Strategic Modularization for Efficient i-SMR Construction and Deployment

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***Keywords :** Small modular reactors, i-SMR, Modular, Modularization, Construction Package, Critical Path

1. Introduction

The primary advantage of SMRs lies in modularization, which reduces upfront capital and mitigates schedule risks through off-site fabrication and enhanced installation efficiency (Oh et al., 2024; OECD/NEA, 2021). Despite these benefits, research on i-SMR construction scheduling remains limited due to its early R&D stage.

Building upon Lloyd's (2020) methodology, which utilizes power-scaling formulas from reference plants like Sizewell B, this study proposes a construction schedule for the i-SMR using the APR1400 as a baseline. The objective is to identify critical modularization factors and evaluate their impact on schedule reduction, providing a strategic framework for future SMR deployment.

2. Background

2.1 Lloyd's Methodology and Findings

Lloyd (2020) employs a top-down power scaling methodology to derive SMR estimates - including cost, weight, and schedule - by extrapolating from existing Large Reactor (LR) datasets. This approach establishes a functional relationship between rated power (kWe) and construction magnitude, enabling the transformation of historical LR reference data into preliminary SMR estimates.

The construction duration model is based on as-built data from the Sizewell B NPP, encompassing approximately 3,600 activities categorized into Task Time and Wait Time. Central to this framework is the Degree of Modularization (DoM), defined as the fraction of total work transferred from the construction site to off-site facilities. Modularization is simulated by reducing site-based task durations in proportion to the specific DoM of each activity. This process quantifies the compression of the project's critical path achieved through a controlled factory environment (Lloyd, 2020).

Analysis of varying modularity levels demonstrated that schedule compression is highly dependent on the scope of work moved off-site:

- Low Modularization: Limiting scope to Mechanical, Electrical, and Piping (MEP) systems yields marginal reductions (7-12%), as structural elements remain on the critical path (Lloyd, 2020).

- Full Modularization: Encompassing structural and MEP systems, removes structural work from the on-site critical path to achieve a schedule reduction of over 30% compared to large reactor (Lloyd, 2020).

2.2 i-SMR

The i-SMR integrates SMART's core technology with the commercial pedigree of the APR1400 to form a next-generation platform. The reactor building accommodates four modules with specialized zones for maintenance and refueling (Lim et al., 2025). While the projected FOAK schedule of 48 months for a four-module plant (KISTEP, 2022), verifying the feasibility of the 48-month timeline is challenging due to limited public data.

This study evaluates the appropriateness of the i-SMR construction period by employing a power-scaling approach based on the 58-month APR1400 milestone (Oh & Park, 2004), thereby establishing a technical basis for its implementation.

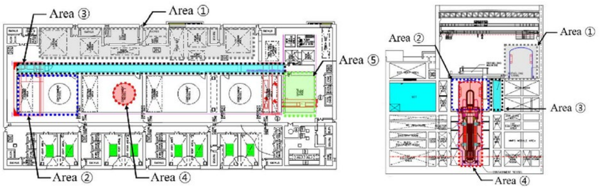

Figure 1. General arrangement of Reactor Building (Lim et al., 2025)

2.3 Construction Package and Critical Path Analysis

The APR1400 utilizes a Construction Package (CP) system to systematically partition construction processes, ensuring organizational efficiency and precise progress tracking. This framework consists of 20 distinct packages categorized into five primary disciplines: C (Civil), A (Architecture), M (Mechanical System), P

(Piping and Insulation), and E (Electrical and Instrumentation & Control System) (Moon et al., 2012).

Data from the APR1400 Level III Integrated Project Schedule (IPS) indicates that a two-unit project encompasses between 3,588 and 3,712 construction activities (Kim, 2017). Although thousands of tasks are managed concurrently, the total project duration is governed by the Critical Path - the specific sequence of activities that determines the shortest possible completion time.

As illustrated in Table 1, the APR1400 critical path is primarily concentrated within five key CPs: Foundation Excavation (C1), Main Building Construction (A1), General Equipment Installation (M1), Turbine Generator Installation (M3), and Piping Installation (P1) (Chae and Jung, 2025a).

