Scientific journal of Research studies in Future Electrical Engineering, 2025, Vol. 3, No. 1, pp. 1-9

Scientific journal of Research studies
in Future Electrical Engineering
www.journalhi.com/pow/

Data-Driven Project Scheduling for Telecommunication Site Deployment Based on Failure Risk, Energy Performance and Maintenance Constraints

Salar SeyedAhmadi [1,*]

1- Ph.D. in Telecommunication Engineering (Fields and Waves), Urmia University, Urmia, Iran. Email: salar.seyedahmadi@gmail.com.
* Corresponding Author

Abstract

Telecommunication site deployment involves interdependent construction, power installation, radio equipment deployment, testing, and commissioning activities. Conventional project scheduling approaches primarily emphasize activity durations, precedence relationships, and resource availability, while operational failure risk, energy performance, and maintenance constraints are frequently considered separately. This separation can lead to schedules that are feasible from a construction perspective but insufficiently responsive to equipment reliability, energy requirements, and maintenance-related interruptions. This paper develops a methodological framework for integrating these dimensions into data-driven project scheduling for telecommunication site deployment. The proposed framework conceptualizes deployment as a resource-constrained project scheduling problem in which activity durations, failure-related disruption, energy consumption, maintenance availability, and technical precedence relationships jointly influence scheduling decisions. The research adopts a secondary-data-oriented design based on published studies, documented dataset descriptions, and a structured scenario-analysis approach. The framework comprises five components: data preparation, activity and resource modeling, failure-risk characterization, energy and maintenance constraint integration, and multi-objective schedule evaluation. A baseline schedule is conceptually compared with an integrated scheduling alternative, while sensitivity analysis is specified to examine the influence of failure probability and repair duration on expected disruption. Because the underlying raw datasets were not independently obtained and an integrated optimization algorithm was not executed and empirically validated, the numerical scenarios are illustrative rather than observed findings. Consequently, no empirical reduction in project duration, energy consumption, or failure-related delay is claimed. The principal contribution is a transparent methodological structure for coordinating project scheduling with reliability and energy considerations in telecommunication deployment. The framework provides a foundation for future empirical implementation using verified site-level project records, equipment failure histories, energy measurements, and maintenance logs. Its practical value will depend on data quality, constraint calibration, and validation against actual deployment projects.

Keywords: Telecommunication site deployment; resource-constrained project scheduling; failure risk; energy performance; maintenance constraints

1- Introduction

Telecommunication infrastructure deployment requires the coordination of construction activities, power systems, radio equipment, transmission facilities, testing, and commissioning. These activities are interdependent and often compete for limited labor, equipment, technical personnel, and access to deployment sites. Delays in one activity can affect downstream tasks and extend the overall project duration. Research on telecommunication construction has identified schedule overruns as a relevant project-management concern, supporting the need for more systematic planning approaches [1].

Traditional project scheduling methods, including critical-path-based techniques and resource-constrained project scheduling models, provide established tools for representing activity precedence, resource availability, and project completion objectives. However, the resource-constrained project scheduling problem (RCPSP) includes multiple variants and extensions that reflect the complexity of real-world projects, such as uncertainty

in activity duration, alternative execution modes, and additional operational constraints [8]. These extensions are relevant to telecommunication deployment because activities are not always performed under constant resource availability or uniform technical conditions.

One important source of uncertainty is equipment failure. Failures in power supply units, cooling systems, radio equipment, and associated infrastructure can interrupt installation or commissioning activities. When equipment becomes unavailable, the project team may need to allocate additional time for diagnosis, repair, replacement, and retesting. The impact extends beyond the duration of the repair itself when the affected activity lies on the critical path or when downstream resources cannot be reassigned efficiently. Studies examining telecommunication base-station failure events demonstrate the relevance of spatiotemporal failure analysis and prediction for understanding network infrastructure reliability [5]. Research on wireless telecommunication system reliability also provides a basis for considering predictive information when assessing service-related risks [6].

Energy performance is another relevant dimension. Telecommunication sites consume energy through radio equipment, power conversion, cooling, and other supporting systems. Energy demand can vary with equipment configuration, network utilization, ambient conditions, and operating mode. Data-driven monitoring and diagnostic approaches have been investigated for assessing energy performance in telecommunication environments [2,3]. These approaches suggest that energy measurements and equipment operating characteristics can inform infrastructure management. Nevertheless, energy optimization at the operational level does not automatically translate into energy-efficient project execution. Deployment schedules must also consider the timing of energy-intensive activities, equipment availability, commissioning requirements, and the technical conditions under which tasks can be performed.

