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APPLICATION OF FUZZY ANALYTIC HIERARCHY PROCESS IN FRONT-END PLANNING

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Abstract: Project success depends upon the proper implementation of front-end planning (FEP) throughout those phases of a construction project's life cycle that precede the design stage. FEP requires that stakeholders produce a systematic scope definition and alignment. This process necessarily involves uncertainties since stakeholders occupy different roles and have different objectives. Furthermore, the limited availability of project-specific knowledge usually adds to the uncertainty associated with FEP, requiring that project participants work within acceptable tolerances to arrive at a consensus on project objectives and planning. Findings from the Construction Industry Institute (CII) indicate the frequent presence of misalignments between engineering and construction work packages that hinder the execution of installation work packages and introduce uncertainties to the implementation of FEP. Currently, CII uses two methods—the Project Development Rating Index (PDRI) and the Alignment Thermometer—to measure the level of scope definition and alignment on construction projects. However, these CII methods cannot adequately address the aforementioned uncertainties. For example, current CII methods lack approaches that can handle subjective variables and linguistic imprecision. In this study, the fuzzy analytic hierarchy process (FAHP) is used to weigh and aggregate different stakeholders' definition levels of project components and arrive at a PDRI score that recognizes these uncertainties. In addition, a methodology is developed for producing an Alignment Thermometer that captures the subjective uncertainties associated with stakeholders' interests and levels of expertise. The results of this study demonstrate that approaches incorporating the FAHP can more effectively handle uncertainty in the FEP process than current CII approaches.

1 INTRODUCTION

As defined by Construction Industry Institute (CII), front-end planning (FEP) is the "process of developing sufficient strategic information, including project objectives and preliminary engineering specification, with which owners can address risk and decide to commit resources to maximize the chance for a successful project" (CII 2012). Typical products of FEP may include option analysis, scope definition and boundaries, life cycle cost analysis, and cost and schedule estimates, among others (CII 2006).

Some of the tools that CII has developed for use in FEP include the Project Definition Rating Index (PDRI), the Shutdown Turnaround Alignment Review (STAR), the Alignment Thermometer, the Construction Input Assessment Tool (CIAT), and the Front-End Planning Toolkit. These tools can be used independently or together. In this paper, focus will be given to the Alignment Thermometer and the PDRI. These are the two most significant FEP tools produced by CII, and they are used together throughout the FEP phase.

The CII (2006) defines *alignment* as the "condition where appropriate project participants are working within acceptable tolerance to develop and meet a uniformly defined and understood set of project objectives." Alignment is calculated using the Alignment Thermometer tool provided by CII, within a range of (0–100). A score of at least 70 indicates a highly aligned and potentially successful project, while a score of 40 or less means a project is likely to fail. The PDRI is another score computing technique for determining the cumulative project definition; projects are ranked on a scale of 70 to 1000 points, with lower scores indicating a better scope definition. Projects that score below 200 have a higher potential for success (Gibson and Dumont 1996).

The challenge in applying these FEP tools lies in the fundamental nature of construction problems, which are subjective and often conveyed using imprecise linguistic expressions. In this regard, CII's findings have indicated the presence of a major misalignment between engineering work packages and construction work packages that facilitate installation work packages. Furthermore, discrepancies that may arise when using the PDRI for projects of different scales (i.e., small, medium, and large) can complicate the process of FEP.

The objective of this paper is to address the limitations of the PDRI and the Alignment Thermometer as they are used to calculate scope definition and alignment. These methods measure the potential for success, but approaches that incorporate tools (in the form of fuzzy numbers and fuzzy logic) that can better handle imprecise language have not yet been properly explored. It is paramount that such approaches be developed for use in FEP, especially when making decisions at different phase gates in the PDRI process.

The paper is organized as follows: First, a brief literature review on FEP is presented. Second, the methodology for addressing the research gaps described in the introduction is introduced. Third, the methodology is demonstrated using a case study of a building project. Results and interpretations are discussed in the fourth section, followed by conclusions and recommendations in the final section.

