Maximizing Megaproject Performance and Impact with Digital Technologies: The Role of Network Analysis, Machine Learning, and Blockchain

1.1 Introduction

Digital transformation is significantly impacting how organizations operate. There is increasing interest in its impact on projects (Fuchs et al., 2022). This paper addresses the digital transformation of projects. We describe how organizations can better understand its impact on projects and project organizing practices and how they can use it. We aim to advance managerial thinking about digital transformation of projects and improve their success. Our paper will contribute to understanding how to manage large, complex projects using digital technologies successfully. We begin by comprehensively discussing factors that influence success and the nature of project risk. We then present network analysis techniques that we have developed to map the risk to projects. We demonstrate their potential in extracting valuable insights from project schedules and identifying key factors contributing to risk. By combining this with an "outside view" and machine learning (ML), we can more accurately forecast project performance, identify risks and opportunities for improvement. We discuss how digitization tools can reduce this forecasted and mapped risk to improve project performance. We discuss blockchain technology for governance and describe a model for these methods to be employed together to minimize risk and enhance megaproject effectiveness. We also address the challenges and limitations of using these technologies and suggest an agenda to mitigate them for effective implementation.

1.1.1 Megaprojects

Capital project efficiency and accountability are more important than ever. Many capital projects are megaprojects, often defined as projects costing over one billion dollars (Flyvbjerg, 2014), which present unique challenges due to complexity and size, and can exceed the limits of effective control. These projects play a crucial role in value creation, sustainable development, and the transition to a net-zero economy (NCE, 2014). Megaprojects, which account for a significant and growing portion of global GDP (Flyvbjerg, 2014) are in several sectors. Infrastructure projects, including energy and transportation, can significantly impact local communities and entire regions with far-reaching geopolitical implications. Infrastructure investment requirements are forecast to reach $94 Trillion by 2040 (Global Infrastructure Outlook, 2017).

However, projects in several critical sectors such as infrastructure, national defense, science, and healthcare (Insinna, 2019; Ehley, 2013; GAO, 2018) exhibit high overruns and delivery shortfalls. Research has shown that only about one in a thousand megaprojects meets planned cost, schedule, and benefits, a phenomenon referred to as the "iron law of megaprojects" by megaproject expert Professor Flyvbjerg (Flyvbjerg, 2017), who argues that project participants are incentivized to underestimate costs, overstate income, and exaggerate social and economic benefits due to a lack of accountability and risk-sharing mechanisms. This lack of accountability and transparency leads to a cycle of cost overruns and benefit under-delivery, undermining public trust and confidence in these large-scale projects. Thus, there is a pressing need for more efficient and verifiable project execution.

Furthermore, large-scale projects are complex systems characterized by high uncertainty and risk. Megaproject complexity can lead to unpredictable high-impact emergent issues. To effectively manage this complexity, it is necessary to understand the interactions between the various components and stakeholders involved in the project. Machine learning and network analysis can help overcome limitations to forecasting in complex systems and to human cognition. Blockchain technologies can play a crucial role in improving verifiability and trust. By leveraging these technologies, we can break the cycle of cost overruns and benefit under-delivery and improve the performance and impact of megaprojects which are critical for economies and societies.

1.2 UN SDGs

Effective organization of complex large-scale projects is relevant to several UN Sustainable Development Goals (SDGs). For example, Goal 6 (Clean water and sanitation) requires the successful organization and execution of large infrastructure projects, such as water treatment plants and sanitation systems. Similarly, Goal 7 (Affordable and clean energy) often involves developing large-scale projects like renewable energy plants or transmission systems. The requisite investment of $3.5 Trillion by 2040 (Global Infrastructure Outlook, 2017) is indicative of the related project portfolio.

Goal 8 (Decent work and economic growth) is also closely related to the effective organization of projects. This is also true in Goal 9 (Industry, Innovation, and Infrastructure), to promote the development of sustainable industries and infrastructure development. Projects can lead to the creation of new businesses, expansion of existing ones, and the development of sustainable infrastructure, all of which contribute to economic growth and the creation of decent work. Goal 11 (Sustainable cities and communities) requires the construction of sustainable housing, development of public transportation systems, and creation of green spaces to improve the livability and sustainability of cities and communities. Goal 13 (Climate action) is closely related to the organization of projects focused on climate change mitigation and adaptation, including reducing greenhouse gas emissions, and helping communities adapt to a changing climate. The successful organization of projects is essential to addressing the global climate crisis.

1.3 Research Questions

We will address the following research questions to build a comprehensive and well-grounded understanding of risk in capital projects and how digital technologies can contribute to risk reduction and management:

1. What is the nature of risk in capital projects, how does it arise, where does it get engendered, and how does it propagate?

2. How can digital technologies contribute to reducing risk reduction and closing the gap between planned and actual megaproject outcomes?

    1. How can risks be accurately forecasted and reduced during planning?

    2. If risks occur, how can they be mitigated and controlled?

3. How can the conceptual model of risk and mitigation strategies in capital projects be developed using the extant literature and empirical evidence?

1.4 Methodology

We employed a mixed methods approach whose components are discussed below.

1.4.1 Systematic Literature Review

The literature review identified relevant research articles, books, and reports to gather information on the nature of risk in capital projects, existing risk management strategies, and the role of digital technologies in risk reduction and management. We used well-defined inclusion and exclusion criteria to select the most relevant studies, and synthesized the findings to answer our research questions and build a conceptual model.

1.4.2 Empirical Analysis

Using insights gained from the literature review, we conducted a network analysis of a capital project to demonstrate how to identify critical milestones, paths, and risk patterns. This applies our conceptual model of risk to an existing project network. This helped us understand how these technologies can contribute to risk reduction and management in capital projects and provide empirical support for our conceptual model.

1.4.3 Conceptual Model Development

Based on findings from the literature review and empirical analysis, we developed a comprehensive, well-grounded conceptual model of risk and mitigation strategies in capital projects. This model integrates our insights and provides a framework for understanding how digital technologies can contribute to risk reduction and management. It also offers practical recommendations for implementing these technologies for better outcomes.

1.5 Project Risk

1.5.1 The nature of project Risk

In project management, risk refers to deviations from planned performance. Risk is related to factors that affect the likelihood of expected project outcomes being realized. Outcomes can be classified into three broad buckets of scope or the expected result, budget, and schedule. A capital project is a temporal construct beginning with a planning phase, often using a stage-gate process (Figure 1-1), leading to a final investment decision (FID) where the scope, budget, and schedule are determined with comprehensive plans to achieve them. Risk management aims to forecast, avoid, manage, and control occurrences that can lead to deviations from this plan, which is the basis of investment. The chronic and severe underperformance track record of capital projects in every sector (Fuchs, et al., 2022) demonstrates realized risks reflecting systemic governance issues. We will show the nature of risk in these projects and why they are not accounted for before discussing how emerging digital technologies offer the potential to break this cycle of underperformance.

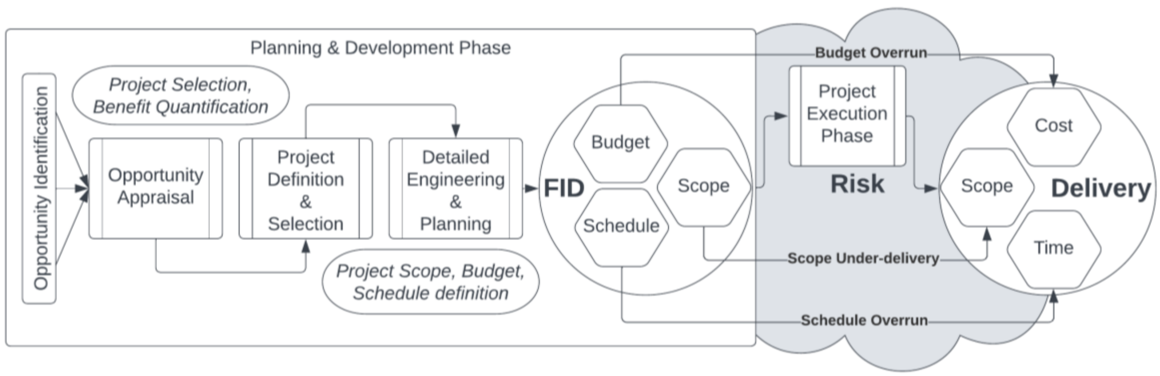

Figure 1-1: Front-End approach to FID; based on Merrow (2011, p.24)

Uncertainty or the potential for deviation from the forecast is innate to planning long-duration complex endeavors. According to Hubbard (2009), uncertainty is the probability of possible deviations, while risk is its subset containing undesirable outcomes. Strict uncertainty refers to the knowledge of possible deviations without knowing the probabilities of their realization (pp. 79-93). Thus, emergent risks can be known or unknown, with or without known probabilities. During the planning stage, project management aims to identify and mitigate risks by forecasting and reducing the probabilities of deviations from the plan, and planning how to manage emergent risks. However, several factors affect accurate cost, time, and benefit estimation, and the risk related to these outcomes. Similarly, during execution, many factors affect detection and response to events that affect outcomes.