This study analyzes these activities to identify management priorities. By extending this analysis to the i-SMR project, we aim to observe potential shifts in the critical path.

Table 1. Activities and Critical Paths by CPs of APR1400 (Chae and Jung, 2025a)

No.	Package	Activities	Critical Path
C1	Foundation Excavation	Excavation, RCB Basemat	○
C2	Concrete Production	Plant Concrete Facilities	
C3	Outdoor Underground	Yard Work (Installation)	
C4	Cooling Water System	Cooling Water Structure Work	
Y1	Underwater Drainage	Yard Work (Drainage)	
A1	Construction of Main Building	FR&P Wall, Dome, Strucural Steel	○
A2	Architectural Finishing Work	Install Elevator & Equipment	
A3	Painting Work	Painting & Coating	
M1	Equipment Installation	Install Equipment, Wall/Dome Liner	○
M2	Condenser Installation	Re-Fabrication and Erect Condenser	
M3	Turbine Generator	Install Turbine Components	○
M4	HVAC Installation	Install HVAC Duct & Equipment	
M5	Nuclear Steam Supply System	Install RC Pump, Set Reactor Vessel	
M6	On-Site Assembly Tank	Yard Tanks Installation	
P1	Piping Installation	Install L/B, S/B Pipe & Support	○
P2	Insulation Work	Pipe Insulation	
E1 E2 E3	Electrical EQ Cable Switchyard	Cable Tray, Elect. Equipment, Conduit, Cabling	
E4	Instrumentation and Control	Install I&C Equipment	

3. Methodology

3.1 Phase 1: Activity Selection and Integration

The construction schedule for two units of the APR1400 reactor typically comprises approximately 3,600 activities (Kim, 2017). For the purpose of developing a streamlined SMR schedule from this LR reference, a structured five-step procedure was established as a development framework, as depicted in Figure 2. This methodology assumes that the core SMR scheduling logic can be derived through the following systematic refinements:

■ Step 1. Selection of Target Buildings

To define the scope of the model, the Reactor Containment Building (RCB) and Turbine Generator Building (TGB) of a single unit were selected from the major APR1400 buildings, assuming their dominance on the critical path represents the most significant scheduling impact.

■ Step 2. Exclusion of Sub-construction Disciplines

Under the assumption that certain sub-disciplines have minimal influence on the overall sequencing for this high-level schedule, disciplines such as painting, finishing, and HVAC were excluded.

■ Step 3. Elimination of Non-scalable or Non-critical Activities

Activities deemed not directly applicable to SMR construction, highly design-specific, or unlikely to form part of the critical path (e.g., sump liner, embedded piping, and conduit) were systematically removed from the reference set.

■ Step 4. Integration of Activities

The remaining activities were consolidated by discipline and modularity. In this step, it was assumed that similar structural, piping, and electrical tasks could be merged, while major Nuclear Steam Supply System (NSSS) and turbine components were grouped into unified tasks to reflect the specific modular design characteristics of SMR.

■ Step 5. Adjustment of Key Activities

The integrated activities were finally refined to align with i-SMR characteristics by removing redundancies and standardizing terminology. This proposed process resulted in 90 main activities, which serve as the foundational framework for the SMR construction schedule developed in this study.

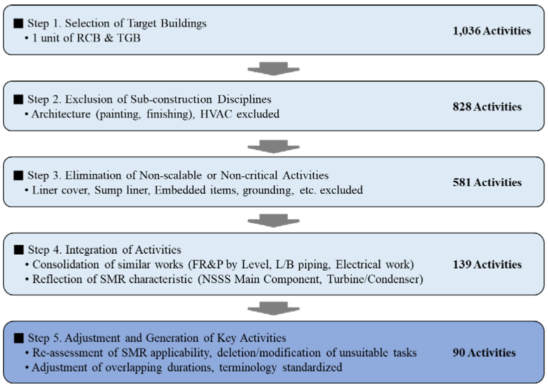

Figure 2. Process for activity selection and integration

3.2 Phase 2: Development of i-SMR Scheduling

3.2.1 Top Down Modeling: Power Scaling

Top-down estimation methods are appropriate when detailed design information is unavailable and during preliminary planning stages when fundamental changes in design or strategy are likely. Power scaling is widely applied in the nuclear industry for estimating project costs (OECD/NEA, 2011)