2 LITERATURE REVIEW

2.1 Alignment Thermometer and PDRI

When team alignment is achieved on construction projects, project performance can be greatly improved because the integration between key project participants facilitates much smoother FEP. In relation to project execution planning, which is a deliverable of FEP, Liang and O'brien (2016) identified 44 elements critical for improving team alignment. They used a scaling system of 1 to 10 to rate the importance of the elements' criticality to overall project alignment (1—very unimportant; 4—unimportant; 7—important; 10—very important).

The Alignment Thermometer calculates alignment using a self-evaluation survey administered during the pre-project planning phase. Survey respondents assess ten issues: stakeholder representation; project leadership; cost and schedule prioritization; communication within the team; team-meeting productivity; trust; sufficient funding, schedule, and scope to meet objectives; reward and recognition system; teamwork; and availability of planning tools (e.g., checklists, simulations, etc.). The issues are scored out of 100, and the average of the respondents' scores is compared with the benchmarks (less than 40—failure; between 40 and 70—mediocre; above 70—successful).

The PDRI is a powerful tool for scope definition that can be of use to owners, designers, and constructors. It can also greatly improve the process of continued alignment while helping project participants keep track of key project priorities. In calculating the PDRI score for the cumulative project definition, projects are ranked on a scale of 70 to 1000 points. The PDRI process consolidates the scores of several project teams to calculate an overall cumulative project definition score (CII 2012).

The PDRI, despite its use in large industrial projects, is less applicable for planning small infrastructure projects (Burke et al. 2016). This is because the scope definition elements and associated risk factors are different (Collins et al. 2016). Furthermore, it can be difficult to define *small projects* when developing a PDRI. The CII defined small projects as those whose value is less than $10 million (USD) with a duration of three to six months; the CII also produced a scope definition for such projects (CII 2015). In relation to this study, Burke et al. (2016) convened a research group that determined the main delineating factor of project size was complexity. Complexity was related to the total installed cost and engineering hours of a project, and the contributing factors were construction duration, core team numbers, and availability. A more specific definition of small projects was provided by ElZomor et al. (2018), who defined infrastructure projects with a total investment cost (TIC) of $20 million as small. Collins et al. (2016) further tried to justify the need for a specific PDRI for small industrial projects by claiming that the main focus of FEP for small projects should be on project execution rather than project feasibility.

The PDRI–Buildings tool was developed by the CII and provides a scope definition tool for buildings projects (CII 2015). Some of the projects that fall under this category are offices, schools, banks, apartments, and airport terminals, where scores are determined based on 64 element descriptions that focus on the complex aspects of building or commercial construction projects.

2.2 Fuzzy and Probabilistic Approaches in Front-End Planning and Alignment

As with all construction problems, issues related to FEP and alignment have fuzzy features. The challenges of FEP, which can involve cost and schedule estimations, selecting the best options for design, interpreting stakeholder interviews (which are usually subjective in nature), and assessing client satisfaction, all have to be addressed at some stage of the FEP process (CII 2006; Yussef et al. 2018; ElZomor et al. 2018).

Li et al. (2006) used fuzzy logic to forecast a project's status (potential cost overruns and schedule delays) using a set of performance indicators. This model, however, was developed for projects that have already started and does not address the features associated with FEP. Shaheen et al. (2007) used fuzzy numbers in cost range estimating. The authors showed that results using Monte Carlo analysis are comparable to results obtained using the fuzzy logic approach. However, the main feature of FEP, which is supporting decisions that must be made at several phase gates, was not covered in their paper. Salah (2012) used fuzzy sets to model the uncertainty inherent in cost contingency estimating and management, focusing on contingency depletion over a project's duration to mitigate risk during a project's life cycle.