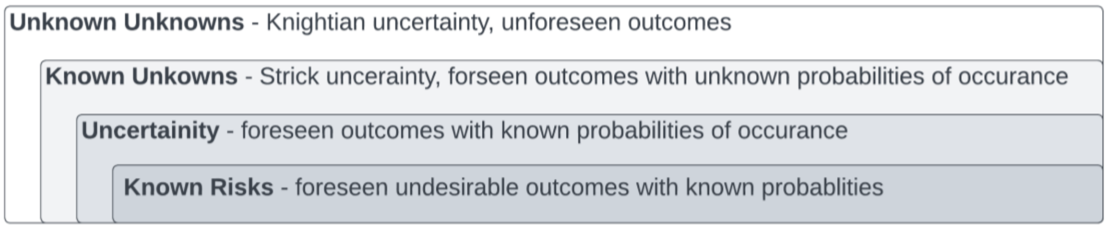

Figure 1-2: Risk and uncertainty

1.5.2 Project Risk Distribution

Accurate prediction and mitigation of risks and challenges is a critical challenge in megaprojects, characterized by high uncertainty and risk. However, traditional risk assessment methods, like the Monte-Carlo method, which uses normal distributions, need to be revised. This is because the Gaussian or normal curve, a standard measure of randomness (Burkardt, 2014), is unsuitable for complex human systems influenced by biases and principal-agent issues. The reliance on normal distributions and traditional risk assessment methods can lead to a false sense of security and a tendency to underestimate the potential impact of extreme events, or "black swans," which are often related to unknown unknowns (Taleb, 2008). These events, while rare, can have significant consequences.

Figure 1-3 showing the distribution of cost and schedule overruns in offshore oil and gas projects from (Natarajan, 2022) is typical in all megaproject sectors. The overruns were measured as the deviation from the budgets and schedules that formed the basis of project investment decisions. Given that this budget and schedule are the basis of investment, it is implicit that if the overruns from this baseline be plotted, the expectation is for a distribution, often assumed to be Gaussian, centered on zero i.e. equal chances of overrun or underrun. However, this is clearly not the case in nearly any capital project segment. Many megaprojects experience extreme cost and schedule overruns, which can be considered black swans or even more extreme dragon king outliers (Natarajan, 2022).

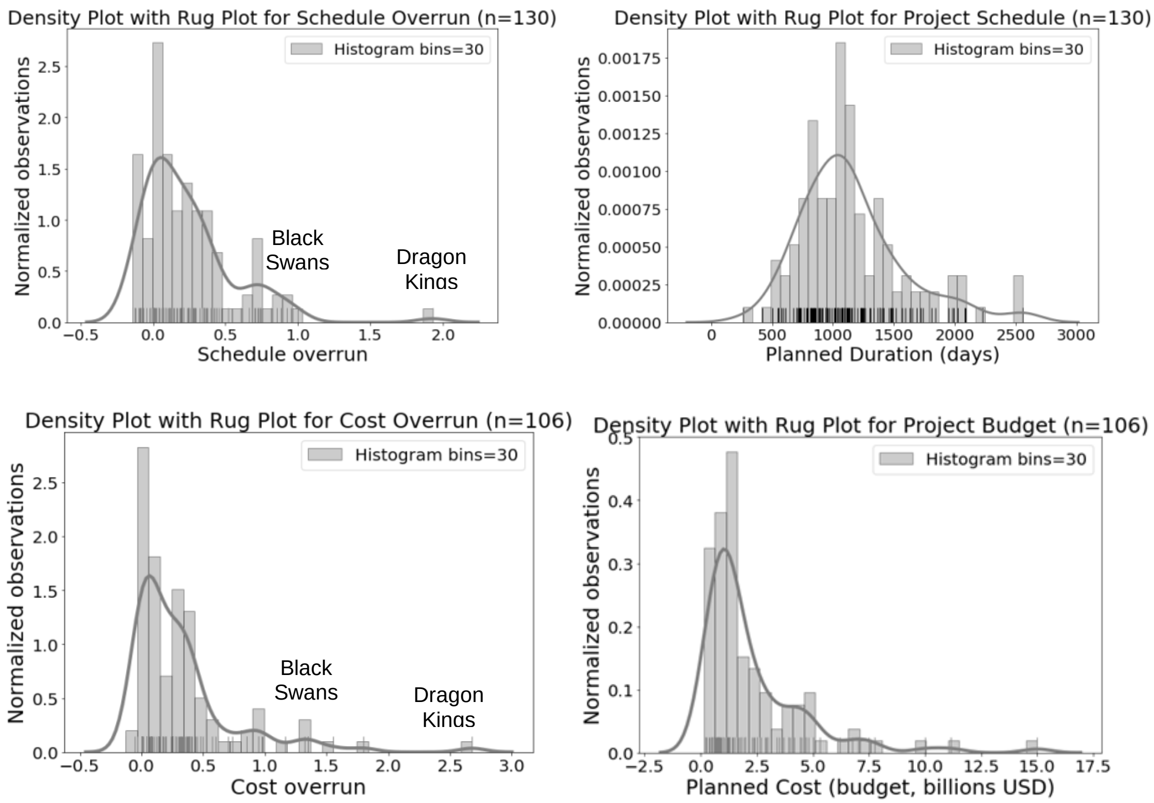

Figure 1-3: Cost, schedule overruns, and corresponding budget, schedule for Offshore O&G projects (Natarajan, 2022)

The distribution of overruns is "consistently and significantly non-normal with averages that are significantly different from zero" (Flyvbjerg, 2006). Research has demonstrated that project cost and schedule overruns follow non-normal distributions (Flyvbjerg, 2006), with many outlier projects experiencing significant overruns (Flyvbjerg & Budzier, 2011) from black swan events in the fat-tail. These overruns exhibit a power-law distribution - many projects with relatively small overruns and a smaller number with extreme overruns in the tail (Lovallo, et al., 2023). This "regression to the tail" (Flyvbjerg, et al., 2020) makes projects vulnerable to large risks, underscoring the importance of outliers.

1.6 Factors Causing Underperformance

1.6.1 Principal Agent Issues

Megaprojects are complex systems involving multiple stakeholders, such as project managers, owners, contractors, and subcontractors. These stakeholders may have conflicting interests, leading to principal-agent issues. Principal-agent issues can also cause companies in megaproject networks to intentionally provide overly optimistic schedules, cost, and benefit estimates. Additionally, loyalty conflict arises from tension due to competing loyalties to different parties in a project (Arvidsson, 2009). These issues negatively impact project performance, causing cost and schedule overruns (Flyvbjerg, et al., 2018).

1.6.2 Cognitive Biases

Cognitive biases can significantly impact projects by leading to underestimation of effort and cost. These biases are systematic errors in judgment that can result in skewed judgments and decision-making (Kahneman & Tversky, 1979). Key biases affecting project estimation accuracy include optimism, uniqueness, anchoring, as well as planning and cost-benefit fallacies (Lovallo, et al., 2023). These biases not only exacerbate principal-agent issues but are also magnified by the inherent complexity of megaprojects.

1.6.3 Complexity

Megaprojects are characterized by high complexity from the number of components, connections, and interactions. Complex systems exhibit unpredictable emergent and chaotic behavior because of interactions between constituent parts, resulting in behavior "greater than the sum of the parts" (Hitchins, 2007, p.21), limiting the ability to forecast outcomes. This highlights the importance of considering the interactions and relationships between different components in complex systems, as these can significantly impact the overall behavior and outcomes. This concept is particularly relevant to megaprojects which involve many interconnected components and stakeholders, making it challenging to understand and predict the consequences of actions and decisions.

To mitigate these challenges, megaprojects are often decomposed into subprojects that can be independently managed and connected through interfaces (Davies & Mackenzie, 2014). Systems engineering, closely related to complexity theory, can help to manage emergence in megaprojects. However, interfaces between companies handling distinct scopes on subprojects are prone to principal-agent issues and fractured governance.

1.6.4 Limitations to Forecasting

In megaprojects, which are complex systems-of-systems (Chang, et al., 2013), emergent issues are difficult to anticipate, limiting forecastability. Thus, the effects of complexity must be reduced, managed, and mitigated. The implementation of effective risk management and governance systems, and of forecasting methods and distributional data into decision-making processes is required. Advanced technologies can aid in this and help manage emergence in complex systems to improve the success of megaprojects.

1.7 AI, Data Analytics, Blockchain

During the planning phase, it is crucial to identify potential risks, assess their probabilities, and reduce them. As complete risk elimination is unattainable, response should minimize their impact and prevent them from becoming a crisis during execution. Data analytics and AI can help identify and forecast risks (Steen, et al., 2022), determine their probabilities during the project planning phase, and help reduce those probabilities. These tools can also help identify and manage emerging risks arising during project execution.

