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Principles For Developing Effective Project Schedules Under Extreme Climate Conditions

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Abstract: The article provides principles for creating efficient project schedules in extreme climatic conditions. The rationale for the relevance of the work is essentially defined, considering recent trends regarding the increasing frequency and magnitude of weather-related catastrophes. The purpose here is to develop a methodology for adaptive planning based on quantitative diagnostics regarding climate, probabilistic windows related to favorable conditions, and the dynamic redistribution of tasks. It will be new in that non-stationary extremes will be integrated within an analysis approach to evaluate changes in parameters regarding climate distributions; climate windows shall be calculated based on multi-year meteorological data and NOW-cast forecasts; adaptive buffers shall be applied within the critical chain by APD rule and modular decomposition of tasks; the digital twin will function to perform operational revision of priorities; finally parametric insurance as well as climate clauses shall be included in contracts. The main conclusions affirm that the application of the above-stated rules allows up to 28% acceleration of the calendar with budget maintenance, reduces downtime uncertainty by 15%, and keeps schedule shifts within 5% of the planned date for up to three years. This paper is likely to find its best audience among project managers, planners, and risk management specialists working in the building construction, infrastructure, and maritime sectors.

Keywords: climate windows, adaptive buffers, non-stationary extreme analysis, digital twin

Introduction

The shift to climate-resilient schedule management is necessary because extreme weather is already becoming more frequent. In 2024, according to Munich Re, global losses from natural disasters totaled USD 320 billion — approximately ninety percent of those losses were attributable to weather-related events; in other words, factors that directly disrupt logistics, supply, and work schedules (MunichRe, 2022). Similar dynamics are observed by the National Centers for Environmental Information (NCEI) in the USA. From 1980 to 2024, the country experienced 403 weather-related disasters costing over $1 billion each. In 2024 alone, the number of such events approached 30, a historical maximum (NCEI, 2023). For project managers, this means that traditional fixed time reserves no longer guarantee sustainable execution of the critical path, and an effective schedule must be based on accurate climate diagnostics for the work region.

A multi-scale diagnosis begins with collecting past meteorological parameters and long-term forecasts. Such forecasts would include, for example, multi-model ensembles, satellite reprojections, and SSP climate scenarios. Another issue that matters is how deep and even the sampling has been, as extremes are sensitive to both temporal resolution and the correction method applied. As practice has shown, surface-based observations in combination with ERA5 or any other global reanalysis data reduce the estimation error for rare storms and heatwaves by up to 15 percent when compared to a single source. This is very important for the techno-economic justification of protective measures. The next step is probability tooling, which involves specialized tools for estimating the probability of extremes and is increasingly used in progressive infrastructure investments. Nonstationary extreme analysis captures distribution parameter drift due to climate change, meaning more accurate results, such as inference regarding the midlife asset one-day rainfall return level probability. A review of the use of such models in coastal engineering reveals that they possess better predictive capabilities than stationary schemes for planning horizons exceeding ten years (Radfar et al., 2023). Along with classical tools such as SPI indices, wind and heat stress threat indicators, non-stationary models form a multi-level risk profile suitable for direct upload into project management software.

The final element of diagnostics is the integration of the resulting climate profile into the pre-project analysis. The international standard ISO 14090 mandates the inclusion of climate vulnerability assessments in the earliest stages of development, ensuring that project decisions regarding routing, drainage system capacity, and seasonal work schedules take probabilistic weather risk metrics into account (ISO, 2019). Practically speaking, this integration is achieved through a single risk matrix in which probabilities and potential impacts on major milestones from each climate hazard are quantitatively assessed. Thereafter, adaptive time reserves and alternative technological routes are articulated as described above. Consequently, the calendar schedule emerges as a dynamic system, rather than just a static network diagram, which reorders tasks upon early warnings of storms or heatwaves while maintaining steady overall project delivery time without a sharp rise in costs.

Materials and Methodology

The study relied on multi-channel meteorological data, including historical ground observation series, global reanalysis from ERA5, multi-model ensembles of seasonal and sub-seasonal forecasts, and SSP scenarios (MunichRe, 2022; NCEI, 2023). Primary data sources included the European Center for Medium-Range Weather Forecasts (ECMWF) ERA5 and NOW-cast forecasts (Blanchonnet, 2014), which reduced the error in estimating rare storms and heatwaves by 15% relative to single datasets (Radfar et al., 2023). To confirm the practical applicability of the methodologies, case studies on coastal engineering in Ireland (Moore et al., 2024), reports on the implementation of digital twins in construction (Ventures Connect, 2024), and the international standard ISO 14090 on assessing climate vulnerability in early design stages (ISO, 2019) were used.

