A Preliminary Study on AWP for Optimizing SMR BOP Construction Schedules

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1. Introduction

NPP construction is a large-scale, long-term project characterized by stringent regulatory requirements and complex EPC interfaces [1]. Schedule delays in NPP projects have been associated with design changes, productivity issues, and inadequate engineering support [2]. Some large reactor (LR) projects in Korea have experienced delays of several years. Internationally, the construction periods of U.S. Vogtle Units 3 and 4 were more than twice their planned durations [3].

Advanced Work Packaging (AWP) has been adopted in the petrochemical industry as an approach to reducing construction delays. AWP integrates EPC activities around the planned construction sequence so that drawings, materials, labor, and other resources are ready before work begins [4]. However, AWP application to NPP construction remains limited. SMRs may be suitable for AWP because of standardized designs and modularization, while the BOP scope of SMR construction still involves traditional site work and complex interfaces.

A previous study compared AWP-based schedule structures for LR projects, with a primary focus on the Reactor Containment Building (RCB) [5]. Studies analyzing NPP construction delay cases from an AWP perspective are limited. Accordingly, this study focuses on the BOP to identify delay factors and mitigation strategies related to AWP from representative LR cases and literature, and evaluates their applicability to SMR BOP construction through a two-round Delphi survey.

2. Literature Review

2.1 Framework of AWP

AWP is a project execution methodology developed through industry efforts led by the Construction Owners Association of Alberta (COAA) and the Construction Industry Institute (CII) to improve planning and coordination in industrial construction [4]. CII formally adopted AWP as a Best Practice in IR 272-2. AWP integrates engineering, procurement, construction, and project management through work packaging from the early planning stage, with the aim of reducing productivity losses caused by poor planning and coordination.

The AWP execution framework includes the Path of Construction (POC), Engineering Work Packages (EWP), and Procurement Work Packages (PWP) during Interactive Planning, together with Installation Work Packages (IWP) during Workface Planning and Constraint Management [4]. Previous studies have identified organizational maturity, data standards, system interoperability, planning ambiguity, and capability gaps as important factors affecting AWP implementation [6].

2.2 Schedule Delay Characteristics of NPP

NPP construction differs from general industrial plant construction because of complex regulatory and licensing interfaces, the need to manage long-lead equipment, and a system-based turnover structure [1]. Incomplete design and drawing changes are major schedule delay factors in NPP projects. Procurement delays can also cause labor idle time and disruption to subsequent construction activities [2]. Regulatory and licensing requirements may further restrict the release and execution of construction work [7].

3. Research Method

3.1 Research Design

This study combines NPP construction delay-case analysis with a two-round Delphi survey. In the first stage, 10 delay cases from domestic and overseas LR construction projects were analyzed by AWP component to identify major delay factors and possible mitigation strategies. These factors and strategies were then used to develop the Delphi questionnaire. In the second stage, the questionnaire was administered over two rounds to evaluate expert agreement on the applicability and expected effectiveness of the AWP-based mitigation strategies. First-round statistical results were provided to the panel before the second round so that the experts could reconsider their responses.

3.2 Case Analysis

The case analysis covered 10 delay cases: six from domestic fast-track large NPP construction projects and four from public reports on the U.S. Vogtle Units 3 and 4. The scope was limited to the BOP area, excluding standardized major equipment such as the NSSS and turbine generator systems as well as delays caused by political or social factors. Each case was analyzed in three steps: (1) identification of the relevant AWP component, (2) analysis of the structural cause of delay in the LR case, and (3) assessment of the expected effect

under SMR application. The expected effects were classified as root-cause controllable, preventable, impact mitigable, or uncontrollable.

3.3 Delphi Expert Panel and Procedure

Seventeen experts with more than 10 years of practical NPP construction experience were selected from owner, engineering, and construction organizations. Fifteen experts (88.2%) responded to the first round, and all 15 participated in the second round. The 15 survey items were generated by linking the seven delay factors identified from the 10 LR cases with the corresponding AWP components and mitigation strategies. The questionnaire used a 5-point Likert scale and covered six areas: AWP adoption effect, design/licensing, equipment procurement, schedule interference, quality/rework, and overall effect. Open-ended questions were also included to collect additional expert opinions.