In Section 2, we discuss network analysis and present important characteristics of project networks. We show how the non-normal distribution of risk in the project track record appears as a characteristic shape within project networks such as milestone duration and path length distributions. We will examine how these self-similar patterns can be analyzed and exploited. This insight can help identify and better manage risk-related milestones and pathways. We show how ML and data analytics can be used to understand complex interactions between various project components and stakeholders and identify key patterns and trends to inform decision-making. Network analytics with AI/ML represents a paradigm shift from traditional project management methods such as the critical path method (CPM). It can help optimize activity chains, manage criticality of milestones, and reduce risk. Network analysis tools can help project managers better understand the complexities in megaprojects and take effective action to optimize performance. Visualizing the project as a system can provide insight into inefficiencies and potential solutions. A visual representation of potential loss can also motivate stakeholders to prioritize and address these issues.

We also discuss how distributed governance, enabled by blockchain technology, can allow for greater transparency, accountability, and collaboration among all parties in the project. Collective planning can help reduce risk during the planning phase and help forestall crises, which often arise from unknown unknowns. Collaborative project execution can help manage emergent unknown-unknown risks as they occur. Collaboration and trust among stakeholders are important for success (Lahdenperä, 2012). Blockchain technology (Hewavitharana, et al., 2019) enables decentralized storage and data sharing, enabling distributed governance of project networks. This can prevent miscommunication and ensure that all stakeholders, including internal and external ones, are working towards similar goals. External stakeholders, such as local communities and users, are critical to project success (Henisz, 2014). Their inclusion in the decision-making process can be facilitated using distributed governance. By considering the needs and concerns of all stakeholders, the overall impact and sustainability of megaprojects can be improved. Distributed ledgers allow for smart contracts, which can help ensure that all parties follow through on their commitments and that the project is completed on time and within budget.

Our analysis of the potential of these technologies in megaproject management, grounded on a theoretical foundation, will contribute to the growing body of knowledge on their application. Section 3 presents a conceptual model that links these technologies to projects, demonstrating how their integration can enhance efficiency, accountability, and risk management. In the concluding section, we suggest ways in which the project management community and research institutions can support the successful adoption of these technologies in megaprojects.

2 PROJECT NETWORK ANALYSIS

Several AI, machine learning, and data analytics methods have been proposed for large projects (Wijayasekera, et al., 2022), with several in ongoing development and testing. However, the limited number of these large-scale projects, their length, and their unique complexities makes it challenging to determine the effectiveness of these methods and make definitive conclusions. We focus on characteristics that can be leveraged to develop and improve these methods rather than delving into the specifics of each. In this section we show that network analysis is important to characterize the nature of risk, how it emerges and how to mitigate it. This will inform our discussion of employing digitization technologies.

To manage a megaproject's complexity effectively, it is necessary to understand the interactions between its components and stakeholders. Network analysis of projects has become more feasible due to the proliferation of advanced tools. Network analysis can analyze data, identify key patterns and trends, and provide valuable insights into the structure and dynamics of a project. It allows visualization of the interconnections and dependencies within a project and identifies critical paths and potential bottlenecks. By mapping the various activities and milestones within a project, network analysis tools can reveal patterns of recursive interconnectivity, identify critical value generation paths, and highlight the connectivity between milestones and activities.

2.1 Project Networks

Megaprojects are temporary (Sydow & Braun, 2018) meta-organizations, networks of independent firms with independent interests that come together temporarily for system-level goals (Natarajan, 2022). These meta-organizations are characteristic of cross-organizational supply chains (Gulati, Puranam, & Tushman, 2012) and projects (Lundrigan, et al., 2015). The complex contracts, interdependent networks, fractured systems, and principal-agent issues make megaproject governance challenging.

2.1.1 Activity Networks

Projects schedules are networks of milestones and activities. These networks can be modeled as Directed Acyclic Graphs (DAG) (Natarajan, 2021), which consist of a set of vertices (or nodes) connected by directed edges. In project activity networks or schedules, vertices represent activities or milestones, and edges represent relationships between them. Our network analysis discussion focuses mainly on these networks.

2.1.2 Participant Networks

Project success depends on effectively managing relationships and interactions between networks of internal and external stakeholders. Internal stakeholders, such as contractors, subcontractors, and financiers, are involved in project creation. They are responsible for design, construction, and financing and interact through contracts and agreements. External stakeholders are affected by the project but not directly involved in its creation. These stakeholders may include communities who will use the project, communities impacted by construction, government agencies, and environmental organizations. It is necessary to establish clear lines of communication and collaboration and address conflicts of interest or misaligned incentives to create value and achieve the project's intended goals. Managing these project networks effectively is crucial for project success.

2.2 Methods

In our years of managing megaprojects, and participation in professional bodies and research communities related to project management, we observed a lack of consistent standards even within a project sector. Project scheduling varies from company to company in a single capital project and from project manager to manager within a single company.

To use a reliable schedule, we chose a schedule for a FEED (front-end engineering design) project for an FPSO (floating production storage and offloading) vessel project we managed to illustrate project network analysis methods. The FEED project involved 159 activities. The schedule was created using Oracle P6 software and contained 120 paths linking the various activities from start to finish. The paths ranged from 1552 days (the critical path) to 54 days. As the project manager for this project, we had applied rigorous scheduling practices to ensure connectivity and consistency and have intimate familiarity with the activities. We will use this as a case study to demonstrate patterns and methods.

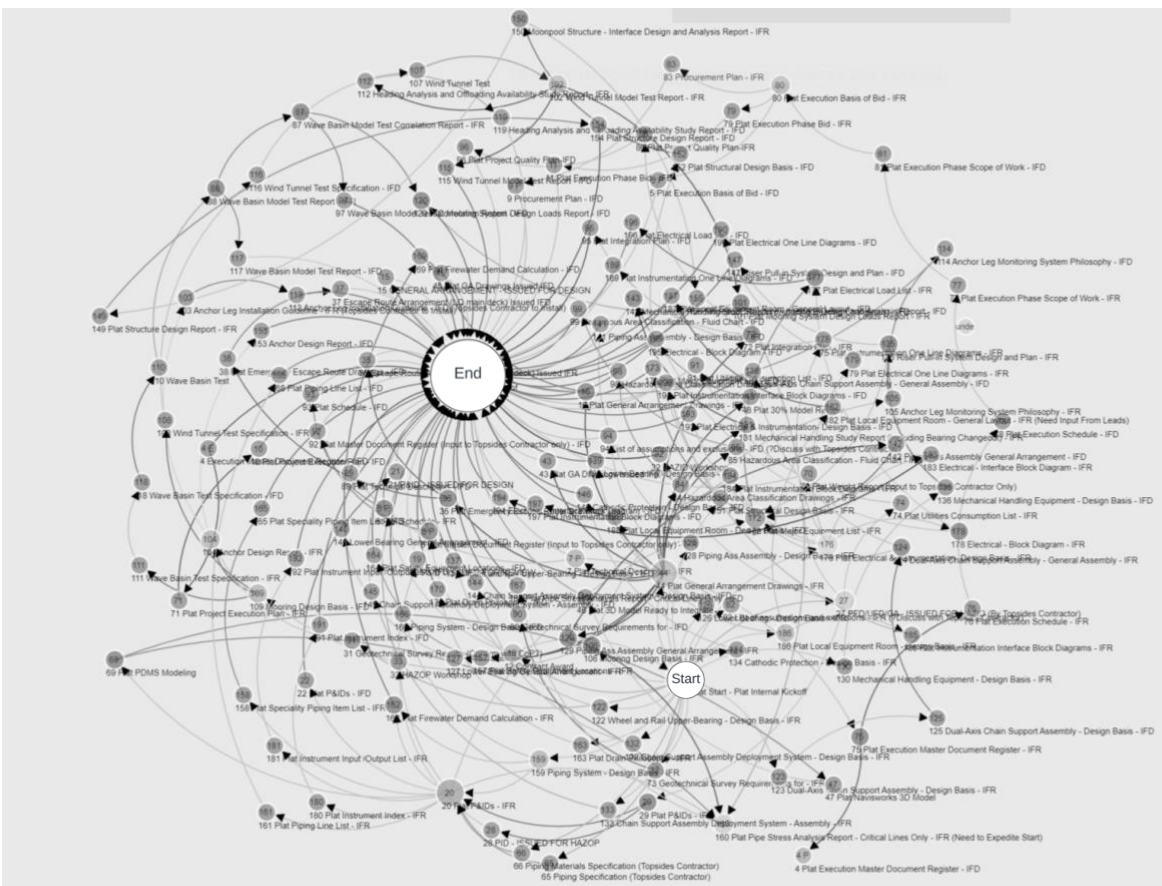

Figure 2-1: Our Project Activity Network (schedule) with 159 activities – edge length is proportional to activity duration

The project schedule was imported into Jupyter Python. We used several algorithms to extract insights about the interconnectivity and criticality of the activities and milestones. We identified all activity chains by linking each activity's start and end dates. We wrote an algorithm to connect each path to the project's beginning and end, ensuring no dangling activities. This allowed us to see the dependencies between activities and understand how they fit together in the overall plan. Next, we focused on the recursive interconnectivity of the schedule, examining how the various activities and milestones were connected. By analyzing these connections, we were able to identify the most critical value generation paths in the schedule and extract a granular picture of risk build-up at activities.

