Article

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A Risk-Based System Dynamics Model for Sustainable Expert Workforce Allocation in Industrial Multi-Project Environments

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Abstract

This study constructs and refines a dynamic simulation framework that brings together risk and effectiveness factors affecting qualified workforce allocation in multi-project contexts, specifically in the construction of industrial production facilities. Based on a case study of three overlapping projects in West Java, Indonesia, the paper examines significant challenges in estimating and planning the requirements for an expert workforce across the Engineering, Procurement, and Construction (EPC) phases. In fact, mitigation measures generally assume that a qualified expert workforce is immediately available. However, getting the right personnel for a project takes time and must be done in line with the specific qualifications. To fill this gap, the paper presents a dynamics-based model that measures project risks and execution effectiveness to determine the need for the expert workforce at the multi-project level. The mixed-methods strategy includes the literature study, variable validation, simulation modeling, and case analysis. The results show that workforce planning based on risk and effectiveness significantly improves project delivery by anticipating expert workforce shortages and reducing the need for reactive solutions. The model contributes to sustainability by enhancing long-term workforce resilience, reducing resource waste, and supporting more efficient industrial project delivery.

Keywords: multi-project environment; system dynamics simulation; risk-based modeling; sustainable industrial project management; human capital sustainability; sustainability EPC

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1. Introduction

To address production needs in an organization's daily operations, innovation and product development are crucial. These things ensure that the organization stays in business and becomes more competitive. Projects are activities planned to achieve innovation or development while staying within specified time and resource limits. These undertakings need practical resources and good time management to be successful [1,2]. Organizations commonly undertake projects to address internal needs [3,4] and fulfill strategic ob-jectives [3,5], such as enhancing efficiency, creating new products, or adapting to changing market and regulatory demands [6]. Projects aimed at diversifying products or meeting current requirements may result in the development of industrial production facilities, thereby affecting the company's operational strategy [7,8]. The project life cycle is a series of steps that take a project from start to finish [9,10]. It gives project leaders an organized way to ensure projects move forward and achieve their goals [5,10–12]. The first stage is the feasibility assessment, during which the business case is analyzed to ascertain the project's viability [13]. The subsequent phase involves planning and organization. This ensures the organization is prepared to achieve its objectives by establishing a management framework, forming teams, and allocating resources. Engineering, construction, and testing are important parts of the implementation process. They ensure that the project's deliverables meet quality requirements before they are handed over. The

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closure phase formally ends the project by documenting all deliverables and ensuring that the organization receives the benefits it was supposed to. This project life cycle framework can be used in several ways, including in sequential order or with overlapping phases. The best way to use it depends on how complicated and unique each project is. There are three primary project types: infrastructure, building, and industrial [14]. Human resources are significant for industrial initiatives, especially those involving the construction and development of production facilities [7]. The main factor in determining whether a project will be successful is having qualified personnel [1,2,10]. An expert team is essential during the engineering phase, as they turn project requirements into a clear scope of work. Experts plan, analyze, and monitor the acquisition of goods and equipment during procurement [9]. During the construction and installation phase, a team of experts is responsible for planning, reviewing, supervising, and testing to ensure that every work item meets the project's quality requirements [15]. In a multi-project setting, where projects may develop simultaneously, overlap, or run one after the other, it becomes harder to manage them [4,16–19]. There are numerous ways to manage the building of production facilities in industrial construction projects. One way to do this is for the project owner to manage the project themselves, utilizing their own resources [1,2,16,18,20]. Another method is to hire consultants to help with planning, design, supervision, and implementation. The project owner would then contract the vendors and subcontractors directly [21]. A third option is to hire a main contractor to complete the entire project under a lump-sum or EPC (Engineering, Procurement, and Construction) contract. The contractor takes on all the project's risks. This study focuses on the execution phase of industrial construction projects, during which the project owner is tasked with hiring consultants to supervise implementation and provide expert workforce resources. These professionals are used throughout various phases, including planning, engineering, procurement, construction, and the setup of production facilities [22]. In this situation, one of the biggest problems is accurately planning and assigning an expert workforce, especially when multiple projects are underway simultaneously or overlap, which makes the required workforce more complex [1,4,16,17]. When there were differences between planned and actual demand for the expert workforce, shortages often occurred, affecting project timelines and outcomes [1]. Project owners who use external expert workforce contractors must deal with additional delays, as it takes time to mobilize the expert workforce and ensure everyone is qualified [4,21]. To tackle these issues, this research presents a predictive and adaptive modeling methodology grounded in system dynamics that integrates quantifiable project risks and execution effectiveness variables into a feedback loop. This system enables organizations to dynamically predict the needs of their expert workers and make better decisions across multiple projects. This research also contributes to the broader sustainability discourse by linking human-capital planning to industrial resource efficiency. Sustainable projects management requires not only minimizing environmental and financial waste but also ensuring the long-term availability and effectiveness of expert personnel, a vital yet often neglected component of organizational sustainability.