Methodologically, the work included several stages. The first stage was the systematic collection and preprocessing of data, with unification of temporal resolution and correction using reprojection data, ensuring the uniformity of the sample for extreme event analysis. The second stage involved non-stationary extreme analysis to account for the drift of distribution parameters, with a retrospective comparison of the predictive ability of stationary and non-stationary models for planning horizons exceeding ten years (Radfar et al., 2023; Moore et al., 2024). The third stage involved calculating climate windows based on multi-year hourly ERA5 data and SWAN hydrodynamic simulations, with refinement through two- to three-week NOW-cast forecasts (Blanchonnet, 2014; Moore et al., 2024). The fourth stage involved integrating the obtained climate profile into the pre-project analysis, as per ISO 14090, through the development of a risk matrix. Each extreme impact scenario was matched with its corresponding probability and effect on key milestones, forming the basis for adaptive time reserves.

Results and Discussion

The climate window, defined as the minimal continuous interval during which an operation can start and finish without exceeding weather thresholds, is calculated from a multi-year hourly series of wind and wave data and then refined using an ensemble of forecasts over a two- to three-week horizon. For example, an analysis of a twelve-year ERA5 and SWAN dataset for Irish coastal sites shows that turbine operational readiness falls to 80 percent compared to 98 percent onshore, underscoring the necessity of an accurate window instead of a fixed seasonal buffer (Moore et al., 2024).

Downtime models reinforce the probabilistic approach: pairs of Markov chains based on actual metocean conditions generate binary sequences of operation/waiting, after which thousands of synthetic realizations permit estimation of the total downtime distribution for the sequence of operations. A case study in the Tasman Sea demonstrated that this technique reduces uncertainty in downtime estimation compared to single simulations, enabling the selection of a shorter yet statistically reliable window for initiating complex marine transports (Bruijn et al., 2019).

Once window durations and downtime variations are obtained, the scheduler aggregates them into an adaptive buffer following the critical chain methodology. First, an aggressive baseline schedule is constructed in which each task is stripped of individual just-in-case reserves (Cretu, 2025). The total protected portion is relocated to the end of the critical chain as the project buffer. Modern CCPM variants employ the adaptive APD rule, whereby the buffer size is proportional to the square root of the sum of task variances, making protection sensitive to actual rather than declared risk. This rule is recommended in newly modified CCPM schemes for construction (Meabed et al., 2025). In climate-sensitive projects, the buffer is further segmented by season, so that its consumption reflects not only contractor variances but also increases in storm activity. When one-third of the buffer is consumed, the system automatically restructures the task sequence and activates alternative resource routes.

Practical allocation of reserves by phase follows a related principle: early earthwork and foundation cycle tasks receive a minimal cumulative buffer, since they have greater flexibility in shift changes and equipment; super-critical marine or high-rise operations receive an extended buffer tied to the length of the shortest statistically sufficient climate window; finishing and commissioning tasks are often converted into floating packages that can be inserted into emerging periods of favorable weather. Such a sliding reserve, integrated with online monitoring of weather indicators, maintains the total project shift within five percent of the planned completion date over a horizon of up to three years, as confirmed by comparative retrospectives of transportation and energy projects in Northwestern Europe (Moore et al., 2024).

Thus, embedding climate reserves evolves from a dogmatic percentage add-on to a controlled instrument that links probabilistic weather models, adaptive critical chain buffers, and phase-by-phase task redistribution, thereby ensuring schedule resilience without excessive inflation of overall duration.

The dynamic component of the schedule relies on the long-view, short-step concept: strategic decisions are made based on extended and seasonal forecasts covering up to 46 days ahead, while operational adjustments utilize hourly NOW-cast data (Blanchonnet, 2014). This two-scale cycle is supported by global early-warning initiatives: the World Meteorological Organization requires that by 2027 each construction site have reliable weather threat alerts at least 24 hours in advance, and in February 2025 the European Centre for Medium-Range Weather Forecasts commissioned the AI-powered AIFS model, which delivers sub-seasonal probabilistic forecasts with accuracy comparable to the traditional IFS physical scheme but at twice the speed (World Meteorological Organization, 2023).