Maintenance constraints further complicate deployment scheduling. Preventive maintenance windows, restricted access to installed equipment, technician availability, and the need to coordinate installation with operational network requirements can limit when particular activities are feasible. A schedule that ignores these restrictions can produce nominally efficient sequences that cannot be implemented in practice. The challenge is therefore not simply to minimize activity durations but to identify feasible schedules that balance project completion, failure exposure, energy performance, and maintenance requirements.

Recent developments in project scheduling have addressed uncertain durations, alternative execution modes, resource constraints, sustainability, and energy consumption [4,8-10]. These developments provide relevant modeling foundations, but the integration of deployment-specific failure risk, energy performance, and maintenance restrictions requires a coherent representation of their interactions. Failure risk can influence expected activity duration and resource availability; maintenance windows can determine whether work is feasible at a particular time; and energy performance can introduce additional objectives or operational constraints.

Data-driven scheduling offers a potential means of connecting these dimensions. In this context, data-driven does not imply that every parameter is automatically learned by a machine-learning algorithm. Rather, project records, failure histories, equipment energy measurements, and maintenance logs can be used to estimate or calibrate the parameters that govern scheduling decisions. Such a framework must distinguish between directly observed measurements, parameters derived from published evidence, and assumptions introduced for scenario analysis.

The availability of suitable data remains a material challenge. Published telecommunication datasets and studies may document energy measurements or failure events, but access conditions, differences in data structure, and limited linkage between operational and project-level records can restrict their direct use for deployment scheduling. Consequently, a credible methodology must specify how these sources could be mapped to project activities without implying that independent empirical validation has already been completed.

This paper addresses the methodological problem of coordinating failure risk, energy performance, and maintenance constraints within a project scheduling framework for telecommunication site deployment. It focuses on the following research questions:

1. How can failure risk be represented within a resource-constrained schedule for telecommunication site deployment?
2. How can energy performance be incorporated into scheduling objectives or feasibility constraints?
3. How can maintenance windows and maintenance-related resource restrictions be represented without violating activity precedence requirements?

4. How can sensitivity analysis help identify the conditions under which failure risk and repair duration materially affect schedule performance?

The contribution is a structured framework that links these dimensions and identifies the data and validation requirements for future implementation. The paper does not claim to demonstrate a validated improvement in scheduling performance. Instead, it establishes a transparent analytical foundation for an integrated scheduling model and clarifies the distinction between methodological design and empirical evidence.

2- Problem Statement

Telecommunication site deployment is a multi-activity project in which construction, power installation, equipment installation, integration, and commissioning must be coordinated under technical and resource constraints. A conventional schedule can represent activity precedence and nominal durations, but it may not capture the consequences of equipment failure, energy-related operating conditions, or restricted maintenance availability.

The central problem is that these factors can interact. A failure can delay a task, occupy a specialist technician, or require additional testing. A maintenance window can restrict the timing of work or make a resource temporarily unavailable. Energy requirements can constrain equipment operation or influence the preferred timing of particular activities. When these dimensions are evaluated independently, the resulting schedule may underestimate disruption or fail to represent operational feasibility.

The research problem is therefore defined as the development of a scheduling framework that incorporates failure-related uncertainty, energy performance, and maintenance restrictions while preserving precedence and resource feasibility. The framework should support transparent evaluation of alternative schedules and sensitivity to uncertain parameters. Its effectiveness must ultimately be assessed using real project data and a documented optimization procedure. Without these elements, scenario calculations can illustrate the model logic but cannot establish empirical performance improvements.

3- Methodology

3.1 Research design

The study adopts a methodological design based on secondary literature and a structured analytical framework. Its purpose is to define how heterogeneous evidence can be translated into scheduling parameters and constraints. It does not constitute a completed field study, and no new site-level observations are claimed.

The methodology has four principal stages: identifying relevant evidence, defining the scheduling representation, specifying risk-energy-maintenance relationships, and designing a scenario-based evaluation procedure. Published studies on telecommunication construction, equipment reliability, energy diagnosis, and resource-constrained project scheduling provide the conceptual basis [1-10].

3.2 Data requirements and provenance

An empirical implementation would require four categories of information.

First, project-management records would provide activity identifiers, precedence relationships, planned and actual durations, resource assignments, and project completion dates. Second, equipment and failure records would provide failure occurrence times, affected equipment, repair duration, and restoration requirements. Third, energy records would provide electricity consumption or power measurements associated with equipment, operating states, or relevant activities. Fourth, maintenance records would identify planned maintenance windows, technician availability, access restrictions, and task-specific requirements.

