49030	-0.0579	(-0.2346; 0.1189)	-0.72	0.501
R.A. - N.W.	0.26352	0.49030	-0.2268	(-0.4035; 0.0000)	-2.83	0.011
N.W. - L.D.	0.49030	0.43242	0.0579	(-0.1189; 0.2346)	0.72	0.501
C.R. - N.W.	0.36417	0.49030	-0.1261	(-0.3029; 0.0506)	-1.57	0.168

Figure 2. MCB Comparisons for Confidence Interval



One out of five categories, the Resource Allocation (R.A.) category has an upper bound of 0 and thus it is not the "best" category. There is no evidence to indicate a significant difference between four out of five categories, which are Quality of Life (Q.L.), Leadership (L.D.), Natural World (N.W.), and Climate and Risk (C.R.) categories because their confidence intervals contain zero (no difference), meaning that the four categories have statistical similarities. Moreover, the values of the Natural World (N.W.) category are the ones with the lowest bound and closer to 0. Therefore, the Natural World (N.W.) category is the best category with 95% confidence because it has a lower bound close to 0, which indicates that the category is close to the best as per Hsu's method (Hsu 1996). Also, the SCI not only provides the means to identify the best treatment(s), but also gives information about how far removed each of the other four categories is from the best, which will be presented in a future study. The deviations in percent were used for sensitivity and reliability of data analysis presented here. They were calculated for all projects by dividing the difference between the maximum credit verified scores achieved and possible applicable maximum points. The deviations are 20.12%, 21.89%, 18.47%, 27.08%, and 17.14%, for the Quality of Life (Q.L.), Leadership (L.D.), Resource Allocation (R.A.), Natural World (N.W.), and Climate and Risk (C.R.) categories respectively.

6. Summary & Conclusions

The authors presented the statistical results on the critical sustainability determinants that affect the success of meeting sustainability goals of infrastructure construction projects based on the credit scores using Envision v2. The statistical analysis used a complete set of 14 projects' Envision score card data for California infrastructure construction projects and yielded the following findings:

(1) The Natural World category had the highest average score from the submitted and verified data. The comparison results for the percentage means of verified and submitted credit scores for five categories led to the observation that the mean value of one category did not differ statistically from that of other categories. These findings show that five categories are equally important determinants in infrastructure construction projects in California.

(2) Two-sample *t*-tests for comparing the submitted credit scores and the verified credit scores demonstrated no statistically significant differences in each of five categories. However, the results showed that the verified credit scores are 18.63% lower than the submitted credit scores for all five categories.

(3) A multiple comparison with best method results showed that the Natural World (N.W.) category is the best category with 95% confidence because it has a lower bound close to 0. The results from the MCB comparison also indicate that Quality of Life (Q.L.), Leadership (L.D.), New World (N.W.), and Climate and Risk (C.R.) have a higher possibility to be verified on a similar level, proving that those projects are close to the "best" category and present less challenges to be certified than the Resource Allocation category.

While this report has presented sustainability managers of public agencies and project owners of infrastructure construction projects in California with meaningful data on the critical sustainability factors based on Envision v2, several critical limitations remain. Some of the open research areas to address these limitations include the following:

- The need to obtain more data on credit score data from California infrastructure construction projects. Collecting more credit score data, which is the most practical way, can enable the research outcomes to increase the power of a hypothesis test. Also, a higher significance level could be considered so that the probability of rejecting the null hypothesis can be increased.

- The results obtained from this report need to be compared with the results obtained from other states' sustainability rating systems for infrastructure construction projects using Envision v2 as well as the latest version of Envision (v3).

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About the Authors

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Dr. Kim is Professor and Department Chair of the Department of Civil Engineering and Construction Engineering Management at California State University, Long Beach. He was involved in supervising a graduate student assistant and was responsible for overall project coordination, ensuring successful project completion, and preparing the final MTI report. Prior to this research, Dr. Kim played an important role in a research project that evaluated several ITS-based treatments for the safety of a pedestrian crossing the streets funded by the Federal Highway Administration. He worked on the overall management of that project, which included the supervision of students collecting data based on either human or video observation, organization of data, statistical analysis using non-parametric tests, and reporting of the results. The outcomes have been featured in several publications and presentations at the meetings of the Transportation Research Record: Journal of the Transportation Research Board and the annual Transportation Research Board. Dr. Kim has previous experience as a GIS specialist at the Gainesville Police Department in Florida and has a minor in statistics, which is a significant advantage for conducting this research.

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Jose is a civil engineering graduate student at the Department of Civil Engineering and Construction Engineering Management at California State University, Long Beach who contributed to accomplishing the goals of this research project. His interests within the field include transportation engineering and project management. The scope of his contributions includes assistance in the analysis of collected data with Dr. Kim and the preparation of the MTI report.

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