2. Literature Review

2.1. Multi-Project Environment

A multi-project environment is when an organization works on numerous related projects simultaneously [2]. Managing these kinds of projects is different from managing just one project [16]. This complexity creates problems in assigning workers, such as finding the right balance between workloads and project lifespans [1,18]. Numerous studies have underscored the essential function of resource and personnel management in ensuring the efficacy of multi-project management [23]. Construction projects frequently encompass numerous unique complications, especially in multi-project environments, including the following: (1) meeting the expectations and getting the attention of senior management; (2) clearly defining what a multi-project environment is; (3) effectively managing shared resources; (4) setting up and keeping an integrated scheduling system; (5) making sure that communication and coordination across projects are good; and (6) managing risks that come

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up when doing multiple projects at once [17]. Managing multiple projects simultaneously is what multi-project management entails. These projects may differ significantly in complexity and quality, and they are often tied to one another [2]. It can also refer to situations in which one organization works on multiple initiatives simultaneously, even if they aren't immediately related. In this managerial setting, there are unique problems, such as allocating resources, coordinating teams, and maintaining standards across projects [23].

In summary, descriptions of multi-project settings as provided in prior research gen-erally cover the following aspects: (1) organizational activities that involve doing sev-eral projects at the same time, whether or not these projects are related [1,19,22]; (2) pro-jects that use intangible resources, like ideas and innovation, but are limited by physical resources that change over time, which means that scheduling and coordination are required to be done well [1,2]; (3) the management of multiple projects within a company at the same time, which often includes planning and optimizing at the portfolio level [2]; and (4) organizational and operational conditions in which several projects are carried out either at the same time or one after the other, depending on the company's strategic and capacity needs [1]. In a multi-project setting, resource flows, risk interactions, and effective feedback loops constantly change and affect one another. Understanding these interdependencies is the first step in building a system-based model that supports adaptive decision-making to deploy the expert workforce across many projects simultaneously.

2.2. Risk and Dynamic Systems in Industrial Development Project

Risk is a possible event or situation that, if it occurs, could either advance or impede the project's goals [24,25]. In project management, risks can manifest as potential problems that affect the schedule, budget, and quality of a product or service [26]. Risk analysis entails assessing the likelihood of a risk occurring and how it could affect project goals, which in turn requires the use of suitable control measures [24]. Modeling and simulation can improve this analysis, particularly by using a system dynamics approach. This method helps capture the complex and changing nature of risks in project environments [27]. System dynamics is a strategy for analyzing and managing complex, changing systems. It offers, which involves creating and using simulation models [28,29]. This method, that had been first developed in the late 1950s, was initially used to evaluate industrial systems [30].

In construction and project management, system dynamics modeling helps tackle challenges that involve (1) complex systems with many interconnected parts and (2) dynamic systems defined by processes that include feedback loops [31]. Industrial projects relate to building or renovating facilities that support industrial activities. This includes production facilities and buildings used for economic activity, such as processing or manufacturing raw materials into final products. These projects include a variety of facility types, such as production plants, refineries, power plants, and chemical plants, along with their related components [14]. Building industrial facilities requires a thorough approach encompassing planning, design, construction, operation, and maintenance. These procedures must follow existing technical and environmental regulations. This study combines risk analysis and system dynamics to examine how uncertainty and feedback loops shape the need for an expert workforce in industrial development initiatives. This approach provides a foundation for a practical system innovation framework.

3. Methodology

The technique applied in this research combines literature analysis with a case study approach to address issues in multi-project management, specifically within the construction industry facility. This study identifies and validates critical variables affecting project execution by integrating qualitative and quantitative methodologies, particularly through the allocation of expert personnel in multi-project settings [1,4,28]. Initially, a comprehensive literature review was conducted to identify relevant and valid variables from previous studies. These variables were thereafter examined through questionnaires distributed to experts and practitioners pertinent to the research focus. The

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verified variables highlighted the underlying study issues, which were further confirmed by field observations from different ongoing construction projects. Case studies were used throughout the project lifecycle to make sure it was viable and to validate both the conceptual and simulation models. A causal loop diagram (CLD) was created to examine how the variables are connected and how the system operates. Then, a stock-and-flow diagram (SFD) was constructed to show how the system's output changes over time. Ensure that it was appropriate. Model validation was performed across the phases. Validate the model's estimate of the required man-hours for the expert workforce using data from previous projects. The model was used for scenario-based risk analysis, which examined different inputs and provided the relevant outcome. It identified the most significant factors affecting the project's risk, and as a result, an expert workforce would be required.

These include resources, organizational structure, environmental factors, external factors, design, and technical obstacles [6,7]. The entire research method included a few interconnected steps: a comprehensive literature review, empirical testing of variables through questionnaires distributed to experts in the industrial facilities industry [28], and ongoing enhancement of a dynamic system model. This approach was created to simulate and improve the allocation of expert personnel in environments with several projects. It provides a structured approach to efficiently deploy expert workforce resources [28,29,32]. Figure 1 shows how to take a proactive approach to planning an expert workforce in complex multi-project settings to support the entire research process and its sequential stages.