In Equation 1, subscripts i and ref denote the reactor under consideration and the reference baseline reactor. Power represents rated capacity (kWe), while Parameter refers to module weight, task duration, or cost. The scaling exponent n was adopted from historical data in the Nuclear Energy Data Base (NEDB) (Lloyd, 2020), with specific exponents categorized in Table 2.

$$Parameter_i = Parameter_{ref} \left(\frac{Power_i}{Power_{ref}}\right)^n$$

Equation 1. Power scaling equation (Lloyd, 2020)

Table 2. Power scaling exponents (Lloyd, 2020)

Account Name & Number	Scaling xponent, n
Land & Land Rights	0.00
21 - Structures & Improvements	0.59
22 - Reactor/Boiler Plant Equipment	0.53
23 - Turbine Plant Equipment	0.83
24 - Electric Plant Equipment	0.49
25 - Miscellaneous Plant Equipment	0.59
26 - Main Condenser Heat Rejection	1.06

3.2.2 Build Schedule Model Calibration

In the framework proposed by Lloyd and Roulstone (2018), schedule time is distinguished between task duration (on-site activities like FR&P, and M&E installation) and wait time (testing or preceding works). Figure 3 shows that one portion of time is scaled via power exponents based on reactor capacity, while the other remains constant. This method is applied to both time types to enhance model flexibility.

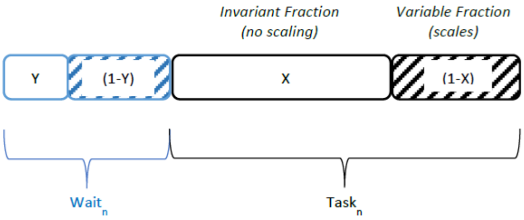

Figure 3. Visual representation of the scheduling model illustrating invariant (empty boxes) and variant (shaded boxes) fractions for both wait times (blue) and task times (black) for activity n (Lloyd & Roulstone, 2018)

Lloyd calibrated the build schedule model using the Berthélemy and Escobar-Rangel U.S. & France model to identify scaling values for task time (T) and wait time (W) (Lloyd and Roulstone, 2018; Berthélemy and Escobar-Rangel, 2015). The "Scaling Case" assumes T and W scale equally with reactor capacity. Figure 4 shows that the historical trend is reproduced when T and W are set to 0.4, meaning 40% of activities scale while 60% remain constant (Lloyd, 2020).

This study adopts Scaling Case II ($T=W=0.4$) as the reference framework, as it has been shown to replicate the Berthélemy trend and align closely with the critical path observed in large reactor data.

Consequently, this framework was utilized to simulate the 90 key activities identified for the i-SMR construction schedule. Furthermore, to comply with the confidentiality requirements of the APR1400 dataset, a 5% random variance was applied to the scaling of activity durations.

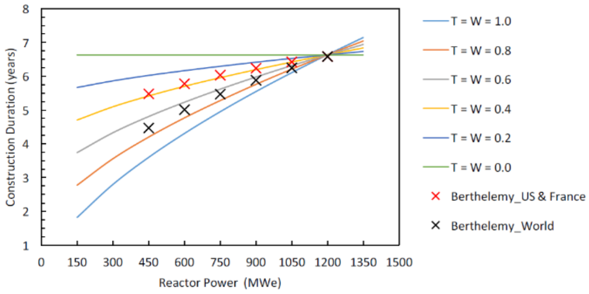

Figure 4. Scaling Case model: Task time (T) and wait time (W) scale equally with reactor size, with T = W for all values. (Lloyd, 2020)

3.2.3 Application of Modularization

In this study, the maximum feasible value DoM_{max} was estimated by synthesizing the modularization scheme, reactor size, and transportation constraints. Within the simulation, DoM_{max} is determined through the Stone & Webster scheme, allowances for special transportation, and the Modular Division Factor (MDF). Specifically, the MDF was set to 3 to balance transportability with the prevention of excessive subdivision (Lloyd, 2020).