Even though knowledge about using fuzzy logic and probabilistic approaches to solve construction problems exists in the literature (Raoufi et al. 2016, Raoufi and Fayek 2018) and different simulation approaches can be used to capture a process (Raoufi and Fayek 2015, Raoufi et al. 2018); there is a gap in the application area of FEP. The CII knowledge base is also lacking in approaches that can handle linguistic imprecision when addressing alignment and FEP issues.

3 METHODOLOGY

This study compares results from the traditional CII approach with two new approaches that use a modified method of calculating alignment and PDRI scores. In the first stage, both alignment and PDRI scores are calculated using the CII approach. The second stage has two parts. In the first part, modified alignment scores are computed by introducing weights to the alignment issues using the FAHP method for computing membership functions. For alignment issues (I_1, I_2… I_N), the pairwise comparisons (on a scale of 1–5) are given in the matrix form R, as shown in Equation 1. The weights are then computed by solving the eigenvalue problem for the membership values of the corresponding issues.

$$[1]\ R = \begin{array}{c|ccccc} & I_1 & I_2 & I_3 & \cdot\cdot & I_n \\ \hline I_1 & 1 & & \cdots & & \cdot\cdot \\ I_2 & & 1 & & & \\ \vdots & \vdots & & 1 & & \vdots \\ I_n & \cdot\cdot & & \cdots & \cdot\cdot & 1 \end{array}$$

where, I_1, I_2… I_n are the alignment issues.

Next, consistency is checked, as shown in Equation 2.

$$[2]\ \nu = \frac{\lambda_{max} - n}{n-1}$$

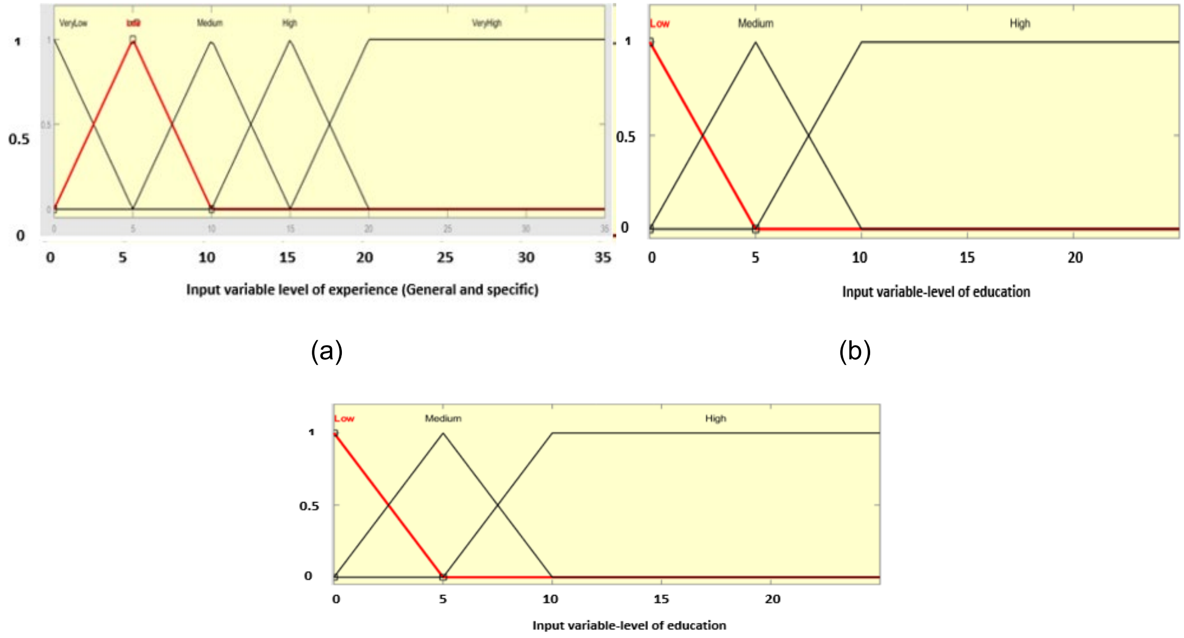
where ν is the consistency index and λ_{max} is the maximum eigenvalue for the reciprocal matrix R.