To turn forecasts into action, their data stream is integrated via API directly into the project management environment and the site’s digital twin. The calculation core automatically compares actual wind, precipitation, and WBGT readings against the climate profile thresholds, then updates each operation’s status to 'ready', 'postponed', or 'requires rescheduling'. Field cases demonstrate that implementing the integration of sensors, the digital twin, and forecasts yields an average schedule acceleration of 28 percent, while simultaneously reducing budget overruns, as task resequencing decisions occur within hours rather than an entire shift (Ventures Connect, 2024).

The operational revision algorithm employs the signal–analyze–resequence rule. When NOW-cast registers a threshold exceedance, the system aggregates incomplete tasks into a pool and classifies them based on duration and resource profile. It then identifies the shortest critical chain while preserving the global buffer, the alternative generator proposes a new sequence, and management approves it at the weekly meeting. Experience with the Last Planner System metrics shows that this approach not only maintains a Percent Planned Complete above 85 percent but also nearly halves the plan-actual gap compared to traditional waterfall schemes (Shehab et al., 2024).

Modularity is based on decomposing large milestones into independent packages that can be moved without cascading delays. Each package is designed with alternatives: for example, external concrete works can be replaced by internal installations, and a daytime shift in extreme heat can be moved to the early morning. This framework integrates flexibly with the adaptive buffer described earlier and maintains even resource loading throughout the project.

Where weather uncertainty is greatest, offsite modular production delivers reliable benefits. A study by the University of South Australia showed that relocating half of critical operations under a factory roof eliminates weather-related delays and saves about 0.6 percent of the estimated cost, equivalent to a significant share of the contractor's profit (University of South Australia, 2023).

Task relocation under adverse weather is impossible without accurate future window estimates. For offshore energy platforms, a twenty-year meteorological analysis along the Irish coast revealed that vessel and crane availability fluctuates between 60% and 87%, compared to near-full onshore availability. Therefore, a flexible schedule must reserve alternative days for marine operations and pre-allocate maintenance crews (Moore et al., 2024).

Thus, dynamic forecasting, digital monitoring, and modular sequencing together produce a self-adjusting network model in which each weather signal triggers a controlled rather than chaotic response, and the overall delivery date remains resilient to climatic uncertainty.

With the transition to the modular schedule described earlier, the next layer of defense is the digital twin, which links weather analytics, the schedule, and actual site conditions. BIM–AI integration is already showing a practical impact: in a recent case involving 20,000 sensors, the system detected early deviations in work progress and proposed real-time corrective scenarios, thereby preventing delays before operations reached the critical path (Chong et al., 2025). When such a twin is deployed to the construction site and updated with minute-by-minute telemetry, it becomes the foundation for an adaptive schedule that automatically changes task status rather than requiring manual meetings. The global market for digital twins was estimated at USD 24.97 billion in 2024 and is forecast to reach USD 155.84 billion by 2030, at a compound annual growth rate (CAGR) of 34.2% from 2025 to 2030, as shown in Figure 1 (Grand View Research, 2023).