3.4 Data Processing

The survey data were analyzed using SPSS 32.0. Mean (M) and standard deviation (SD) were calculated for each item. Content validity was evaluated using the Content Validity Ratio (CVR) proposed by Lawshe [8]. CVR was calculated as follows:

$$CVR = \frac{n_e - (N/2)}{N/2} \quad (1)$$

where n_e is the number of panelists rating an item as essential and (N) is the total number of panelists. For a panel of 15 experts, a CVR of .49 or higher was used as the minimum criterion [9]. The Degree of Convergence was calculated using the first and third quartiles to assess the dispersion of expert responses:

$$Degree\ of\ Convergence = \frac{Q_3 - Q_1}{2} \quad (2)$$

where Q_1 and Q_3 represent the first and third quartiles, respectively. A value closer to 0 indicates greater convergence of expert opinions. The Degree of Consensus was calculated based on the interquartile range relative to the median:

$$Degree\ of\ Consensus = 1 - \frac{Q_3 - Q_1}{M_{dn}} \quad (3)$$

A value closer to 1 indicates a higher level of consensus among the experts. Reliability analysis of the 15 items yielded Cronbach's α values of .740 (N=15) in the first round and .709 (N=15) in the second round, indicating acceptable internal consistency. An item was classified as 'consensus reached' when all four criteria were satisfied: mean ≥ 4.0, Degree of Consensus ≥ .75, Degree of Convergence < .50, and CVR ≥ .49. Items that met the consensus-related criteria but not the CVR criterion were classified as 'reconfirmation,' while items that did not meet either criterion were classified as 're-evaluation.' The same criteria were applied in both Delphi rounds.

4. Results

4.1 Case Analysis Results

Of the 10 cases analyzed, seven were classified as root-cause controllable, one as preventable, and two as impact mitigable. PWP was mainly associated with procurement-delay cases, while POC was associated with construction-sequence and workspace-interference cases. IWP was related to quality and rework cases, and EWP was related to design incompleteness and unconfirmed design-code cases. Table 1 summarizes the case analysis results.

Table 1. Summary of case analysis by AWP component

No	Category	Delay Case	Related AWP	Classification
1	Domestic	Work-area hold due to delayed permit approval	Constraint Mgmt.	Impact-mitigable
2		Captive equipment delivery delay	PWP	Cause controllable
3		Access-route blockage from inadequate construction sequencing	POC	Cause controllable
4		Structural delay from delayed delivery of large equipment	PWP	Cause controllable
5		Fire-protection piping delay from an unconfirmed design code	EWP	Impact-mitigable (partial)
6		Long-lead piping material procurement delay	PWP	Cause controllable
7	Overseas	AP1000 construction starts with incomplete design	EWP	Preventable
8		Work-front congestion and poor sequencing	POC/CWP	Cause controllable
9		Cable-clearance non-compliance; raceway reinstallation	IWP	Cause controllable
10		Shortage of skilled labor; quality incident and rework	IWP	Cause controllable (partial)

The structural causes identified from the 10 LR delay cases were grouped into four factors: fast-track practices, separation among EPC entities, insufficient integrated project management, and existing site inertia. The case analysis indicates that several delay mechanisms observed in LR projects may be prevented or mitigated by applying the corresponding AWP components during the planning stage.

4.2 Delay Factors and Mitigation Strategies

Analysis of the domestic and overseas NPP construction delay cases and related literature identified seven major delay factors associated with AWP application, together with the AWP component and mitigation strategy suited to addressing each factor.

Table 2 summarizes the delay factors, related AWP components, related cases, corresponding mitigation strategies, and supporting references.

Table 2. AWP-based delay factors and mitigation strategies

No	Delay Factor	AWP Element	Delay Case(s) No.	Mitigation Strategy	Ref.
1	Incomplete Design	EWP	5, 7	Align EWP priorities with the construction sequence	[2]
2	Licensing/Regulatory Issues	Constraint Management	1	Resolve constraints and coordinate licensing before work release	[7]
3	Procurement	PWP	2, 4, 6	Procure materials in line with the CWP sequence; align the procurement schedule with the construction schedule	[2]
4	Workspace Interference	POC/CWP	3	Review construction sequence using 3D/4D modeling	[4]
5	Sequence & Interface Coordination	POC/CWP	8	Integrate work-front into POC & CWP planning	[4]
6	Non-Compliance with Quality Standards	IWP	9	Verify labor constraints and construction quality requirements before work execution	[4]
7	Labor Shortage & Rework	IWP	10	Verify skilled labor qualifications before work release	[6]

The identified delay factors and mitigation strategies served as the basis for developing the Delphi survey items described below.

4.3 Delphi Survey Results

Based on the delay factors and mitigation strategies identified in Section 4.2, a total of 15 Delphi survey items were developed. The classification of survey items by category and the results of the two survey rounds are presented in Table 3.