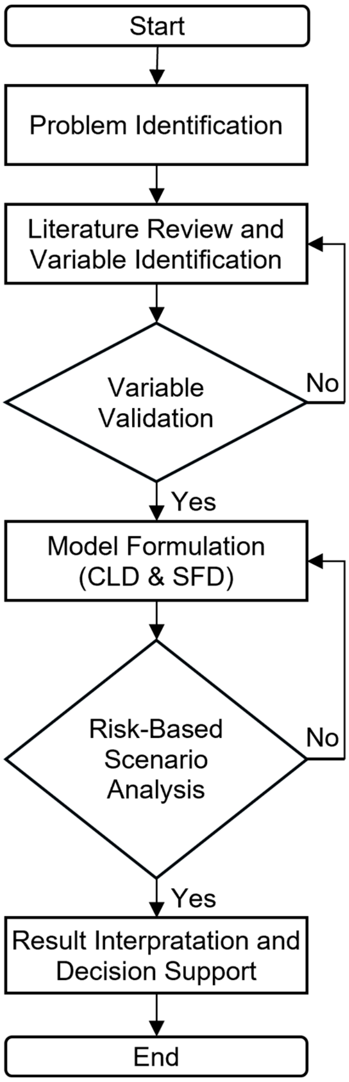

Figure 1. Research flow diagram.

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When several projects are underway at the same time, a special method is needed to track how the need for expert workforce resources evolves over time, especially when it pertains to the risks encountered in project execution [17,33]. These risks may vary in intensity and effect over the course of the project, and they may coincide, affecting the overall demand for experts [24,25,34–39]. Systems dynamics is used to address these complex, continually evolving situations. This modeling technique enables determining and adapting the number of expert workers needed across multiple projects, which is beneficial for allocating them when risk profiles change [1,27,28].

4. Result

This case study examines three chemical-process-based production facility projects in West Java, Indonesia. These facilities, commonly referred to as processing plants, have been executed during the project implementation phase, which includes planning, detailed engineering design, procurement, construction, and installation. The combined scope of work covers Projects A, B, and C, as shown in Table 1, which outlines the overall effort required to complete each project from engineering to commissioning.

Table 1. Volume of work for EPC (Engineering, Procurement, and Construction).

Description	Work of Supply	Unit	Project A	Project B	Project C
General Civil	Concrete Work	m^3	5,900	4,500	3,000
	Steel Structure Work	Ton	1,900	100	200
Mechanical and Piping	Major Equipment and Mechanical Package Work	Each	110	100	120
	Piping and Ducting Work	Inch–dia*	127,000	44,000	60,000
	Valves Work	Each	2,000	1,000	1,500
Electrical and Instrument	Cables Work	Meter (m)	203,000	146,000	76,000
	Cable Tray Work	Meter (m)	18,000	12,000	8,000
	Cable Termination Work	Point	8,000	2,000	2,000

* inch-dia denotes the cumulative quantity of piping installation, calculated as the sum of nominal pipe diameters multiplied by their installed lengths. It represents the total welded inch-diameter of piping installed. All other quantities are expressed in their respective standard units.

The expert workforce is responsible for performing the work during the planning and engineering phase, in accordance with the project owner's requirements and specifications. The group of experts works across many fields, including civil and architectural engineering, mechanical and piping engineering, electrical and instrumentation engineering, process control engineering, and project management [20,21]. During the procurement phase, the expert personnel are responsible for planning and acquiring materials and equipment for the production facility that complies with the project's design specifications. During construction and installation, the expert workforce is crucial to ensuring the work proceeds according to the plans developed during the engineering phase. Table 2 shows the estimated man-hours of the expert workforce on the Engineering, Procurement, and Construction (EPC) phases. All the numbers are in man-hours.

Table 2. Estimated total expert workforce allocation (man-hours) by project phase.

Work Activity	Project A	Project B	Project C	Multi-Project Total
Engineering	155,320	83,440	95,610	334,370
Procurement	25,590	18,580	25,570	69,740
Construction	132,950	98,720	97,880	329,550
Total man-hours	313,860	200,740	219,060	733,660

Figure 2 presents a histogram showing the relationship between the number of man-hours assigned to a project and the cost required to complete it. It also shows how the demand for an expert workforce is spread across different phases. The findings show that the engineering phase has the most demand for expert personnel across all projects. The phrase "expert mh" refers to the total number of expert man-hours, and "cost" refers to the project's total cost. Both numbers have been adjusted to 100%.

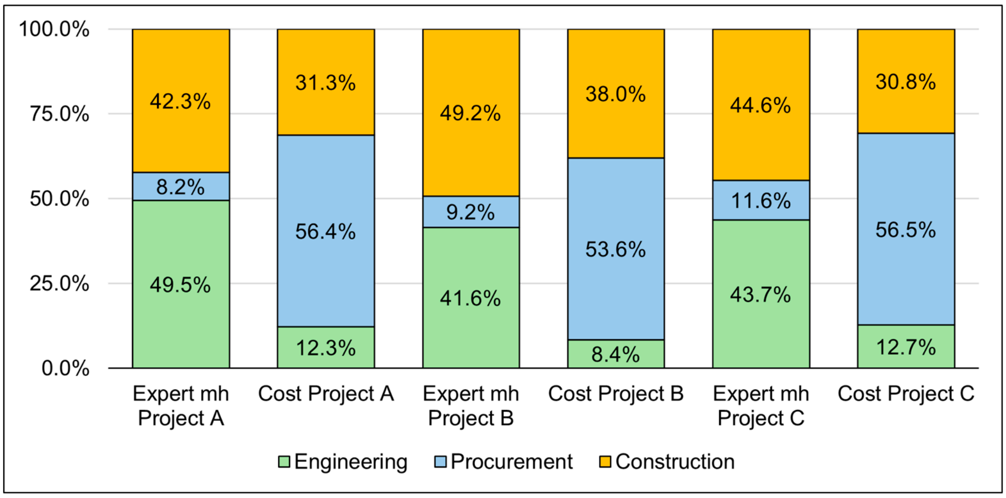

Figure 2. Distribution of expert workforce man-hours and project cost across EPC phases.