Диаграмма

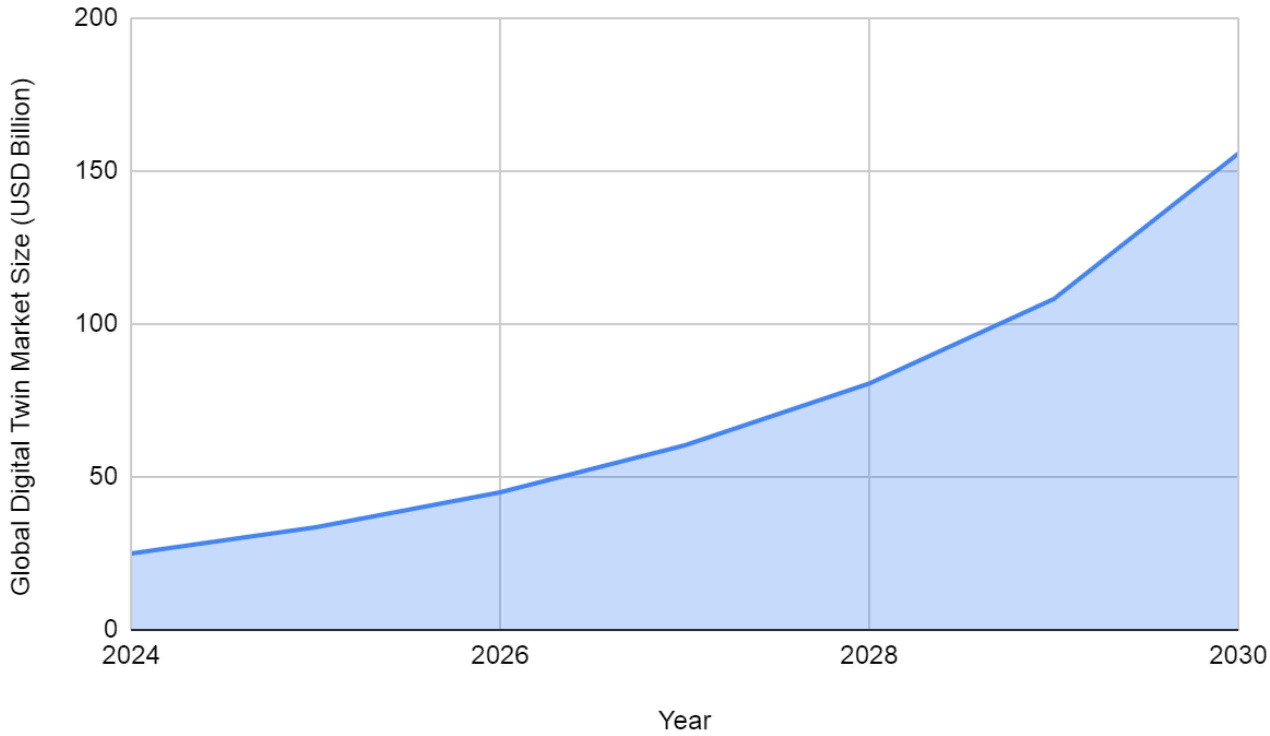

Fig. 1. Digital twin market size (Grand View Research, 2023)

The practical value of the digital twin is enhanced by its what-if capability. The European initiative Destination Earth already employs high-resolution simulations to replay scenarios of future extreme downpours or storms, allowing for the assessment of how planned installations or deliveries respond to anomalous wind gusts two days before the event; the same algorithm also reveals the economic consequences of resource redeployment (IT Pro, 2025). Operational ones complement strategic decisions on a weekly horizon: the global Extremes DT component from ECMWF can rerun forecasts on a 4.4 km grid up to four days ahead, which is sufficient to shift a marine shipment into a reserve window and avoid costly crane idling in port (ECMWF, 2024).

The digital twin operates not only with weather but also with in-plant bottlenecks. A model published in Computers & Industrial Engineering demonstrated that simulating the production flow within the twin allows prediction of bottleneck formation, thereby reducing hidden equipment downtime before an actual queue appears and increasing line throughput without capital investment (Ragazzini et al., 2024). For a construction project, this means that the schedule will automatically reorder resource-constrained operations long before under-utilization of a crane or concrete pump causes cascading delays.

Aggregated assessments confirm the systemic effect: according to Hexagon, the implementation of digital twins increases the operational and service efficiency of assets by an average of thirty-five percent, directly reducing the calendar buffer required for unforeseen events (Hexagon, 2024) (Fig. 2).