As illustrated in Figure 5, structural steel, precast concrete, and mechanical modules exhibit high DoM values, though their contribution decreases as reactor power increases. For the 680 MWe i-SMR, linear interpolation of the overall DoM_{max} indicates a maximum value of 0.4. Based on this analytical approach, the DoM index in this study is capped at 0.4, with trade-specific DoM values allocated under the condition that the total does not exceed this limit.

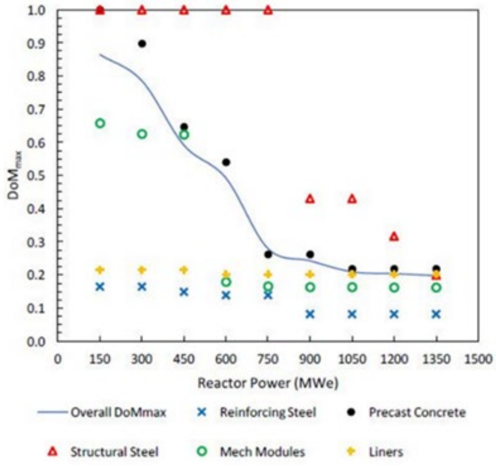

Figure 5. Transportable weight fraction of modules (DOMmax) by module type (MDF = 3) (Lloyd, 2020)

In the proposed model, modularization reduces on-site task duration by transferring work off-site, with the relocated portion replaced by on-site assembly estimated at 5% of the baseline duration (EMWG, 2007). This adjustment is captured in Equation 2, where $\mathrm{t}_{\text{modular task,i}}$ represents the modified on-site time (Lloyd, 2020):

$$t_{modular\ task,i} = (1 - DoM)t_{baseline\ task,i} + 0.05(DoM)t_{baseline\ task,i}$$

Equation 2. Residual on-site construction time after modularization (Lloyd, 2020)

Similarly, wait time is adjusted based on activity dependencies. As shown in Equations 3 and 4, SS wait time is reduced in proportion to the DoM, while FS wait time remains constant to ensure consistency in the schedule's sequential logic (Lloyd, 2020).

$$t_{S-S\ modular\ wait,i} = (1 - DoM)t_{S-S\ baseline\ wait,i}$$

Equation 3. Residual on-site wait time for S-S connection (Lloyd, 2020)

$$t_{F-S\ modular\ wait,i} = t_{F-S\ baseline\ wait,i}$$

Equation 4. Residual on-site wait time for F-S connection (Lloyd, 2020)

4. Result

4.1 Construction Schedule Scenarios by degree of modularization

Following the categorization methodology proposed by Chai and Jung (2025b), four distinct scenarios were defined based on the degree of off-site work transfer to evaluate these effects.

■ Scenario 1 (Baseline, Non-Modularization): Represents a traditional stick-built baseline with no modularization applied.

■ Scenario 2 (Low modularization): Modularization is limited to specific mechanical components and steel structures.

■ Scenario 3 (Medium modularization): The scope expands to include mechanical and steel structures alongside major civil works, such as precast elements and steel-concrete (SC) modules.

■ Scenario 4 (Full modularization): A comprehensive approach where mechanical, steel, civil, electrical, instrumentation, and auxiliary systems are fully modularized.

4.1.1 Non-Modularization Scenario (Scenario 1)

The simulation analysis estimates that the construction duration of the i-SMR baseline is 57.3 months. Figure 6 and Table 3 present the shifts observed in the critical paths between the APR1400 and the i-SMR model. These changes can be characterized by two primary transitions.

First, M1 (Liner Installation) and M3 (Turbine Generator Installation) transitioned from critical to non-critical activities. This shift is likely attributable to the assumption that M1 operates in parallel with FR&P activities and that M3 is simplified within the SMR framework.

Conversely, M5 (NSSS Installation) and E (Electrical Work) emerged as new critical path activities within the model. M5, including reactor vessel placement, is identified as a core sequence due to the i-SMR's integral configuration, directly influencing the Cold Hydrostatic Test (CHT). Similarly, the model indicates that electrical work exerts a determining impact on the Hot Functional Test (HFT); although the building footprint is smaller, the complexity of electrical systems remains unchanged, thereby potentially amplifying their relative influence on the overall schedule.