Each organizational unit assigned to a project is responsible for planning and providing its respective expert workforce man-hour loading, as illustrated in Figure 3 for Project A. Within a multi-project management framework, the project owner supervises and coordinates the overall allocation of expert workforce man-hours across all ongoing projects.

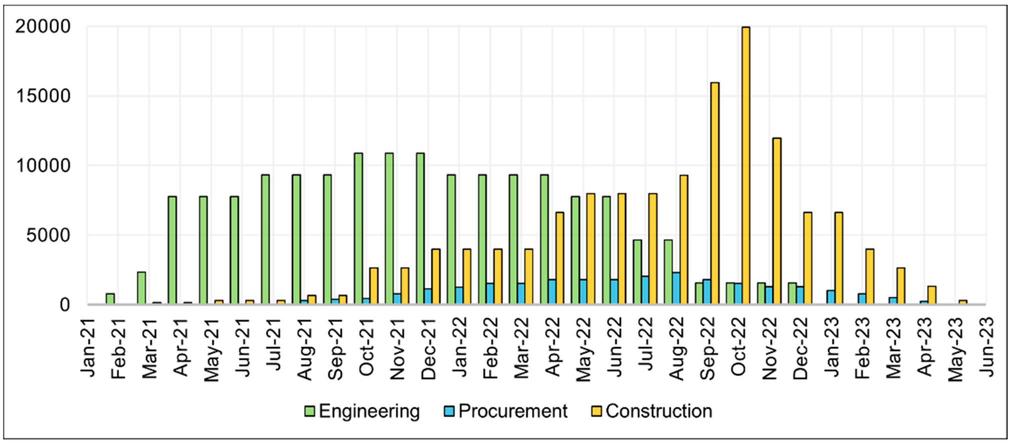

Figure 3. Distribution of planned expert workforce man-hours in Project A.

Risks affecting the demand for expert workers' hours emerge at both the project and multi-project levels. Modeling these demands at both levels improves the ability to identify potential expert shortages throughout project execution. Field observations and literature reviews were conducted to identify relevant risk variables and evaluate the effectiveness of multi-project implementation. These variables were then validated statistically based on feedback from construction professionals. Figure 4 presents a simplified Causal Loop Diagram (CLD) that illustrates the interrelationships among expert workforce man-hour demand, multi-project effectiveness, and project-level and multi-project risks.

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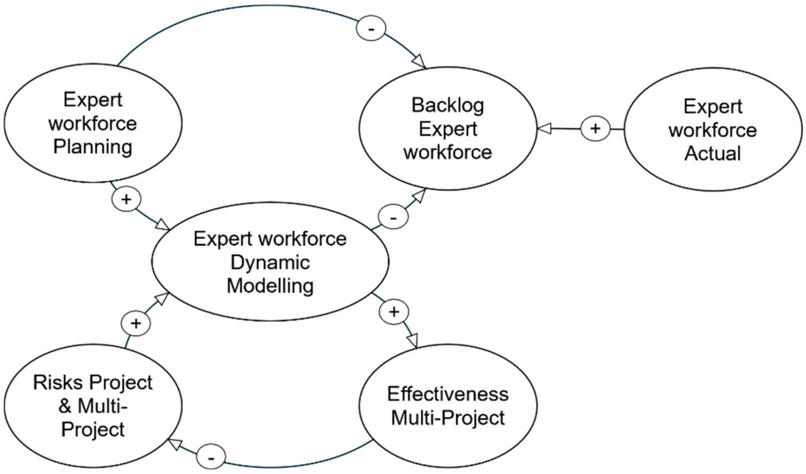

Figure 4. Simplified Causal Loop Diagram (CLD).

Table 3 lists the main risk variables that affect expert workforce man-hour allocation, particularly during engineering-related activities. Risk index values quantify factors such as the degree of supervision and adoption of new technologies; higher scores indicate greater effects on the number of man-hours required. The level of supervision is a crucial factor that directly affects the additional man-hours needed to mitigate project risks.

Table 3. Risks affecting the required expert man-hours for engineering work.

No. Variable	Risk for Engineering Work Affecting Allocation of Expert Workforce Man-hours	Index Value	Occurring Phase
X2.1	Level of Work Supervision	0.25	EPC
X2.10	Level of Project Financing Consistency	0.20	EPC
X3.1	Level of Involvement of Local Workforce (Workforce Qualification)	0.25	EPC
X4.2	Undefined Construction Costs	0.25	EPC
X4.3	Design Not Verified, Leading to Construction Errors	0.25	E
X4.4	Level of Equipment Damage (Inaccurate Planning)	0.25	EPC
X4.8	Request for Project Duration Acceleration	0.25	EPC
X4.9	Different Geographic and Topographic Conditions (Inaccurate Data and Drawings)	0.25	C
X6.1	Design Errors During Tender	0.25	E
X6.2	Level of Work Changes Due to Design Changes	0.10	EPC
X6.3	Level of Work Changes Due to Technological Changes	0.15	EPC
X7.1	Level of Project Cost Changes	0.15	EPC
X7.5	Level of Market Acceptance of the Product	0.10	EPC

Figure 5 depicts the Stock and Flow Diagram (SFD), demonstrating the impact of accumulated risks on the distribution of expert workforce man-hours in engineering operations. By capturing the cumulative effect of engineering-related risks through reinforcing feedback loops, key variables such as supervision levels and technology changes dramatically increase the demand for an expert workforce.