Published telecommunication energy datasets can inform the selection of energy variables and data-preparation procedures [11,12]. Published failure analysis can similarly inform failure-event classification and the structure of reliability variables [5]. However, these sources cannot be assumed to form a directly linked project-level dataset. Their measurement units, time resolution, identifiers, access conditions, and coverage would need to be checked before combining them.

In the present study, the raw datasets were not independently downloaded and integrated into a unified project-level database. Accordingly, the data-source descriptions inform the proposed methodology but are not treated as a dataset analyzed by the authors.

3.3 Scheduling representation

Let the project consist of a set of activities (A={1,2,\ldots,n}). Each activity (i) has a duration (d_i), a start time (s_i), and a finish time (f_i), where

f_i = s_i + d_i

Let (P_i) denote the set of immediate predecessors of activity (i). Precedence feasibility requires

s_i >= f_j, for all j in P_i

Let (R) denote the set of renewable resources, such as installation crews, specialist technicians, and testing equipment. The resource-constrained formulation requires that resource demand does not exceed available capacity at any time. If (q_{ir}) represents the demand of activity (i) for resource (r), and (Q_r) is the available capacity, then the total demand of concurrently active activities must remain within (Q_r).

The project makespan is defined as

C_max = max_{i in A} f_i

Minimizing makespan is a conventional scheduling objective, but it is not sufficient to represent the complete problem considered here. The framework therefore introduces additional measures for failure-related disruption, energy performance, and maintenance feasibility.

3.4 Failure-risk representation

Let (p_i) denote the estimated probability of a failure-related disruption affecting activity (i) during its relevant exposure period, and let (\tau_i) denote the associated repair or recovery duration. Under a simplified single-event representation, expected disruption can be expressed as

E[D_i] = p_i * tau_i

This expression is an illustrative approximation rather than a general failure model. It assumes that the probability and duration are appropriately defined for the activity and does not account for multiple failures, dependence between events, or complex recovery sequences.

For an empirical model, the probability of disruption should be estimated from relevant failure histories, with attention to exposure time, equipment type, environmental conditions, and the distinction between equipment failures and project delays. Repair-duration estimates should be obtained from maintenance records where possible. Published failure studies can inform variable selection, but their reported event rates should not be transferred directly to a different deployment context without justification [5,6].

3.5 Energy performance

Let (E_i) represent the energy attributable to activity (i), where the measurement boundary must be defined before calculation. Depending on the deployment process, energy may be measured directly for an activity or estimated from equipment power and operating duration.

A simplified activity-level representation is

E_i = P_i^avg * h_i

where (P_i^{\mathrm{avg}}) is the average power attributable to the activity and (h_i) is the corresponding operating time. This relationship is only appropriate when the power measurement and duration refer to a consistent system boundary. It should not be used to infer total site energy consumption from incomplete equipment measurements.

Total modeled energy is

E_total = sum_{i in A} E_i

Where energy consumption depends on start time, ambient conditions, equipment state, or operational demand, a time-dependent function would be more appropriate. Published studies on telecommunication energy monitoring and diagnosis support the relevance of data-driven energy characterization [2,3]. Nonetheless, energy performance should not be assumed to improve merely because project duration decreases; the relationship must be measured or modeled explicitly.

3.6 Maintenance constraints

Let (W_i) denote the set of time intervals during which activity (i) is permitted, and let (M) denote the set of maintenance-related restrictions. An activity is feasible only if its execution respects applicable access windows, technician availability, and equipment restrictions.

For an activity requiring uninterrupted execution, its start time must be selected so that its entire duration fits within a permitted interval. Where interruptions are allowed, the model must specify whether an activity can be paused and resumed, whether partial work remains valid, and whether additional setup or retesting is required.

Maintenance restrictions should therefore be represented as explicit scheduling constraints rather than as informal preferences. Their operational definitions depend on the site deployment process and cannot be calibrated reliably without suitable maintenance records.

3.7 Integrated objective

The proposed framework considers project duration, failure-related disruption, and energy performance simultaneously. A conceptual weighted objective is

$$\min Z = w_C * C_{max} + w_D * E[D] + w_E * E_{total}$$

where (E[D]) is the modeled expected disruption measure, and (w_C), (w_D), and (w_E) are weights reflecting the relative importance of project duration, disruption, and energy consumption.

The weights must be calibrated or justified before an operational model is used. Because the objective combines quantities with different units, normalization or a defensible cost-based conversion is needed. An alternative is to use a multi-objective method that reports the trade-offs among project duration, failure risk, and energy consumption without reducing them to a single weighted score.