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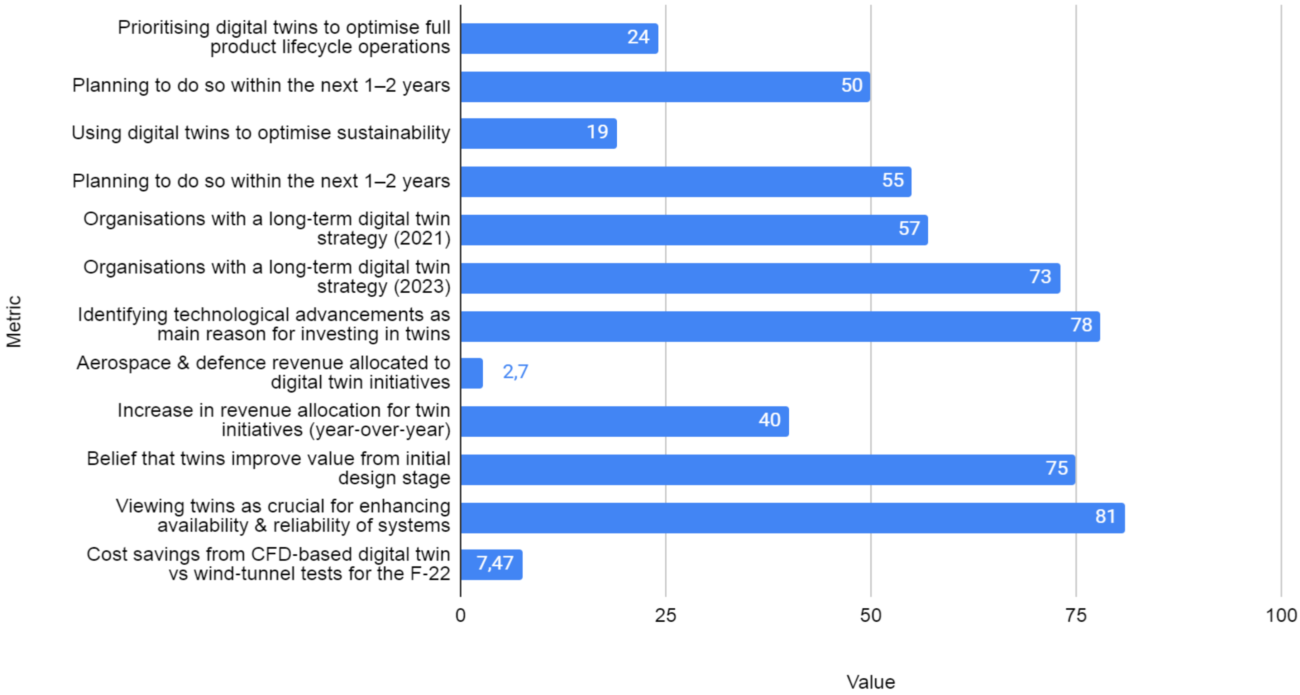

Fig. 2. Digital Twin Adoption and Impact in Aerospace and Defence (Hexagon, 2024)

Each such percentage improvement translates into real days on the schedule, freeing reserve capacity for truly critical climatic deviations addressed in the previous section.

However, schedule resilience ends where supply chains break. Extreme weather is now recognized as the principal logistics risk. An Everstream Analytics report notes that every three weeks, a weather-related billion-dollar loss occurs, and these events most often disrupt delivery schedules for heavy cargo (DC Velocity, 2024). Therefore, contemporary agreements frequently include distinct climate clauses, such as mechanisms for price recalculation upon cost escalation, extended force majeure, and clear delay allocation procedures, as recommended by EPC lawyers in newly updated 2024 templates (Reed Smith, 2024). Where such mechanisms exist, it is determined who pays for a storm before work commences rather than in post-event arbitration.

Insurance solutions complete the financial loop: for chronic heat that prolongs shifts and incapacitates personnel, parametric policies are increasingly used. They trigger payouts based on a simple temperature threshold and close the cash-flow gap almost instantly. According to Aon, heat-related downtime alone costs the U.S. economy USD 100 billion per year, and such policies enable contractors to meet deadlines without sharply increasing receivables (Aon, 2024). The global parametric insurance market was valued at USD 16.2 billion in 2024 and is projected to grow at a compound annual rate of 12.6% from 2025 to 2034 (Ambekar & Wadhwani, 2025) (Fig. 3).