2.3 Self-similarity

Distributions of project network features such as milestone importance, duration, connectivity, risk profile, and stakeholder influence mirror the cost and schedule performance distribution of reference projects. Many project network features follow power-law distributions. We found this to be a recurring pattern within the project network. This self-similar pattern within project networks indicates a fractal structure. While further data is needed to confirm this, a distinct fractal pattern was clearly observed. Fractal geometry is a field that analyzes patterns that exhibit self-similarity across different scales. Fractals are found in many natural and artificial systems. Understanding the fractal nature of project networks can provide valuable insights into their complexity and performance. Traditional forecasting methods do not fully capture these patterns that can significantly impact a project's overall success. Understanding these patterns and developing strategies to mitigate their adverse effects can help better forecast and manage risks in complex projects.

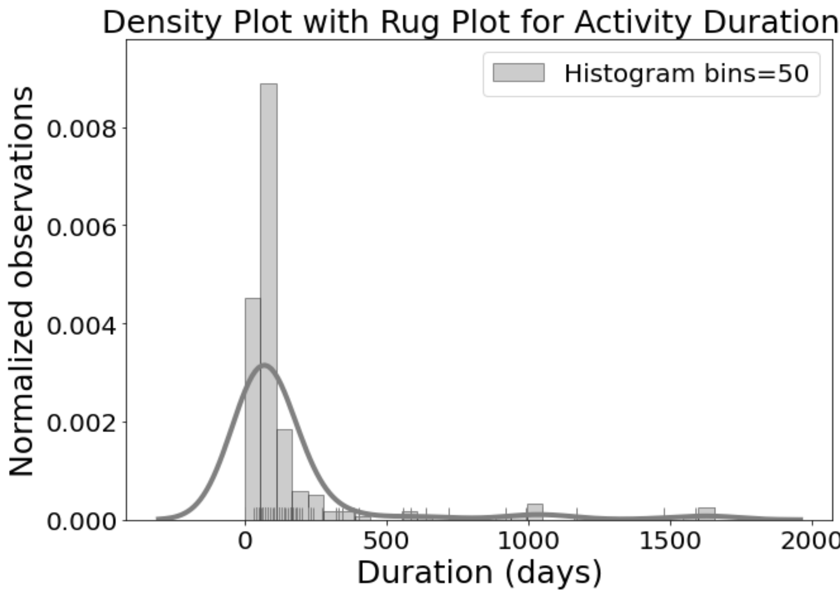

Figure 2-2: Plot of all 159 activity durations in the schedule.

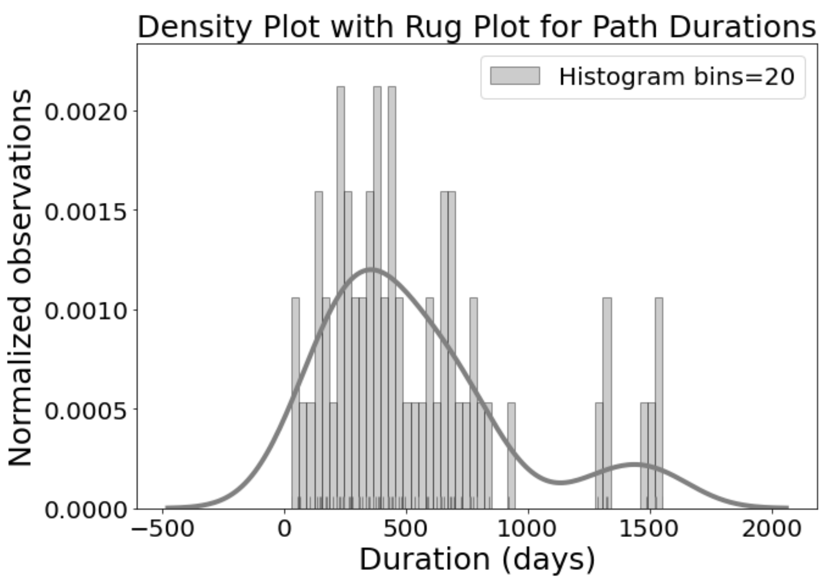

Figure 2-3: Durations of all 120 project paths. Notice the self-similar pattern.

2.4 Centrality Measures

Centrality measures are used to understand the importance or influence of a node or entity within a network. We used several centrality measures to understand the importance of each activity in the schedule, including degree centrality, betweenness centrality, and closeness centrality. Each measure focused on a different aspect of a node's importance. The degree centrality of each activity in terms of incoming and outgoing connections was a basic centrality measure. It is based on the number of connections a activity has to other activities. This measure helps identify the key players or hubs within a network, as they likely have the most connections and, therefore, the most influence. An activity with a high degree centrality is connected to many others, indicating its centrality or influence within the schedule.

Another type of centrality measure is betweenness centrality, based on the number of shortest paths that pass through a particular node. This measure helps identify activities that play a central role in connecting other activities or identify bottlenecks or points of vulnerability within a schedule. An activity with high betweenness centrality is located on many of the shortest paths between other nodes in the network. Other centrality measures include eigenvector centrality, based on the influence of a node's neighbors, and PageRank, which measures a node's influence based on the number and influence of its incoming links. These measures help understand the relative importance of different nodes within a network and identify critical players or influencers.

We used the PageRank algorithm to analyze schedule connectivity, considering the connectedness of each activity by accounting for the connectedness of the activities it was connected to. PageRank is a measure of the importance of a node in a network based on the number and quality of incoming and outgoing connections. In the context of a project schedule, PageRank can analyze the connectivity of activities and milestones within the schedule. By recursively analyzing the connectedness of an activity, PageRank allowed us to understand the relative importance of each activity. This is useful in identifying critical value generation paths and optimizing the schedule's activity chains. By understanding the interconnectedness of activities and milestones within the schedule, we can more effectively optimize the use of resources and reduce the risk of delays or other problems.

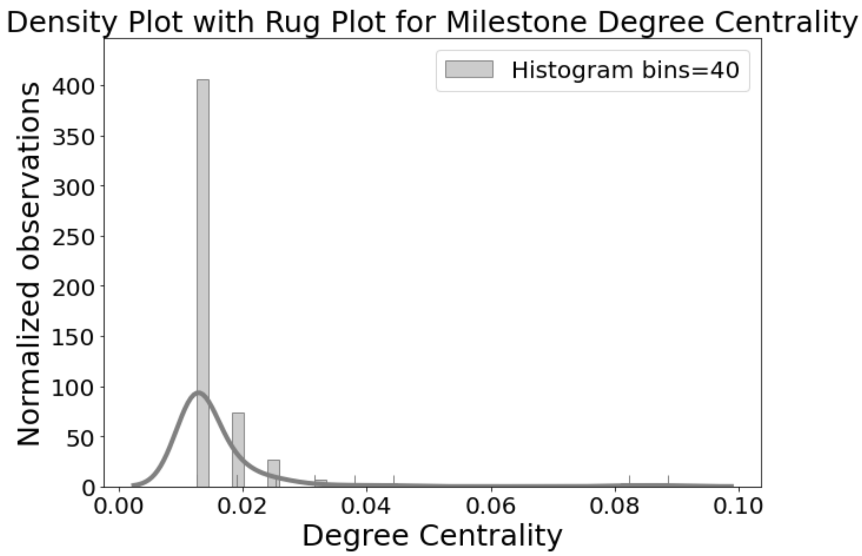

Figure 2-4: Degree Centrality of all schedule activities. Notice the self-similar pattern.