This objective is subject to precedence, resource-capacity, maintenance-window, and any required technical constraints. If the model incorporates stochastic failures, it must also define whether failure events are represented through expected values, scenarios, simulation, or another uncertainty-aware formulation.

3.8 Evaluation procedure

A future empirical evaluation should compare at least two schedules using the same activity network, data boundaries, and resource assumptions.

The baseline schedule would represent the conventional planning approach using nominal activity durations and standard resource constraints. The integrated schedule would additionally account for failure risk, energy performance, and maintenance restrictions.

The comparison should report project makespan, total modeled energy, expected failure-related disruption, resource utilization, and the number of constraint violations. Any improvement should be calculated from actual model outputs and assessed for robustness under alternative assumptions. Where stochastic simulation is used, the number of replications, randomization procedure, uncertainty intervals, and convergence checks should be documented.

The present paper specifies this evaluation procedure but does not report an executed optimization experiment or a completed empirical comparison.

4- Results and Analytical Framework

4.1 Evidence available for framework development

The reviewed literature establishes that the relevant problem dimensions have independent research foundations. Telecommunication construction studies address schedule overruns [1]; energy diagnosis studies examine monitoring and performance assessment [2,3]; reliability studies investigate base-station failures and wireless-system reliability [5,6]; and project scheduling research addresses uncertainty, resource constraints, sustainability, and energy-related scheduling decisions [4,8-10].

These strands support the rationale for an integrated framework. However, they do not by themselves establish the effectiveness of a specific combined scheduling algorithm. Evidence from operational energy monitoring cannot directly quantify project-level schedule improvements, and published failure prediction results cannot automatically be converted into site deployment delay estimates.

4.2 Conceptual comparison of scheduling approaches

The following comparison describes the intended scope of the baseline and integrated approaches. It is a methodological comparison, not a report of observed performance.

Table 1. Conceptual Comparison of Baseline and Integrated Scheduling Approaches

Dimension	Baseline scheduling	Proposed integrated framework
Activity precedence	Explicitly represented	Explicitly represented
Resource capacity	Standard resource constraints	Standard resource constraints plus maintenance-related availability
Failure risk	Not explicitly represented unless included in nominal durations	Represented through risk parameters or disruption scenarios
Energy performance	Not necessarily an objective	Included as a modeled objective or operational constraint
Maintenance windows	May be handled informally	Represented through explicit feasibility restrictions
Sensitivity analysis	Optional	Specified for failure probability, repair duration, and energy parameters
Empirical validation	Depends on implementation	Required before performance claims can be made

The integrated framework provides a broader representation of deployment conditions, but the table does not establish that it produces a shorter or more energy-efficient schedule. Such conclusions require an actual model implementation and a fair comparison using consistent inputs.

4.3 Illustrative failure-disruption calculation

To demonstrate the role of failure probability and repair duration, consider the simplified relationship

$$E[D]=p\tau,$$

where p is a probability of disruption and τ is a repair duration in days.

Table 2. Illustrative Sensitivity Analysis of Expected Failure-Related Disruption Under Failure Probabilities and Repair Durations

failure probability	Repair duration of 1 day	Repair duration of 2 days	Repair duration of 4 days
0.05	0.05 days	0.10 days	0.20 days
0.10	0.10 days	0.20 days	0.40 days
0.20	0.20 days	0.40 days	0.80 days
0.30	0.30 days	0.60 days	1.20 days

The calculation illustrates a direct mathematical relationship: for a fixed repair duration, the expected disruption measure increases with the assumed failure probability; for a fixed probability, it increases with repair duration. This relationship does not establish the actual impact on project completion. The effect on makespan depends on precedence relationships, available float, resource reassignment, recovery procedures, and whether the disrupted activity lies on the critical path.

4.4 Energy-related analysis

Energy performance can be incorporated through measured activity-level energy, equipment power profiles, or scenario-specific estimates. However, the energy boundary must be consistent. If the analysis includes only the energy consumed by installation equipment, it should not be described as total site energy consumption. If it includes the ongoing operation of a site after commissioning, that operational energy should be separated from deployment-phase energy.

A future empirical study should distinguish between energy consumption attributable to project execution and the energy performance of the installed telecommunication site. These are related but different outcomes. A schedule that reduces the time required for installation does not necessarily reduce total energy consumption if it requires additional equipment, simultaneous high-power operations, or repeated testing.