Then, the alignment score A is computed by multiplying the alignment scores with their respective membership values ($A(I_1)$, $A(I_2)$,… $A(I_N)$), as shown in Equation 3.

$$[3]\ AT_S = \sum_{i=1}^{N} A(I_i) * I_i$$

where AT_S is the Alignment Thermometer final score, $A(I_i)$ is the alignment score for issue (I_i), and I_i is the membership value for alignment issue (I_i).

In the second part, PDRI scores are assigned by several experts, and the scores are weighted using a multi-criteria approach. Here, the weight is a function of three criteria, namely, years of general experience, years of experience on similar projects, and level of education. The weight is computed using the fuzzy rule-based system (FRBS) using MATLAB. The membership functions (MBFs) for these criteria are shown in Figure 1, and the properties for the fuzzy inference system (FIS) are shown in Table 1.



(a)

(b)

(c)

Figure 1: (a) MBF for general and specific experience (input variables 1 and 2); (b) MBF for level of education (input variable 3); (c) MBF for score (output variable)

Table 1: Properties for the FIS

FIS Name	FIS-Expert Score
And method	min
Or method	max
Implication	min
Aggregation	max
Defuzzification	centroid

The FRBS, as analyzed in MATLAB, is shown in Figure 2.

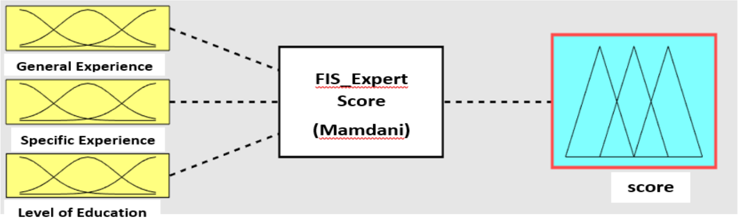


Figure 2: Fuzzy rule-based system (FRBS)

The rule matrix is shown in Table 2, and the rule surface is shown in Figure 3.

Table 2: Sample of rule matrix

General Experience	Specific Experience	Education	Score
Very low	Very low	Low	Low
Low	Low	Medium	Medium
Medium	Medium		
High	High		
Very high	Very high	High	High

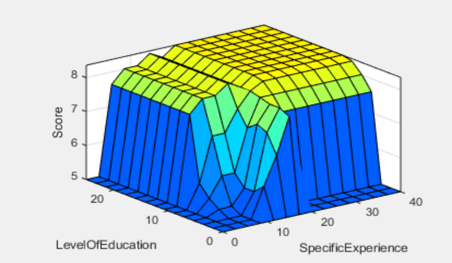


Figure 3: Rule surface

This FRBS is used to compute the defuzzified value of the score for each expert, which is then normalized and converted to an appropriate weight for each expert, as shown in Equation 4.

[4] $\mathrm{Wi} = \frac{S_i}{\mathrm{sum}(S_i)} \quad i = 1, N$

where S_i is the score of expert *i* and N is the number of experts.

These weights are used as coefficients for the PDRI scores given by each expert, as shown in Equation 5.

[5] $\text{Final PDRI Score} = \sum_{i=1}^{N} W_i * PDRI(i)$

where W_i is the weight of expert *i*; and $PDRI(i)$ is the PDRI score of expert *i.*

4 CASE STUDY

A warehouse project was chosen to demonstrate the developed research methodology. Warehouses are classified under PDRI–Buildings studies and the corresponding procedures are used. The PDRI–Buildings classification is applicable to multistory or single-story commercial, institutional, or light industrial facilities such as offices, schools, industrial control buildings, and warehouses. PDRI validation studies carried out by the CII research team were performed on projects that had already been completed, and a similar approach was adopted here. The project discussed in this case study has already been completed, and its bottlenecks, challenges, and success rate have been established. Works related to substructure and superstructure construction are shown in the work breakdown structure for the warehouse in Figure 4.