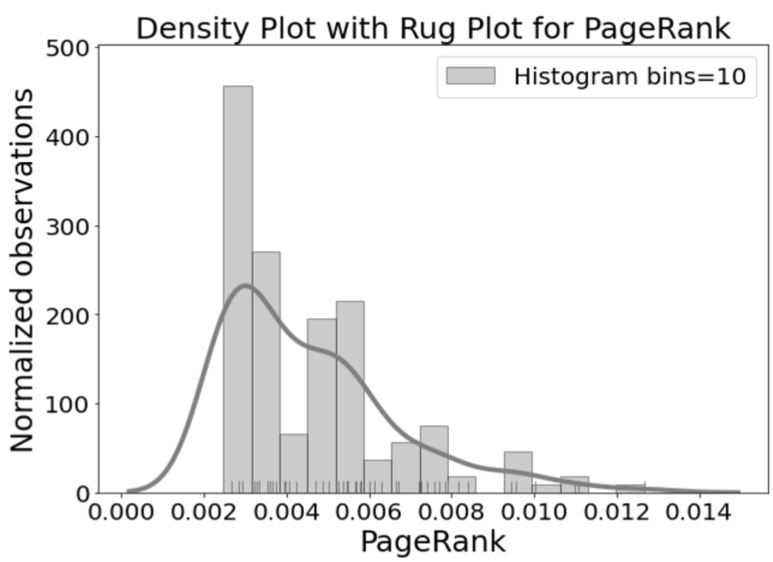

Figure 2-5: PageRank score of all schedule activities. Notice the self-similar pattern.

The dominating set for a graph is a subset such that every node not in the subset is adjacent to at least one member of the subset. We extracted the set of activities that had a high influence on other activities by using algorithms to identify the dominating sets in the schedule. This helped us identify the key activities driving the project's progress.

2.5 Identification of related activities

In addition to quantifying the importance of individual activities, we analyzed the connectedness of groups of activities within the schedule. By identifying groups of closely related activities, we can better understand the relationships between different parts of the schedule and identify areas where changes in one activity might have cascading effects on other activities. We extracted the groups of activities in the schedule that were closely related using algorithms like the greedy modularity maximization algorithm, which begins with each node in its own community and repeatedly joins the pair of communities that lead to the largest modularity until no further increase in modularity is possible. This helped us understand the relationships between different groups of activities in the schedule.

2.6 Outliers

Outliers are a recurring theme in these distributions, and their significance is a recurring theme in their relevance. We identified outliers in activity and path data using the conventional definition of 1.5 inter-quartile ranges from the IQR boxes, used for cost and schedule overrun distributions in IT projects by Budzier and Flyvbjerg (2013). The presence of these outliers, and discrepancies between the mean and median, suggests skewness and fat-tailed distributions (Budzier & Flyvbjerg, 2013). Histograms of different centrality measures applied to activities, activity paths, and activity durations revealed fat-tailed, non-normal distributions, like those reported for megaproject cost and schedule overruns. These findings suggest that a small number of activities or activity paths can disproportionately impact overall project performance. Further analysis is needed to fully understand the significance of these outliers and their significance to risk management improvement.

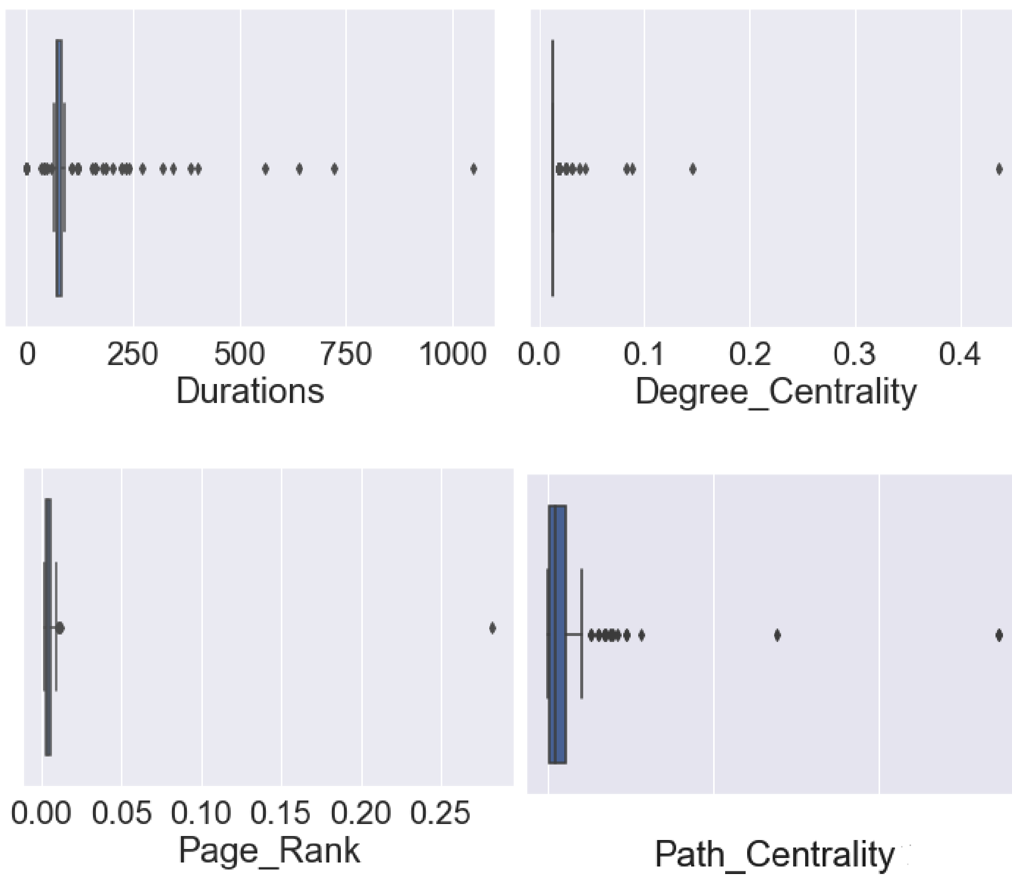

Figure 2-6: Outlier identification - Activity durations and Centrality measures

2.7 Critical Paths

The Critical Path in a project schedule is the longest chain of activities between project start and end. The Critical path method (CPM) focuses on managing this path as the project is expected to increase or decrease in duration in proportion to the critical path. Activity durations are summed up along this path setting the expected duration of the entire project. However, When the length of 120 paths linking activities from project start to finish were plotted, a bimodal distribution emerged, as seen in Figure 2-7. The critical path is one of a distinct subset of outlier paths. Any one of these can become the new critical path.

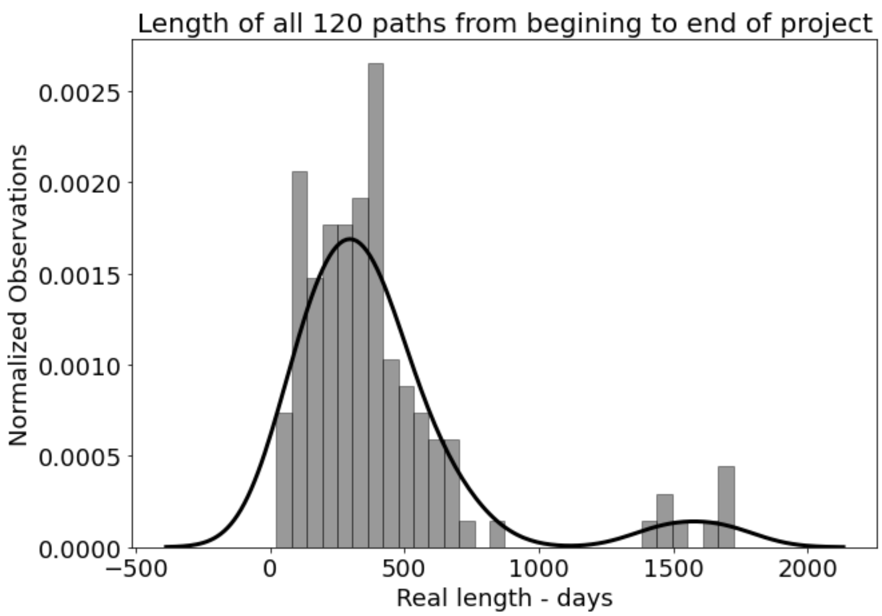

Figure 2-7: Duration in days of all 120 paths. Outlier paths are clustered to the right

Each activity in those paths is associated with a different risk profile. Each risk profile is associated with characteristics of that activity, such as length and connectivity, as well as its record from previous projects. We mapped the risk for the entire project, obtained using RCF and ML (described subsequently), to activity risk profiles. After summing risk corrected activity durations over each path, the mean of the length distribution for certain paths became higher than the path length before risk correction. These expected durations obtained by accounting for the risk distributions for each activity resulted in some other outlier paths becoming longer than the critical path. As seen in Figure 2-8, the CPM Critical Path of 1552 days became 1727 days (average), and another outlier path became the riskadjusted Critical Path with a duration of 2098 days. The importance of this is that Critical Paths can change, and the Critical Path identified by CPM may not be the actual critical path when weighted by risk as we have shown.