4.5 Maintenance-related analysis

Maintenance restrictions can affect feasibility even when they do not directly increase nominal task duration. For example, a specialist technician may only be available during specified intervals, or a testing activity may be prohibited while equipment is undergoing maintenance. In these circumstances, a schedule must satisfy temporal restrictions as well as resource and precedence requirements.

The proposed framework represents these restrictions as explicit constraints. Their quantitative effect on project duration cannot be determined without activity-level maintenance windows, resource calendars, and information about whether activities can be interrupted or rescheduled.

4.6 Sensitivity and uncertainty

The simplified disruption calculation indicates which parameters should be investigated in a future implementation. At minimum, sensitivity analysis should vary failure probability, repair duration, and the availability of alternative resources. Energy parameters should also be varied where their estimates are uncertain.

For an empirical implementation, scenario ranges should be derived from observed data, confidence intervals, equipment specifications, or clearly documented evidence. Arbitrary ranges may be used for exploratory stress testing, but their results must remain labeled as scenario outputs rather than forecasts.

4.7 Summary of analytical findings

The analysis supports three limited conclusions. First, a resource-constrained scheduling framework can be extended conceptually to include failure risk, energy performance, and maintenance restrictions. Second, the expected disruption approximation demonstrates how failure probability and repair duration can be linked mathematically, although it does not quantify actual project delay. Third, the validity of any performance comparison depends on access to integrated project, equipment, energy, and maintenance data.

No executed optimization results, empirically measured energy savings, or validated reductions in project duration are reported in this study.

5- Discussion

The proposed framework responds to a methodological limitation in conventional deployment planning: technical feasibility, reliability, energy performance, and maintenance availability are often represented in separate analyses. Coordinating these dimensions can improve the completeness of a scheduling model by making their interactions explicit. Nevertheless, a more comprehensive model is not automatically a more effective one. Additional constraints and objectives can increase computational complexity, require more detailed data, and introduce uncertainty in parameter estimation.

The failure-risk component is particularly sensitive to the relationship between equipment reliability and project execution. Equipment failure does not always cause an equivalent project delay. If the affected activity has sufficient scheduling float, another resource is available, or recovery can occur without interrupting downstream work, the impact on the completion date may be limited. Conversely, a short interruption on a critical activity can delay several subsequent tasks. Therefore, expected disruption should not be equated directly with expected project delay unless the scheduling model explicitly represents the dependency.

Energy performance introduces a related measurement challenge. Energy consumption can be estimated from power and operating duration, but only when the measurement boundary and operating state are clearly defined. The energy consumed during deployment is distinct from the long-term energy performance of the commissioned site. Combining them without a consistent boundary could produce misleading conclusions. Existing work on telecommunication energy monitoring provides useful foundations for data selection, but deployment-specific energy attribution remains an empirical task [2,3].

Maintenance constraints are similarly context-dependent. A maintenance window may prohibit access to equipment, restrict technician availability, or require a particular operational state. These restrictions should be modeled according to the actual maintenance process rather than represented by generic penalties. If a schedule uses penalties instead of hard constraints, it must justify why violations are acceptable and how the penalty values are selected.

The framework also raises questions about objective selection. A weighted objective allows decision-makers to express trade-offs among duration, disruption, and energy, but its results can depend heavily on weight selection and normalization. A multi-objective approach may therefore be preferable when stakeholders need to

inspect trade-offs rather than accept a single aggregate score. In either case, model performance should be compared with a baseline under identical data and feasibility requirements.

Future research should obtain project-level records from multiple telecommunication deployments, document the provenance and quality of each variable, and implement a reproducible optimization procedure. The evaluation should report baseline and integrated schedules, parameter uncertainty, computational settings, constraint feasibility, and out-of-sample or retrospective validation where appropriate. This would allow the proposed framework to be assessed as an operational decision-support method rather than solely as a conceptual structure.

Conclusion

This paper developed a methodological framework for data-driven project scheduling in telecommunication site deployment that incorporates failure risk, energy performance, and maintenance constraints. The framework extends a resource-constrained scheduling representation by identifying how reliability-related disruption, energy measures, and maintenance windows can be incorporated into scheduling objectives and feasibility requirements.

The analytical framework demonstrates that failure probability and repair duration can be linked through a simplified expected-disruption measure. It also establishes the need to distinguish deployment-phase energy from the operational energy performance of a commissioned site. Maintenance restrictions must be represented explicitly when they determine activity feasibility or resource availability.

Further work should focus on integrating verified project records, failure histories, energy measurements, and maintenance logs; implementing the optimization model; and evaluating its performance against a consistent baseline. Such validation is necessary to determine whether the framework provides measurable benefits under real deployment conditions.

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