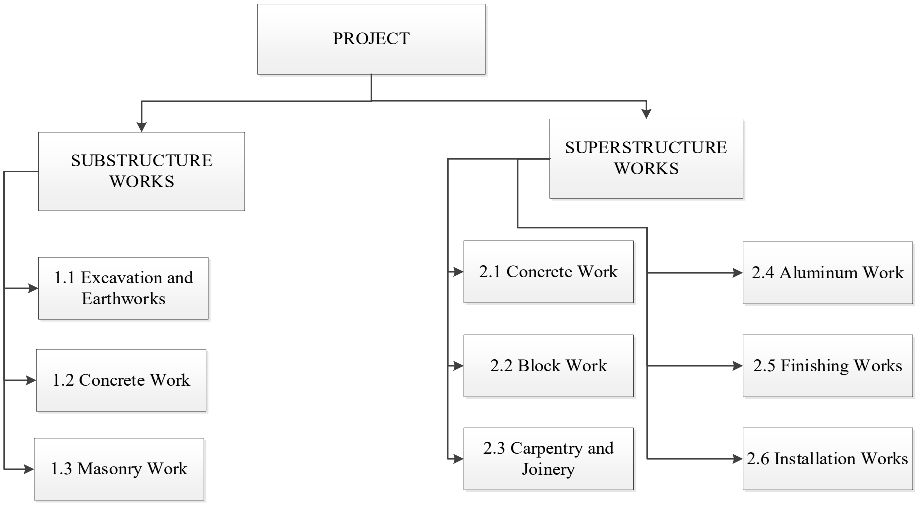


Figure 4: Higher level WBS of the project

5 RESULTS AND DISCUSSION

The Alignment Thermometer for the case study project is shown in Figure 5. This was computed using Equation 3. The calculated average and range of all 10 issues is shown in Figure 6.

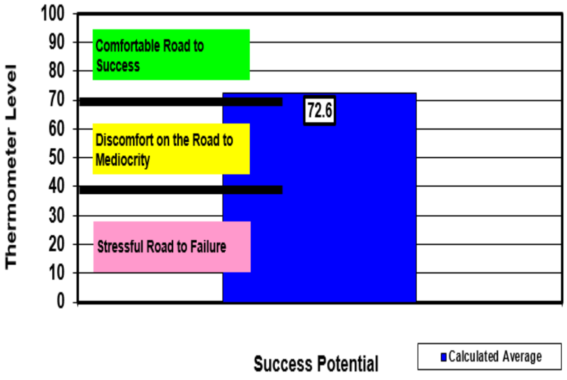


Figure 5: Alignment Thermometer score (CII method)

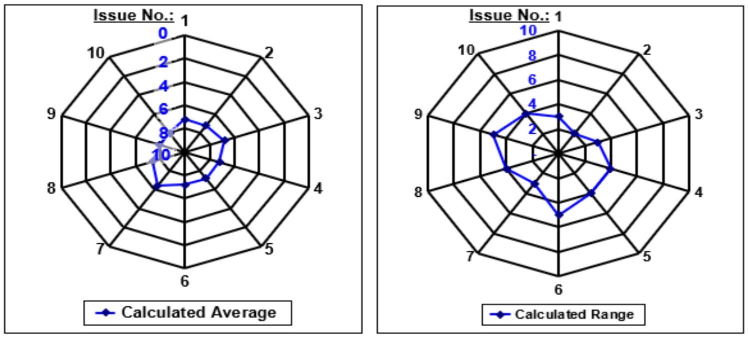


Figure 6: Range and average of alignment issues (CII method)

The Alignment Thermometer score shows that the project was on a comfortable road to success with an overall score of 72.6. This indicates that at the time of scoring, the project did not have main alignment issues requiring intervention by members of the alignment team. The range and average of the alignment issues also indicate a relatively healthy project. The position of the calculated average within the inner circle of the spiderweb signifies a relatively good individual score for each issue. The calculated range stays within the second inner circle, signifying only a slight disagreement in relation to individual scores.