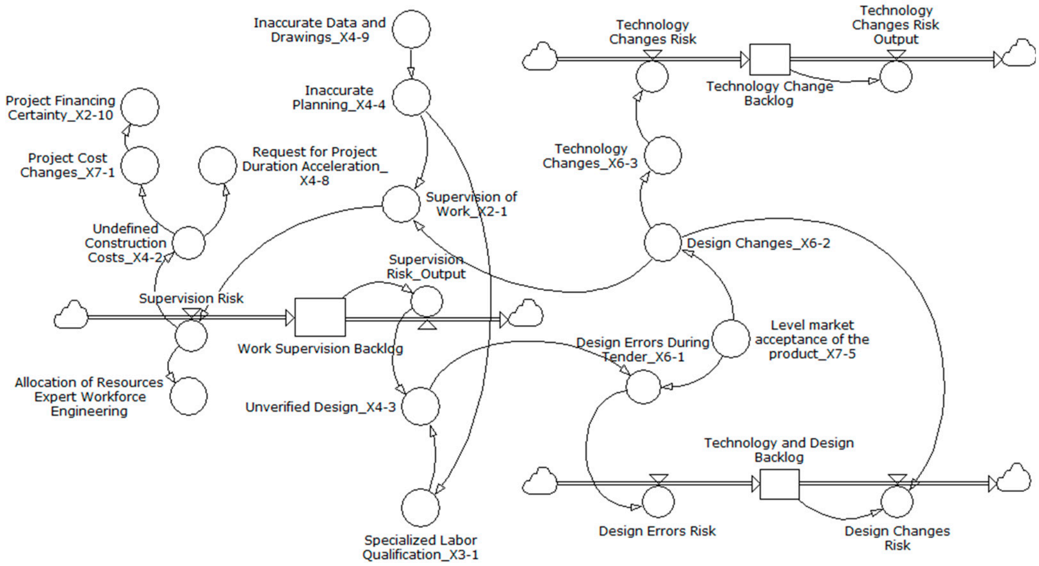

Figure 5. Stock and Flow Diagram (SFD) representing risk factors influencing expert workforce allocation during engineering work.

Besides engineering-related risks, the quality of contractor performance could impact the allocation of expert workforce man-hours. Factors, including environmental conditions, changes in labor regulations, and delays in contractor payments, are incorporated into a risk index that measures the possible escalation in necessary man-hours. A higher score signifies a bigger potential impact, especially in multi-project contexts where stakeholder collaboration is essential. The engineering-phase model accurately delineates the effect of accumulated risks on the allocation of expert personnel through supervision levels, technological changes, and feedback loops. The analytical methodology utilized here can be extended to both the procurement and construction phases, adopting the same modeling principles.

The dynamic model reveals that quality and coordination risks significantly influence workforce requirements through rework and process inefficiencies. Higher rework and coordination risks increase the additional workforce demand needed to manage inter-project interactions and stakeholder alignment. In contrast, effective multi-project coordination improves allocation efficiency by minimizing process losses. A dynamic system model was developed to determine the optimal allocation of expert man-hours during the engineering phase. The model consists of two simulated scenarios, as shown in Figure 6. Scenario 1, the estimated expert workforce assumes a static allocation model, in which expert resources are immediately available from the market whenever shortages occur. This reflects a simplified assumption that an expert workforce can be mobilized on demand, leading to minimal change in the overall workforce profile over time.

Scenario 2, on the contrary, employs a dynamic modeling technique that leverages the quantifiable risk and effectiveness variables created in this study. As risks arise and effective values evolve, the needs of the expert workforce change throughout the project. As a result, the entire allocation of experts to the workforce expands over time, including changes that may not be obvious when employing solely an estimated expert workforce without dynamic modeling. In the real world, when there are insufficient workers, it might affect the timing, scope, quality, and cost of a project. It also combines multi-project maturity by continually changing workforce demands based on feedback on risk and effectiveness.