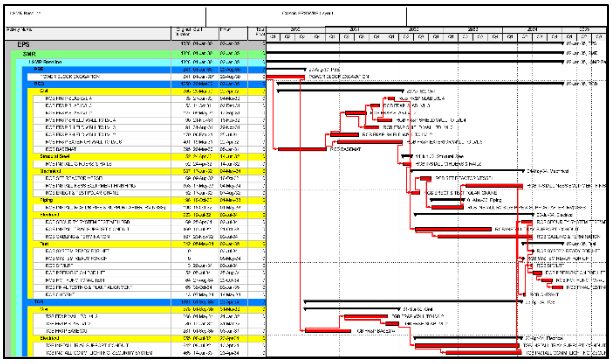

Figure 6. Critical Path of the i-SMR Construction Schedule under Non-Modularization (Scenario 1)

Table 3. Comparison of Critical Paths by Packages between APR1400 and i-SMR

PKG No.	Package	LR	i-SMR Baseline
C1	Foundation Excavation	○	○
A1	Construction of Main Building	○	○
M1	General Equipment Installation	○	
M3	Turbine Generator Installation	○	
M4	HVAC Installation		
M5	Nuclear Steam Supply System		○
P1	Piping Installation	○	○
E1 E2 E3	Electrical Equipment Cable Laying and Wiring Outdoor Switchyard		○

4.1.2 Low Modularization (Scenario 2)

Figure 7 illustrates that under the 'low' extent of modularization scenario, which includes mechanical systems, piping, equipment, and steel structures, the construction duration remains identical to the baseline.

This result suggests that modularization limited to mechanical systems, piping, equipment, and steel structures provides only marginal benefits, as the associated advantages are absorbed into other scheduling activities rather than leading to overall time savings.

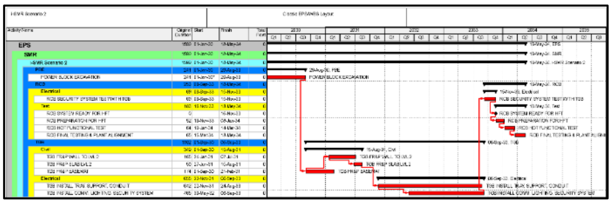

Figure 7. Critical Path of the i-SMR Construction Schedule under Low Modularization (Scenario 2)

4.1.3 Medium Modularization (Scenario 3)

Figure 8 illustrates that under the 'Medium' level of modularization, which expands to include major civil works, the construction period is shortened by approximately 7.5 months, representing a reduction of over 13%. Consequently, this suggests that meaningful schedule reduction for the SMR project is achievable when modularization is applied to civil works, which constitute the largest share of construction activities.

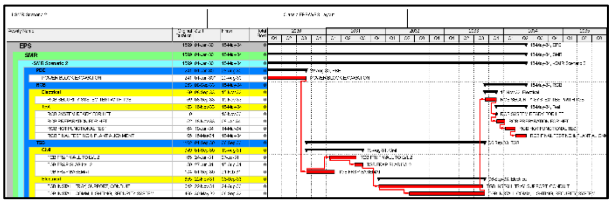

Figure 8. Critical Path of the i-SMR Construction Schedule under Medium Modularization (Scenario 3)

4.1.4 Full Modularization (Scenario 4)

Figure 9 illustrates that under the 'full' extent of modularization, which includes mechanical systems, steel structures, major civil works, electrical and instrumentation systems, and auxiliary systems, there is a significant 11 month schedule reduction, representing over 19% of the total construction period.

This finding indicates that maximizing modularization to include electrical and instrumentation systems in addition to auxiliary packages, such as insulation and coating, could yield further significant reductions in the i-SMR construction timeline.