Next, the calculation for alignment using the FAHP method and its results are shown below. The ranks of the alignment issues were analyzed in MATLAB (eigenvalue and eigenvector computation). The results of the FAHP in terms of the eigenvector were calculated as the transpose of the matrix A(I).

$A(I)^T$ = [0.950514,0.940228,0.848763,0.838198,0.748679,0.772032,0.881012,0.899917,1.0,0.881012]

λ_{max} was computed to be 10.11. Using Equation 2, the consistency index ν was computed as

$\nu = \frac{10.11-10}{10-1} = 0.0122 < 0.1$; hence, the matrix is consistent.

The recalculated Alignment Thermometer score is shown in Figure 7 and its range and average are provided in Figure 8.

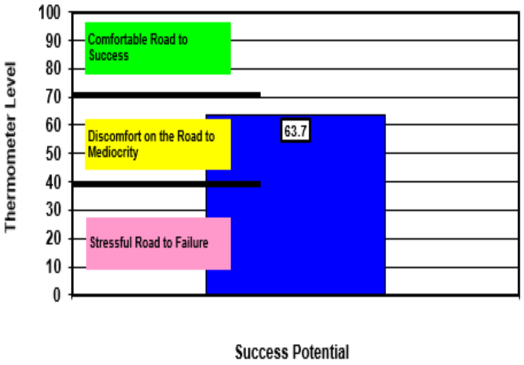


Figure 7: Recalculated alignment score using the FAHP method

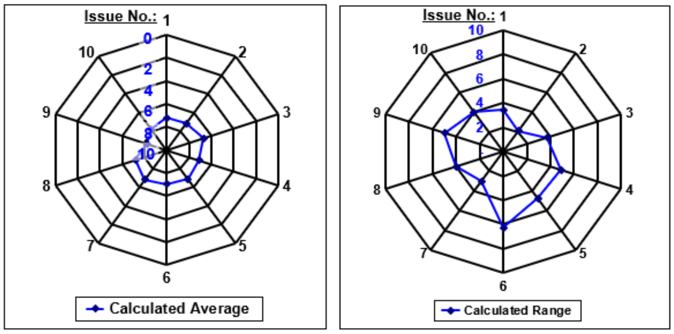


Figure 8: Range and average of alignment issues using the FAHP method

These alignment values were adjusted using Equation 3 by multiplying each respondent's value by their respective weight (A(I)) for all stakeholders. The results show a meaningful difference in the Alignment Thermometer score, which was enough to label the project's road to success mediocre. This result is significant in that the FAHP method was able to capture the success rate of alignments whose scores lie around the boundaries of success or failure. In this specific case, barriers to alignment were underestimated in the CII approach. Furthermore, the FAHP approach was able to capture disagreements in cost and schedule prioritization, team-meeting productivity, and trust. This is very important in that these issues cover a broad range of spectrums within the ten alignment barriers, namely, cultural, information, and tools. The three issues (most importantly trust) tended to be within the third level of the spiderweb, which typically necessitates recalculations, team meetings, and further discussions to avoid future failures.

The PDRI scope definition calculation was computed for PDRI 2i (detailed scope definition). This was assumed to be the representative PDRI level that can be used for comparing the two approaches as it is carried out during the detailed scope phase of the project. The CII Excel template was used to carry out calculations for both approaches while incorporating weights for the FRBS approach (as mentioned in Section 3).

The result of the PDRI calculation using the CII method is 446. This is the normalized score for the scope definition at phase gate 2i (during the detailed scope stage). This number is just below the typical max threshold for the project, indicating that the project had a definition level that did not expose it to unknown risks. The corresponding PDRI chart is shown in Figure 9.