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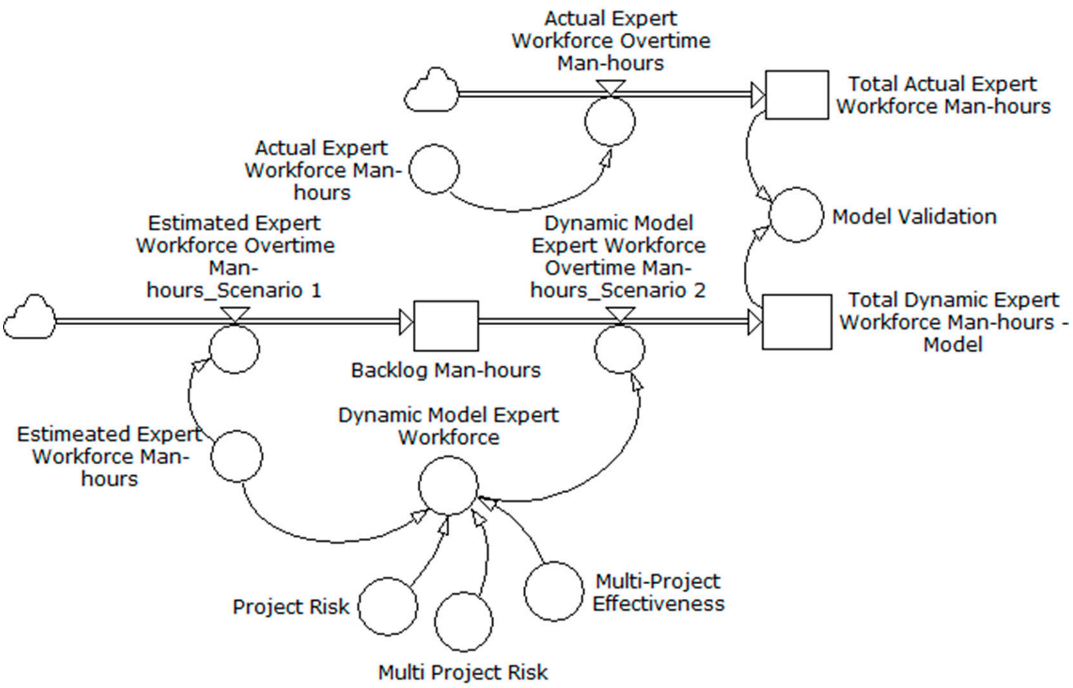

Figure 6. Stock-and-flow diagram (SFD) illustrating two simulated scenarios of expert workforce man-hour allocation.

The simulation integrates the three-phase categories—Engineering (E), Procurement (P), and Construction (C)—within this EPC framework to reflect how functional risks influence man-hour requirements across the phases, resulting in a distinct quantitative impact distributed throughout the EPC process distributed throughout the EPC process, with standard deviation and time-delay parameters. Table 4 summarizes these parameters applied to the simulation scenarios.

Table 4. Simulation parameters influencing expert workforce man-hours across the engineering, procurement, and construction phases.

Parameter for Expert Workforce Allocation	Scenario Definition	Phase Implementation		
		Engineering	Procurement	Construction
Baseline case without risk quantification or effectiveness adjustment over time	1 (Estimated)	-	-	-
Standard deviation accuracy for allocating expert workforce man-hours	2 (Dynamics)	5%	5%	5%
Standard deviation of allocating expert workforce man-hours at the single-project level		5%		5%
Standard deviation of allocating expert workforce man-hours at the multi-project level		5%	5%	5%
Standard deviation of allocating expert workforce man-hours for multi-project effectiveness		5%	5%	5%
Assumed delay in allocating expert workforce (days)		14	30	30
Standard deviation of the delay in allocating the expert workforce		5%	5%	5%

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The simulation results reflect real-world conditions by integrating quantified risk and effectiveness factors as mitigation inputs to estimate expert workforce man-hour requirements. Figure 7 illustrates how this method compares real project data with the expert workforce need over time for both situations. Scenario 2 incorporates additional man-hours as risks change and effectiveness of the multi-project, however, Scenario 1 projects workforce demands without accounting for effectiveness or risk. The third curve in Figure 7 shows actual data from Project A (2021–2023), validating the simulation results.

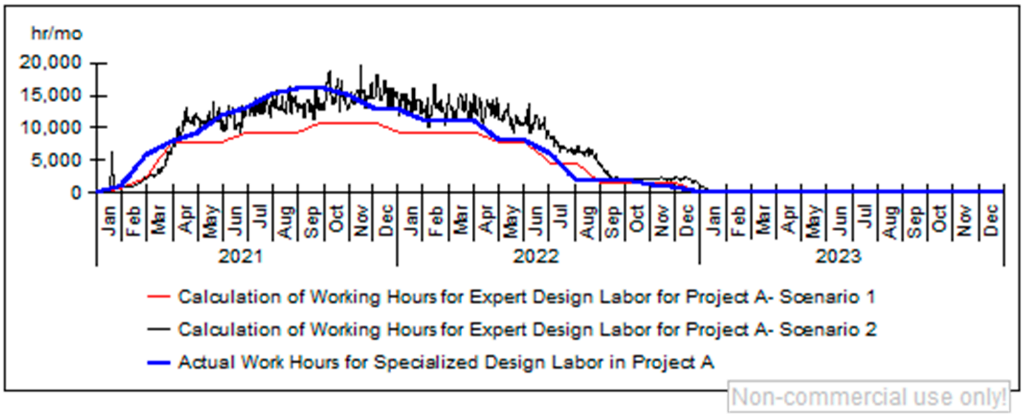

Figure 7. Expert workforce man-hour demand for the engineering design work of Project A.

The simulation results, shown in Figure 8, illustrate the deviation among the three data sets. Two comparisons are made: first, between Scenario 1 and the actual expert workforce man-hour demand, and second, between Scenarios 1 and 2. The results confirm that Scenario 2 provides a close approximation to real-world conditions, serving as a reliable method for simulation-based prediction of expert workforce requirements.