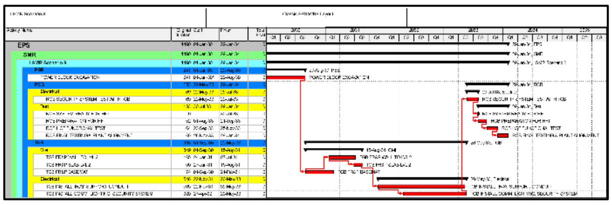

Figure 9. Critical Path of the i-SMR Construction Schedule under Full Modularization (Scenario 4)

Contrary to Lloyd (2020), who suggested that modularizing major civil elements captures most time-saving potential, this study suggests that civil works, combined with Electrical and Instrumentation, Auxiliary Packages significantly influence the i-SMR critical path. While physical plant size is reduced, the scope of these systems remains largely unchanged, amplifying their relative schedule impact. Therefore, to maximize schedule reduction, the results suggest that modularization should extend beyond traditional mechanical and civil domains to include electrical and instrumentation systems.

5. Conclusion

5.1 Change in Construction Schedule

Table 4 compares the baseline i-SMR schedule with construction durations estimated under varying degrees of modularization. The simulation results suggest that while Low modularization yields no significant schedule reduction, the construction period could be decreased by 13.1% under Medium modularization and 19.2% under the Full modularization scenario.

KHNP, the lead organization for i-SMR development, has set a target construction period of 48 months for a first-of-a-kind (FOAK) four-module i-SMR plant (KISTEP, 2022). The findings of this study suggest that achieving this target may require modularization efforts beyond the levels currently applied to domestic nuclear projects. Consequently, the development and implementation of highly advanced full modularization strategies appear essential to meet these aggressive deployment goals.

Table 4. Comparison of the i-SMR construction schedules under different level of modularization

Level of Modularization	**Construction Duration**	**Schedule Reduction**
Scenario 1 None Modularization	57.3 Month	-
Scenario 2 Low Modularization	57.3 Month	No change
Scenario 3 Medium Modularization	49.7 Month	- 7.5 M (13.1%)
Scenario 4 Full Modularization	46.2 Month	- 11 M (19.2%)

5.2 Change in the Critical Path in CPs

Table 5 summarizes the changes in the critical path (CP) of the i-SMR according to the degree of modularization. Within the simulation framework, as modularization is introduced, packages M5 (NSSS system) and P1 (Piping) are no longer included in the critical path. This suggests that modularization effectively reduces the schedule impact of mechanical and piping activities, allowing their durations to be absorbed by parallel processes.

The analysis further indicates that starting from the Medium modularization scenario, where a significant reduction in construction duration is observed, packages C1 (Foundation Excavation), A1 (Main Building Construction), and E1–E3 (Electrical) remain on the critical path. Even in the Full modularization scenario, these specific construction packages continue to dictate the overall timeline, identifying them as the primary drivers of the SMR project schedule.

Table 5. Critical path variations of the i-SMR according to modularization scenarios

PKG NO.	**Scenario 1 'Non'**	**Scenario 2 'Low'**	**Scenario 3 'Medium'**	**Scenario 4 'Full'**
C1	○	○	○	○
A1	○	○	○	○
M5	○			
P1	○			
E1 E2 E3	○	○	○	○

5.3 Limitations and Recommendations

The i-SMR schedule proposed in this study was derived by scaling activities from the APR1400, which may lead to discrepancies as it does not fully reflect the unique design characteristics of the i-SMR. Furthermore, the modeling process uniformly applied the methodology from Lloyd (2020), which is based on international data, and therefore did not account for the specific influences of advanced Korean construction technologies and environments.

Based on the results of the scenario analysis, the following modularization strategies are proposed for the i-SMR:

First, the A1 package is the highest priority because it remains on the critical path across all scenarios. The extensive application of Steel-plate Concrete (SC) technology, complemented by modular dome and steel-structure development, is recommended to optimize this sequence.

Second, modularizing mechanical and piping (M1, P1) systems is a necessary prerequisite. Furthermore, enhancing Electrical and Instrumentation modularization, specifically including MEP systems, is critical for achieving substantial schedule reductions.

Third, auxiliary packages such as insulation and coating should be considered for factory prefabrication. Since these activities occur in the final stages, modularizing them alongside mechanical and electrical systems is projected to maximize the overall reduction in project duration.

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