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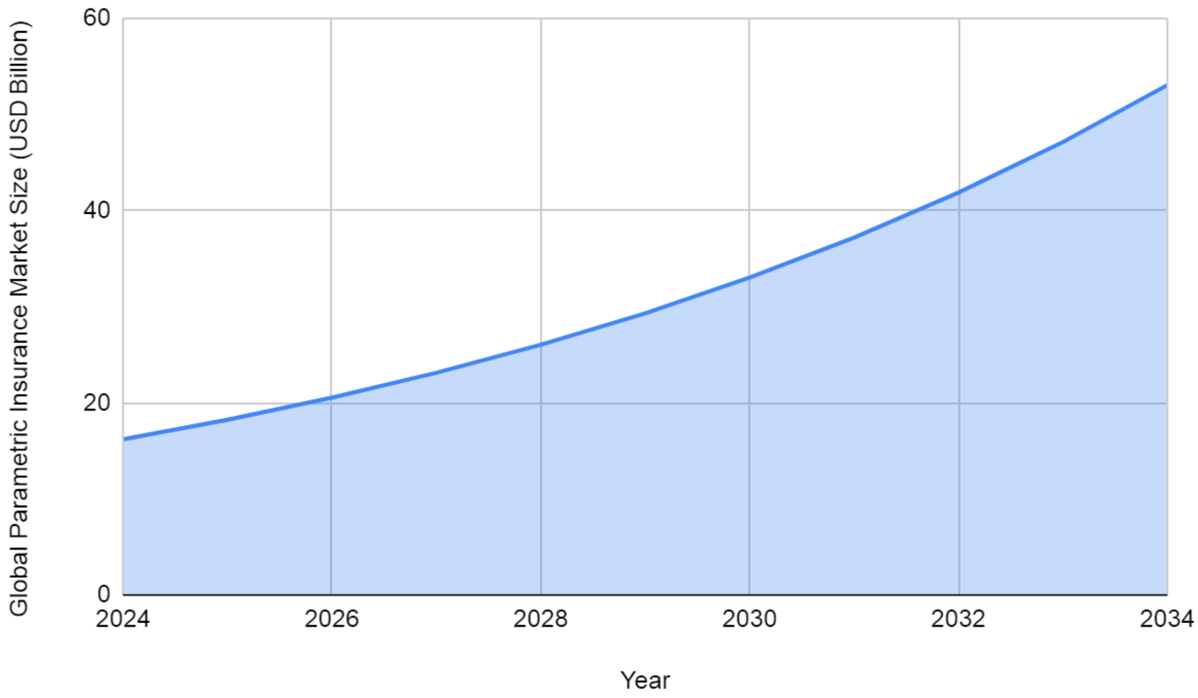

Fig. 3. The global parametric insurance market size (Ambekar & Wadhwani, 2025)

Ultimately, a comprehensive picture requires a direct connection with logistics partners. A supply-chain digital twin described by BCG synchronizes carrier, port, and warehouse data, thereby predicting where a storm or delay in the Suez Canal will force slot reallocation two days in advance (Schuster et al., 2024). If such data feed into the project schedule, material orders automatically shift to another window, or a regional alternate supplier is activated without dispatcher intervention. As a result, the schedule remains live yet predictable: the digital twin detects the threat, the contract provides the basis for risk redistribution, the insurance instrument covers the financial gap, and the logistics network restructures before weather moves from forecast to reality.

Thus, the comprehensive approach—combining quantitative climate diagnostics, probabilistic windows, adaptive critical-chain buffers, and a digital twin—transforms a static network schedule into a dynamic model capable of flexibly responding to extreme weather risks. The integration of multi-model forecasts and API linkage with the project management system enables data-driven decision-making, phased reserve allocation, and parametric insurance, supplementing technical measures with financial instruments. Accordingly, the presented principles form a robust foundation for developing effective schedules under variable climate conditions.

Conclusion

This work substantiates the need to shift from fixed time reserves to dynamic schedules grounded in quantitative climate diagnostics and probabilistic extreme-event models. The systematic collection of multi-channel meteorological data, combined with the use of non-stationary extreme analysis, yields an accurate climate profile for specific locations and seasons, thereby enabling the determination of climate windows with minimal downtime probability. Integration of these profiles into pre-project analysis under ISO 14090 establishes the basis for adaptive reserves and alternative technological pathways that can maintain overall timelines without excessive project duration inflation.

At the operational planning level, implementing critical-chain methods with an adaptive buffer and the signal–analyze–resequence algorithm transforms the calendar schedule into a living system capable of automatically reprioritizing tasks when weather thresholds are exceeded. Use of digital twins and API integration of forecast data permits real-time decisions based on sub-seasonal and NOW-cast predictions, as evidenced by a 28 percent schedule acceleration and reduced budget overruns in field trials. Modular work structures and offsite production further mitigate risks associated with maximal weather unpredictability.

Finally, inclusion of contractual climate clauses and parametric insurance closes the loop by coupling technical measures with financial instruments, ensuring transparent allocation of delay liability and instantaneous compensation upon temperature triggers. Consequently, the integrated approach—combining climate diagnostics, probabilistic windows, adaptive buffers, digital twins, contractual mechanisms, and insurance policies—provides a reliable methodology for crafting effective project schedules amid intensifying extreme climate events, maintaining the balance between schedule resilience and economic efficiency.

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