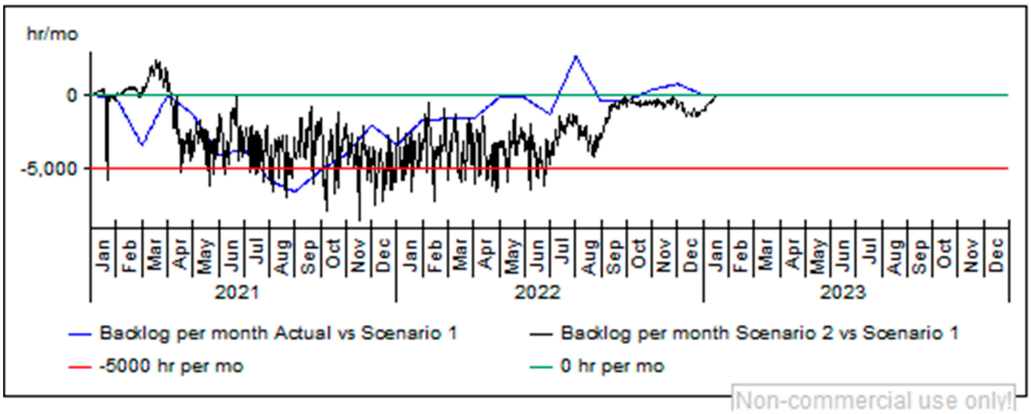

Figure 8. Gap for the man-hours calculation of the expert design workforce for Project A.

Model validation was performed by comparing simulation outputs with actual historical data. As summarized in Table 5, the Scenario 2 simulation accurately predicts expert workforce demand in engineering activities over time, incorporating both risk and effectiveness factors from 2021 to 2023. Further detailed validation for procurement and construction phases, following the same modeling approach, is provided in the Supplementary Materials.

Following Barlas [32], two validation criteria were applied. First, the model's average monthly allocation of expert workforce man-hours was compared with the actual values, and the model was considered valid when the deviation was within ±5%. Second, data variation was assessed by comparing the standard deviation of simulated and actual allocations; deviations within ±30% were considered valid.

Table 5. Comparison of expert workforce man-hour demand for the engineering phase (Scenario 2 versus actual).

Engineering Work (2021)			Engineering Work (2022)			Engineering Work (2023)		
Month	**Scenario 2**	**Actual**	**Month**	**Scenario 2**	**Actual**	**Month**	**Scenario 2**	**Actual**
Jan-21	-	-	**Jan-22**	13,921	12,720	**Jan-23**	952	-
Feb-21	1,018	990	**Feb-22**	13,259	11,030	**Total (2021-2023)**	218,078	203,220
Mar-21	2,221	5,760	**Mar-22**	13,011	10,930	**Average (2021-2023)**	9,087	8,836
Apr-21	7,450	7,790	**Apr-22**	13,145	10,930	**Std Dev. (2021-2023)**	5,095	5,018
May-21	10,977	9,100	**May-22**	12,094	8,950			
Jun-21	10,779	11,830	**Jun-22**	10,791	7,950			
Jul-21	12,076	13,020	**Jul-22**	8,607	5,960			
Aug-21	12,966	15,110	**Aug-22**	6,592	4,480			
Sep-21	12,776	15,900	**Sep-22**	4,041	2,980			
Oct-21	14,520	16,000	**Oct-22**	2,068	1,980			
Nov-21	15,323	14,910	**Nov-22**	2,066	1,190			
Dec-21	15,349	12,920	**Dec-22**	2,075	790			

The validation results confirm that the Scenario 2 model is valid and consistent with actual project data, effectively supporting the entire man-hour estimation for the expert workforce as part of the overall risk-mitigation and effectiveness strategy in multi-project environments. The validation structure refers to Barlas' multiple-test framework to ensure both pattern and amplitude validity. Table 6 presents the results of the average error (<±5%) and amplitude error (<±30%) tests for Projects A, B, and C, demonstrating that the model's behavior closely aligns with actual expert workforce utilization across the engineering, procurement, and construction phases.

Table 6. Validation model (Scenario 2).

Validation Test	Project A			Project B			Project C		
	Eng.*	**Pro.***	**Cons.***	**Eng.***	**Pro.***	**Cons.***	**Eng.***	**Pro.***	**Cons.***
Average < ±5%	2.36%	4.26%	2.84%	-3.01%	-1.97%	-1.62%	-2.82%	-3.34%	-3.48%
Amplitude <±30%	-1.68%	12.54%	16.09%	-1.72%	-7.59%	6.61%	0.49%	-10.88%	12.50%

* Eng. = Engineering; Pro. = Procurement; Cons. = Construction. Average < ±5% indicates the deviation between simulated and actual man-hour values. Values within ±5% satisfy the validity criterion. Amplitude < ±30% refers to the difference between the standard deviation of simulation results and actual data. Deviations below ±30% follow Barlas' (1989) validation standards.