Table 3. Delphi survey items and results by area (N=15)

Category	Item	Mean		Degree of Consensus		Degree of Convergence		CVR	
		R1	R2	R1	R2	R1	R2	R1	R2
AWP Adoption Effect	Q1. Applicability of AWP to NPP Construction	4.00	4.00	1.00	1.00	0.00	0.00	0.60	0.60
	Q2. AWP effectiveness in reducing SMR BOP delays	4.00	4.00	0.88	0.88	0.25	0.25	0.60	0.60
	Q3. Compatibility with SMR construction characteristics	3.47	3.13	0.63	0.68	0.75	0.50	0.20	- 0.20
Design & Licensing	Q4. EWP prioritization reduces design errors and changes	3.67	3.67	0.75	0.75	0.50	0.50	0.20	0.20
	Q5. Constraint management mitigates licensing delays	3.47	3.00	0.38	0.33	1.25	1.00	0.07	- 0.33
	Q6. Stakeholder consultation reduces licensing delays	4.00	3.47	0.50	0.68	1.00	0.50	0.33	- 0.07
Procurement	Q7. PWP prioritization addresses delivery delays	4.13	4.13	0.88	0.88	0.25	0.25	0.73	0.73
	Q8. Relative efficiency of PWP for SMR	3.93	3.93	0.88	0.88	0.25	0.25	0.60	0.60
	Q9. IWP management reduces field labor idle time	3.93	3.93	1.00	1.00	0.00	0.00	0.73	0.73
Schedule Interference	Q10. POC (3D/4D pre-review) reduces work interference	4.27	4.27	0.75	0.75	0.50	0.50	0.60	0.60
	Q11. POC-based Sequence Coordination reduces work interference	3.80	3.80	1.00	1.00	0.00	0.00	0.60	0.60
Quality & Rework	Q12. Rework reduction from AWP application	3.00	3.07	0.50	0.68	1.00	0.50	- 0.07	- 0.33
	Q13. Quality management improvement from AWP application	3.33	3.33	0.75	0.75	0.50	0.50	0.07	0.07
Overall Effect	Q14. Overall schedule delay reduction through AWP	3.53	3.53	0.75	0.75	0.50	0.50	0.20	0.20
	Q15. AWP suitability for domestic SMR projects	3.20	3.13	0.50	0.67	1.00	0.50	- 0.07	- 0.33

In the survey results, expert consensus was reached for the applicability of AWP to NPP construction, SMR BOP delay reduction, and PWP-based procurement prioritization (R2 mean = 4.13, CVR = 0.73), reflecting strong support for early procurement and schedule-sequencing measures. Schedule interference also received favorable evaluations, though the convergence criterion was not fully satisfied.

In contrast, several items did not reach full consensus: compatibility with SMR construction characteristics (R2 mean = 3.13, CVR = -0.20), constraint management for licensing delays (R2 mean = 3.00, CVR = -0.33), rework reduction (R2 mean = 3.07, CVR = -0.33), and quality-management improvement (R2 mean = 3.33, CVR = 0.07). Overall schedule delay reduction and AWP suitability for domestic SMR projects also failed to meet the full consensus criteria. This pattern suggests greater uncertainty regarding AWP effectiveness in areas influenced by regulatory and organizational factors.

The open-ended responses frequently cited material delivery and design delays as issues AWP could mitigate, and identified insufficient SMR construction experience, limited manpower, and the lack of a defined AWP organization as key implementation barriers.

5. Discussion and Conclusion

This study examined the applicability of AWP to SMR BOP construction using domestic and overseas LR delay cases and a two-round Delphi survey. Expert agreement was relatively strong for equipment procurement and schedule interference. In practical terms, the results suggest that early AWP implementation in SMR BOP should give priority to PWP-based procurement planning and POC-based construction-sequence and workspace planning.

These approaches can help align equipment and material delivery with field priorities and reduce work stoppages caused by sequence or access conflicts. In contrast, lower agreement in the design/licensing and quality/rework areas indicates that AWP alone may not be sufficient because these issues are also affected by regulatory decisions, design maturity, availability of skilled personnel and organizational systems beyond the scope of work packaging.

This study has certain limitations. The analysis was based on 10 LR delay cases and expert judgment rather than schedule data from an actual SMR project, and the Delphi results were based on 15 respondents who completed both rounds. Therefore, the findings should be interpreted as preliminary evidence of AWP applicability rather than a direct measurement of schedule reduction.

Future research should apply the proposed AWP strategies to actual or pilot SMR BOP projects and compare baseline and AWP-based schedules using actual project data, while also examining organizational readiness, contractual requirements, digital integration, and regulatory interfaces required for effective AWP implementation.

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