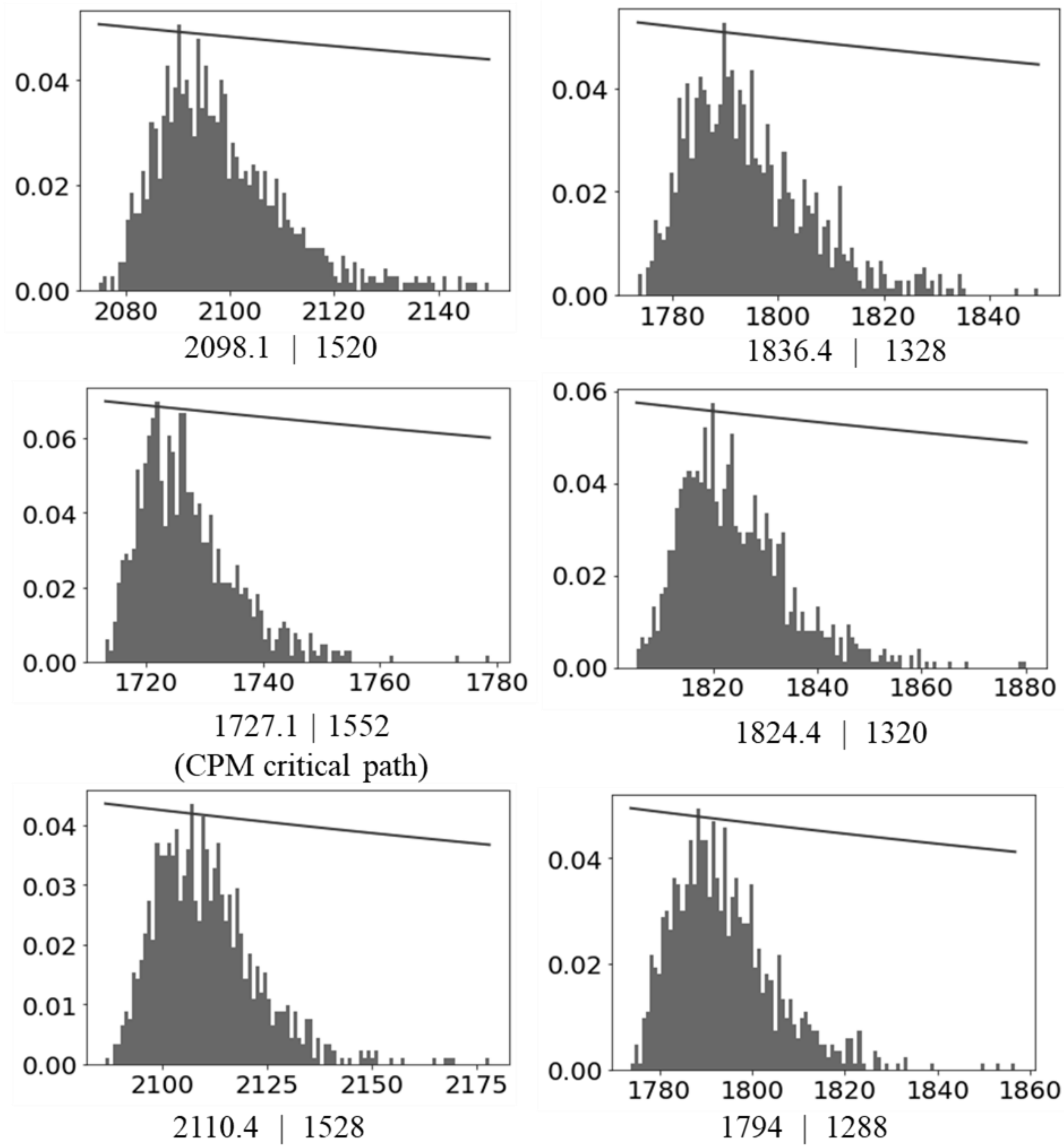

Figure 2-8: Duration (days) probability distribution functions for Outlier paths

AI/ML can improve this further by learning activity-specific risk distributions from previous projects and their relationship to project features. Using data analytics and ML during the planning phase and predictive analysis during project progress makes it possible to assess the probability of different paths becoming the Critical Path during all phases and take action to optimize performance and reduce risk.

2.8 Concluding Observations on Network Analysis

Network analysis in project management is a significant advancement from traditional PERT and Critical Path Methods. This approach optimizes activity chains, manages milestone criticality, and reduces risk. It offers a visual representation of a megaproject's structure and dynamics, allowing project managers to better comprehend its complexities. Visualizing the project as a system simplifies identifying the most effective changes and interventions to identify the most effective solutions. Constructing and analyzing a project network originates from an "inside view" approach, focusing on its internal characteristics, resources, activities, and relationships (Lovallo, et al., 2023). Earlier, we emphasized the "outside view" importance, learning from previous track records. This section demonstrated how to improve and merge both views by mapping learned risks and records to specific nodes, such as milestones within the project network, multiplying their benefits. The granular project network state during planning influences its evolution during execution. By mapping the risk model to the project network, we establish a foundation to reduce risk through effective action. We will now explore how a suite of digital technologies can support this process and optimize project performance.

3 CONCEPTUAL MODEL FOR DIGITAL TECHNOLOGY-ENABLED RISK REDUCTION

We have seen how network analysis tools can effectively analyze and describe complex project networks. In this section, we integrate AI/ML, data analytics for risk reduction, and decentralized technologies for distributed governance of complex multi-party project networks into a conceptual model. Advances in digitally enabled project delivery (Whyte, 2019) enhance communication and data visibility. The vast amounts of data generated in a megaproject serve as a valuable resource for learning and refining planning and decision-making. AI/ML and data analytics tools offer powerful means to utilize this data for gaining insights and making informed decisions. These tools help overcome human cognitive limitations, improving efficiency, accountability, and transparency. By analyzing extensive data and providing insights and recommendations, they assist in making better decisions and optimizing project performance, especially in complex megaprojects where human cognition faces limitations due to scale and complexity.

Decentralized technologies, such as zero-knowledge proofs (ZKP) and smart contracts, facilitate distributed governance, promoting transparency, accountability, and collaboration among all parties. We will describe how AI/ML and decentralized technologies provide a framework for conceptualizing the application of digitization technologies like IoT, BIM, and PLM. By understanding and managing complex interactions within megaprojects, risk can be reduced and managed, moving the mean of project risk distributions closer to zero and decreasing the fat-tail size. This comprehensive approach enables more effective megaprojects management.

3.1 Capital Project Planning

Several professional organizations have developed guidelines and best practices for project cost estimation, including the Association for the Advancement of Cost Engineering (AACE), the International Project Management Association (IPMA), and the Project Management Institute (PMI). These frameworks provide guidance on planning, estimation, and management. However, it is essential to consider the biases and limitations of expert judgment in the estimation process and use actual distributional data in project records to correct these biases and improve accuracy (Natarajan, 2022).

The capital project planning process starts with identifying and evaluating potential projects aligning with an organization's strategic goals. Projects are evaluated, and decisions are made at succeeding stage-gates (Merrow, 2011). The goal is to make informed investment decisions considering a project's risks and benefits. These decisions must consider the non-normal distribution of risk and the impact of human biases on risk assessment. Data analytics and AI can help to predict and mitigate risks by considering the outside view or actual performance records more accurately. By analyzing patterns and trends in historical data from similar projects and connecting them to causation factors related to participants and activities identified by project network analysis, it is possible to develop a more accurate understanding of the likelihood of these risks. Once the probabilities are determined, more informed project selection can happen. During detailed planning, plans to reduce their likelihood of occurrence, such as additional controls or managing occurrence with contingency plans, can be formulated. Proactive management of high-impact unknown risks can mitigate their impact on the project and improve overall outcomes.

3.2 Forecasting

Effective forecasting methods can reduce risk by reducing the gap between planned and actual project outcomes. ML and digitization can improve these methods. To assess risks more effectively during planning, it is necessary to use the "outside view" (Flyvbjerg, 2006) using actual distributional records of similar projects, which incorporate deviations due to cognitive and principal-agent issues in past projects. This approach enables more accurate risk and challenge predictions. ML, learning from distributional data, can enhance this method, further improving risk assessment. For instance, Reference Class Forecasting (RCF) is a structured forecasting methodology (Lovallo, et al., 2023) that compares the planned project to a "reference class" of similar projects to estimate the likely cost and schedule outcomes. ML models can extend RCF to generate project-specific uplifts by learning the relationship between project features and performance outcomes accounting for project variability (Natarajan, 2022). Milestone risk distributions and risk drivers can be learned from past project data and mapped onto individual milestones identified by network analysis. The ability to learn from previous projects using ML and better data from digitization can improve forecasting accuracy and reduce the likelihood of cost and schedule overruns. It can help to ameliorate principal-agent issues and correct biases that affect forecasting.

3.2.1 The future of Earned Value Management

Earned Value Management (EVM) is a project management technique to measure progress and performance. It involves analyzing metrics like the actual cost of work performed (ACWP), planned value of work performed (PV), and budget at completion (BAC) to determine the cost and schedule variance of a project. While EVM can provide valuable insights into project progress, its linear extrapolation does not account for causes of deviation or the risk profile of upcoming milestones. These are limitations for forecasting future cost or schedule performance. The combination of EVM with project network analysis and a granular understanding of risk causation at milestones can significantly improve forecasting accuracy. Risk assigned to milestones and paths by network analysis can be updated with actual project performance using algorithms and ML to forecast probabilistic paths to completion and identify potential issues before they become major problems.