The Scenario 2 results also indicate that expert workforce man-hours are required across the engineering, procurement, and construction phases. Figure 9 shows this relationship, showing the expert workforce man-hours required for both scenarios. Scenario 2 enables accurate estimation of the number and qualification level of experts needed, directly supporting risk mitigation and improving overall execution effectiveness. From a broader perspective, this model enables project owners to plan resource allocation proactively while accounting for risk and performance factors. The proposed model contributes to sustainable industrial operations by ensuring optimal allocation of scarce expert resources, minimizing backlog accumulation, and reducing the need for reactive staffing. This strengthens long-term workforce sustainability and supports more resilient project execution environments.

In multi-project settings, the dynamic modeling technique offers a valuable and thorough framework for evaluating risks and effectiveness and enabling the proactive, data-driven distribution of expert workforce resources.

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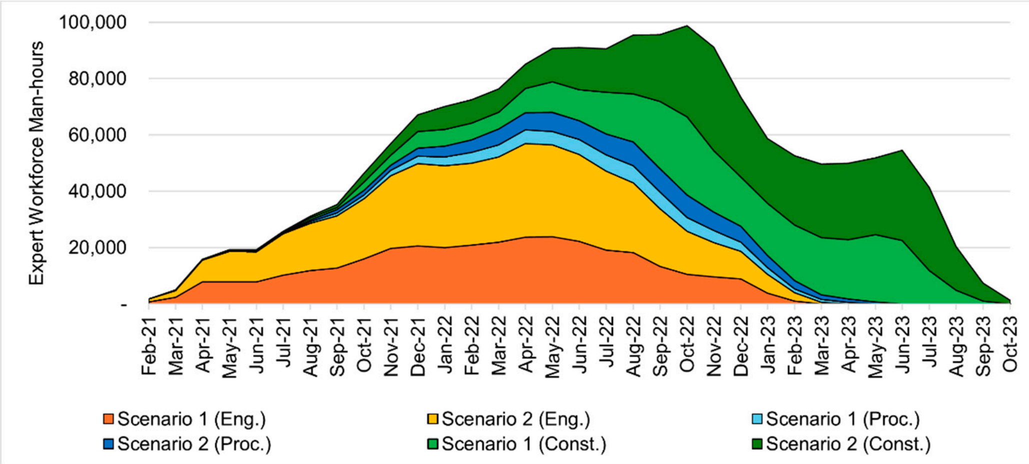

Figure 9. Expert workforce demand for multi-project implementation (Projects A, B, and C).

5. Conclusions

This study emphasizes the importance of risk-based expert workforce allocation for multi-project management. A dynamic model that integrates risk analysis into the allocation process was developed to adjust workforce requirements in real time. Emerging risks, including poor supervision, rework, and differences in project management effectiveness, cause expert demand to shift across concurrent or overlapping projects. By precisely predicting and modifying allocations based on detected risk variables, the suggested methodology reduces the risk of expert workforce shortages that could interfere with project delivery. It also corrects the distribution of the expert workforce from the standpoint of multi-project execution effectiveness.

A system dynamics approach was employed to model expert workforce requirements across the design, procurement, and construction phases. This approach enables predicting and adjusting workforce needs in response to evolving risks and changing project conditions. In multi-project environments—where concurrent execution is common—timely and accurate workforce planning remains a significant challenge. Critical risk factors, such as supervision quality, design changes, and external influences, substantially affect workforce demand. The model was validated using real project data, demonstrating that a risk-based allocation strategy can minimize delays and enhance overall execution efficiency.

This study further highlights the significance of standardized management techniques in multi-project settings, including transparency of information, availability of resources, and project managers' proficiency. The suggested approach anticipates future expert workforce shortages and dynamically adjusts allocations in response to new risks that arise during implementation. Real-world data validation confirmed that workforce planning that accounts for risk variables greatly enhances project outcomes. Therefore, by providing a systematic framework to reduce risks and improve execution effectiveness in multi-project, cross-industry situations, this study adds real value to construction activities in the industrial sector.

Although this research focuses primarily on industrial facility construction, particularly new or greenfield projects, its applicability extends beyond these contexts. The model can be adapted to brownfield projects by incorporating more complex risk factors and varying levels of implementation effectiveness influenced by site-specific conditions, regional dynamics, project types, and ownership structures. Future research should further examine the allocation of the skilled workforce in scenarios in which project owners contract directly with implementing contractors. In industrial construction projects, synergy between experts and skilled workers is critical to achieving efficient, effective task execution. These two workforce groups play complementary roles in maintaining quality and meeting project timelines. Therefore, applying risk-based workforce allocation models for both expert and skilled workforces is essential for achieving optimal project outcomes.

Supplementary Materials: The following supporting information can be downloaded at the website of this paper posted on Preprints.org. *Supporting information for " A Risk-Based System Dynamics Model for Sustainable Expert Workforce Allocation in Industrial Multi-Project Environments" is provided in the Supplementary File.* The document includes: 1. Estimated Expert Workforce Man-Hours for Multi-Project - Scenario 1 (Tables S1–S3); 2. Risk and Effectiveness Factors for EPC Phases (Tables S4–S6); 3. Stock and Flow Diagram - SFD (Figures S1–S3); 4. Risk and effectiveness profiles over time (Figures S4–S7); 5. System Dynamics model documentation (Tables S7–S9); and. 6. Validation and simulation setup summary (Tables S10–S11, Sections 6–7). These materials provide detailed model parameters, risk indices, effectiveness factors, and validation results supporting the findings presented in the main article.

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