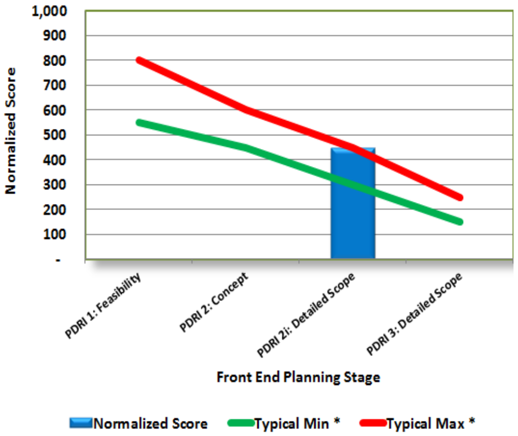


Figure 9: PDRI chart summary (CII)

For the PDRI calculation using the FRBS, three experts were selected to fill out the evaluation form for PDRI-Buildings. Their profile regarding the weighting criteria and their corresponding weight, calculated using Equation 4, is shown in Table 3.

Table 3: Weights for each expert who participated in scoring the PDRI

Expert	General Experience	Specific Experience	Education	Score	Weight
Expert 1	2	0	5	1.83	0.134
Expert 2	9	5	8	4.05	0.297
Expert 3	12	6	13	7.74	0.568

The final weighted and normalized PDRI score, calculated using Equation 5, is 494, as shown in Figure 10.

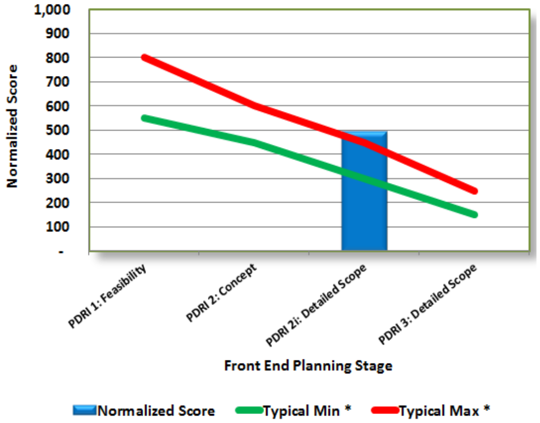


Figure 10: PDRI chart summary (FRBS)

This result shows that the scope definition score is just above the typical max threshold, indicating the need to be cognizant of unknown risks. The result is a very good reflection of the need to consider expert inputs in relation to their knowledge of the specific type of project, their general experience, and their level of education. The PDRI is usually scored in a consensus building process, wherein one voice may dominate. In that scenario, the result can become skewed towards the opinion of a person who may be more vocal or persuasive or who holds a position of relative importance (e.g., affiliation to the owner).

6 CONCLUSIONS AND FUTURE STUDIES

This paper highlights the importance of carrying out a systematic FEP procedure for the overall success of project objectives. The two primary methodologies (i.e., the Alignment Thermometer and the PDRI), usually used in conjunction at different parts of pre-project planning, are critical for capturing many uncertainties that surround a project. Recognizing these uncertainties and addressing them using a structured format can improve decision-making.

This study shows that although the frameworks developed by CII are important for the FEP process, the nature of the uncertainties that surround construction can create a considerable disparity of results. This paper has shown that proper ranking of alignment issues using the FAHP and the assessment of expert levels in the PDRI using the FRBS improves the final results for both scores, indicating that more should be done to address uncertainties during the pre-project planning phase.

Future studies will incorporate more linguistic uncertainties in the models for alignment and the PDRI. For example, the level of agreement that is given a score of discrete values between 0 and 10 should be modified to incorporate the gradual change between consequent scores (e.g., having triangular membership functions for strongly disagree, disagree, neutral, agree, and strongly agree). Furthermore, PDRI definition levels should capture more of the linguistic uncertainties ranging from high to low definition levels.

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