3.3 Distributed Governance

The challenges to centralized governance in meta-organizations (Marrewijk, 2005), their challenges in adapting to change (Davies & Mackenzie, 2014) and dispersed knowledge and expertise across networks (Di Marco, Alin & Taylor, 2012) support a more decentralized governance model. However, the effect of principal-agent issues (Flyvbjerg, 2014) and asymmetric power (Clegg, et al., 2017) make it challenging to achieve in Megaprojects. Blockchain and other technologies have made decentralized governance more feasible by enabling trustless interactions between parties.

3.3.1 Blockchain/DLT

Blockchain or Distributed Ledger Technology (DLT) can codify project contract requirements into smart contracts and facilitate synchronizations across the meta-organization. This makes distributed governance more feasible for complex project participant networks, incorporating internal and external stakeholders in decision-making processes. Collaborative governance can significantly improve the performance issues that plague capital projects. DLT can bring greater accountability and efficiency by enabling selfregulating project networks consisting of authenticated stakeholders referencing a consensus-based single-source-of-truth. Project networks can encompass mutually agreed schedules, commitments and autonomous change tracking without requiring centralized control. DLT can help administer complex contracts across project participant networks or meta-organizations using smart contracts to codify the rules (Natarajan, 2021). Project milestones can be implemented as consensus-based smart contracts, digital contracts executed automatically when specified conditions are met. These smart contracts can be used to encode the project milestone details, such as tasks, roles, responsibilities, and payments.

A single-source-of-truth, with authentication of participants and consensual milestones, will help mitigate the effects of complexity, cognitive limitations, and principal-agent issues. Commitments by participants are verifiable against their public keys without requiring trusted third parties resulting in more accurate forecasts during planning. A single-source-of-truth will enable collective response to unforeseen events during execution. A project can become a responsive organization comprised of all stakeholders. In addition, authenticated and verifiable project and participant track records will enable the practical and effective application of AI/ML. DLT-based platforms for collaborative project governance can revolutionize project management.

3.3.2 Zero-knowledge proofs

Zero-knowledge proof (ZKP) is a cryptographic method that allows one party to prove to another party that they know a specific piece of information without revealing the information itself. ZKPs allow for secure, verifiable transactions without revealing sensitive information. This can be particularly useful for confidential projects, where information needs to be kept private but still verified by all parties. ZKP can be used to verify that a milestone has been completed without disclosing the details of the milestone or its schedule. ZKP can improve project efficiency and effectiveness by ensuring that all teams work towards the same set of goals. Teams can build an Integrated Master Plan (IMP) as a trusted-source-of-truth without compromising the confidentiality of individual schedules.

3.4 Digitization Technologies - Integration with Blockchain & Data Analytics

3.4.1 BIM and PLM

Building Information Modeling (BIM) is a digital representation of a facility's physical and functional characteristics, which can be used to plan, design, construct, and manage the lifecycle of a building or infrastructure. Product Lifecycle Management (PLM) is a digital system for managing the entire lifecycle of a product, from design and development to production, use, and disposal. It is often integrated with CAD/CAE/FEA for design and analysis. BIM can help project management through its ability to organize and exchange information among the parties involved in a project, which may have conflicting views and interests (Scheffer, et al., 2018). Synergistic technologies with BIM and PLM include Augmented Reality (AR) for overlaying digital information onto the real world; Virtual Reality (VR) for training, simulation, and visualization; and 3D Printing for rapid prototyping and customization. All this will support increased Robotics and Automation in construction spaces increasing efficiency and reducing error. BIM and PLM can provide a comprehensive, integrated view of project data, enabling better decision-making and collaboration. Machine learning and data analytics can help analyze the data, and map it to project networks, progression, and risk. Integrating these technologies with blockchain will enhance data traceability and participant accountability, improving trust and collaboration.

3.4.2 IoT/ Digital Twins

Internet of Things (IoT) devices and digital twins can improve project management and asset maintenance by generating large amounts of data for analysis. AI, data analytics, and blockchain can effectively analyze and utilize this data for more accurate forecasting and risk management. By using blockchain technology to track the provenance of data feeds from IoT devices, it is possible to enhance the trustworthiness and transparency of information used in the project.

ICT components and digitization requirements are increasingly significant aspects of physical infrastructure projects. As digital twins and cyber-physical systems gain prevalence, new opportunities for integrating asset operation plans into project creation emerge. Verified Credentials associated with blockchain public keys can represent digital twins, enabling better traceability, transparency, and management. This integration can improve project efficiency, enhance collaboration, facilitate seamless transition from project development to asset operation, and facilitate machine learning for predictive maintenance.

3.4.3 GIS

Geospatial technologies, such as Geographic Information Systems (GIS), Remote Sensing, and Global Positioning System (GPS), help by collecting, analyzing, and displaying geographic information in capital projects. GIS enhances IoT integration by providing geospatial context for sensor data and digital models, improving real-time monitoring and decision-making. Combining GIS with BIM allows visualization and analysis of built environments within geographical contexts, promoting better design and construction. GIS aids PLM implementation by providing geospatial information for asset management and maintenance, optimizing resource use throughout the lifecycle. Integrating geospatial technologies with blockchain and data analytics can help stakeholders visualize and track project progress, allocate resources efficiently, and monitor environmental impacts.

3.5 Conceptual model

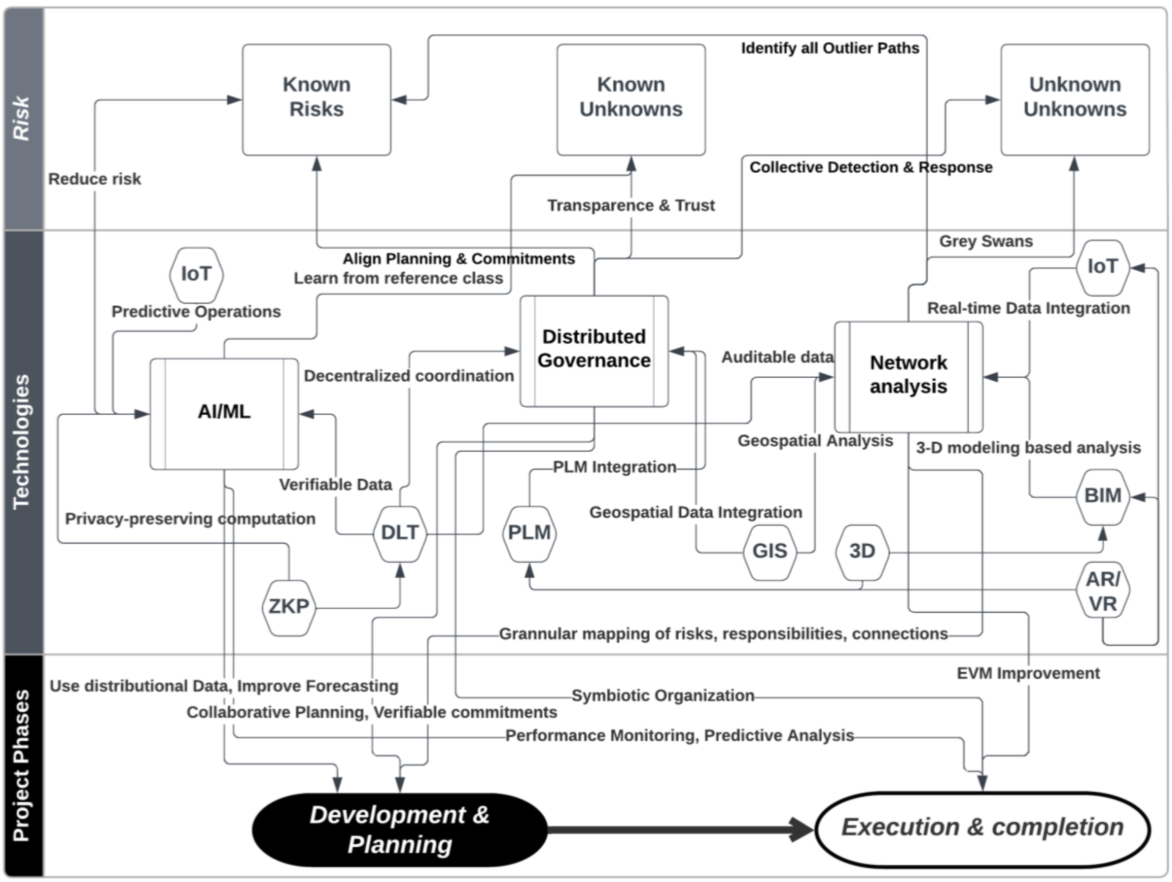

Figure 3-1: Conceptual Model of Integrated Project Governance Framework using Digital Technologies for Distributed Governance, Learning and Network Analysis

Megaprojects involve multiple stakeholders and significant risks, including known unknowns, unknown unknowns, and known risks, characterized by fat-tailed distributions containing black swans. The conceptual model of an Integrated Project Governance Framework is presented in Figure 3-1 to mitigate these risks and improve project efficiency by integrating digitization technologies and risk management strategies.

The project progression layer encompasses the entire project cycle. The development and planning phase uses collaborative planning and verifiable commitments enabled by distributed governance, historical data, and machine learning for risk forecasting. Network analysis is applied to identify critical paths, dependencies, and bottlenecks, providing insight into the risk landscape. In the execution and completion phase, the project progression layer employs symbiotic organization and collective response enabled by distributed governance, as well as predictive analysis and improvement over earned value management (EVM) through machine learning and network analysis. These tools can help to identify and mitigate risks as they arise, ensuring that the project stays on track and within budget.

Mitigation methods include collective detection and response, improved transparency, trust, and collaboration to reduce the gap between inputs to planning and actual commitments. The digitization technology layer comprises DLT, IoT, BIM, PLM, and GIS, which are integrated using AI/ML and network analysis. Distributed governance using DLT and ZKP unifies the meta-organization. Advanced AI and data analytics on cloud platforms can seamlessly process extensive IoT data streams and swiftly deploy predictive analytics and other tools. Cloud and edge computing facilitate efficient data access and real-time analytics, optimizing performance and decision-making.

- IoT integrates with Network Analysis and AI/ML, enabling real-time project performance monitoring and adaptive project plan adjustments.

- BIM connects to Network Analysis, allowing 3D visualization of the built environment, facilitating identification of critical paths, dependencies, and potential bottlenecks in the construction process.
- PLM links to Distributed Governance and Network Analysis, fostering collaborative planning and verifiable commitments.
- ZKP with DLT provides secure and transparent data sharing while protecting sensitive information.
- AI/ML is connected to Network Analysis in all phases, facilitating pattern and trends identification in project data and improved forecasting.
- GIS integrates with network analysis and distributed governance enabling geospatial analysis and governance, fostering data-driven decision-making.

This conceptual model provides a comprehensive framework for understanding how digital technologies can contribute to risk reduction and management in megaprojects. By integrating these technologies with risk management strategies, project teams can improve efficiency, reduce risk, and achieve better outcomes. This model provides recommendations for implementing these technologies and managing project risk more effectively.

4 CONCLUSION

General-purpose technologies (GPTs) such as AI/ML and Blockchain will transform the project management landscape (Steen, et al., 2022). Megaprojects are essential for addressing climate change and fulfilling infrastructure needs in a time of limited resources and significant developmental disparities. However, their complexity leads to performance challenges, making project efficiency a vital concern. Our paper aimed to explore the nature of risk in these projects and the role of digital technologies in risk reduction and management. Through a mixed-methods approach, we developed a comprehensive conceptual model of risk and mitigation strategies.

We provided an integrated conceptual framework combining methods and digital technologies effectively to reduce risk and close the gap between planned and actual outcomes in megaprojects. We examined the use of these technologies for accurate risk forecasting and reduction during project planning and for mitigating and controlling risks when they arise. Our paper emphasized the potential of network analysis and AI/ML in managing complex stakeholder networks, describing several analysis techniques and characteristics of project networks. Our analysis revealed self-similar patterns in project networks, which can be exploited by AI/ML, and data analytics methods. By leveraging data and advanced algorithms, we can better understand complex interactions between components and stakeholders, optimize activity chains, manage milestone criticality, and reduce risk. Network analytics with AI signifies a paradigm shift from traditional project management methods, enabling project managers to better comprehend megaproject complexities and take effective action to optimize performance and reduce risk.

Additionally, we discussed distributed governance, utilizing decentralized technologies like blockchain to make complex multi-party projects more manageable through efficient and effective collaboration among all participants. Blockchain technology can further enhance the benefits of network analytics by providing a decentralized platform for storing and sharing data and governing stakeholder networks inclusively. This fosters greater transparency, accountability, and collaboration among all parties involved in the project, ensuring a unified pursuit of common goals. Moreover, using smart contracts can help ensure that all parties fulfill their commitments, completing the project on time and within budget.

Harnessing advanced technologies in project governance offers tremendous potential for improving megaproject efficiency, effectiveness, and sustainability. It is important to explore and develop their potential and facilitate their rapid adoption as megaprojects grow in complexity and importance. To achieve this, the project management community, including professional bodies and research institutions, must help standardize project outcome reporting and develop a framework for blockchain in multi-party projects. By taking these steps, we can better understand how to effectively implement these technologies and maximize their potential benefits. Further exploration of network analysis and AI applications to stakeholder networks is warranted.

We described how to improve the "inside" and "outside" views, combine them for more potency, and integrate them into a holistic collective governance system for complex multi-party projects. The conceptual Integrated Project Governance Framework provides a foundation for understanding the role of digital technologies in risk reduction and management in capital projects, offering practical recommendations for implementation and setting the stage for future research.

4.1 Limitations

Utilizing distributional data to forecast outcomes in complex systems presents various challenges and limitations. One is that high-impact Black Swans will not manifest the same way in future projects. However, grey swans or prior black swans in the distribution can provide insight into the probability of future black swans. Other challenges include the availability, validity, and reliability of distributional data, which can be subjective, prone to errors and biases, and interpretation errors. Megaprojects often involve unique occurrences specific to their environment, complicating their use in future forecasts (Sovacool & Cooper, 2013). Obtaining reliable or sufficient data can be difficult, and cognitive biases can lead to an overreliance on the representativeness of past occurrences. Noise and errors in the data can significantly impact forecasting accuracy (Gigerenzer & Brighton, 2011).

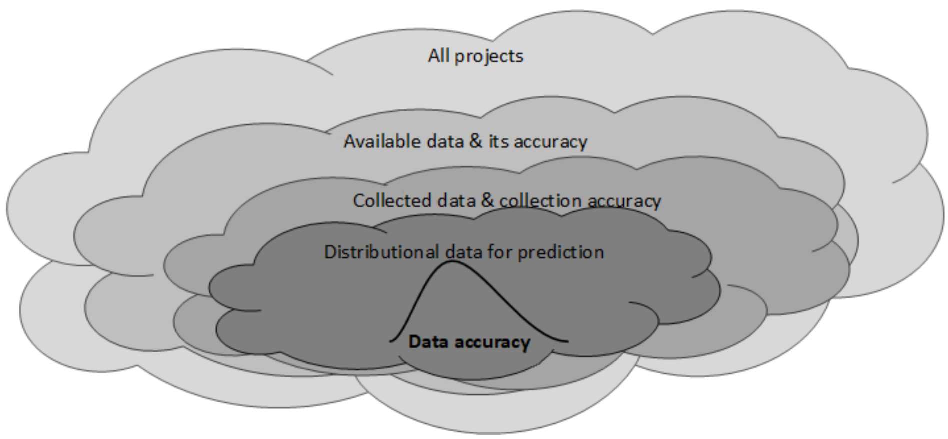

Figure 4-1: Limitations to distributional data

Interpreting distributional information is subject to several sources of error, including cognitive biases and systematic biases in selection mechanisms (Kahneman & Tversky, 1974). Extrapolating from the recent past or a long-time frame can also affect data reliability. In some instances, biased heuristics may be more effective than unbiased models (Gigerenzer & Brighton, 2011). While the "outside view" using ML and analytics operating on data from previous projects can significantly improve megaproject performance, it is crucial to thoroughly comprehend the limitations and challenges of using distributional data in complex systems, and to find ways to mitigate these issues in the context of megaprojects.

4.2 Recommendations

We propose several recommendations to promote the growth and adoption of AI/ML, data analytics, and blockchain in project management. Standardizing project reporting, including planned and realized costs, schedules, and benefits, is crucial. This will enhance data reliability and ensure fiduciary responsibility to stakeholders, including shareholders and external stakeholders. Minimum requirements for project data used in analytics and AI should be established to ensure the quality and size of datasets. Since "garbage in, garbage out" applies to these technologies, ensuring the accuracy and relevance of data is vital. It may be helpful to look to existing accounting standards, such as the International Financial Reporting Standards (IFRS), to develop suitable project accounting standards.

A framework for employing blockchain in multi-party projects should be established, including guidance on data privacy and the relationship between smart contracts and project contracts. Decentralized Identity (DiD) and Verifiable Credential (VC) standards are the lynchpins of identity in decentralized networks; the project management community must take the lead in developing these for projects. Data ownership is an important issue that can affect data sharing on the blockchain. Careful consideration of these issues is necessary to develop a clear understanding of how to implement these advanced technologies effectively in project management. This will maximize potential benefits and accelerate adoption.

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