Framework for Modeling the Propagation of Disturbances in Smart Construction Sites

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Abstract: The construction sector is currently undergoing a paradigm shift by technological advances. This transformation has led to the emergence of the concept of “Construction 4.0”. However, despite these advances, improving resilience - the ability to adapt effectively to unexpected events - remains a major challenge. In this work, we aim to bridge this scientific gap by proposing a framework to systematically characterize and model disturbances and their propagation. We instantiate the framework in a case study using discrete event simulation in FlexSim. In this model, we simulate a smart construction site where construction activities are automated by intelligent and autonomous entities, such as robots, automated guided vehicles, and autonomous cranes. Moreover, we examine two scenarios to understand how a type of disturbance, with specific characteristics, propagates through the system and impacts the continuity of construction activities and operations. The results provide essential insights into the impact of disturbances on work progress, project duration, the capacities of autonomous entities, and stock levels.

1 INTRODUCTION

The construction sector is currently undergoing a paradigm shift by integrating new practices and cutting-edge technologies (Akanmu et al., 2021). This transformation, characterized by the deployment of advanced tools and methodologies such as off-site modular construction (Wang et al., 2020), Building Information Modeling (BIM) (Sepasgozar et al., 2023), 3D printing, and robotics, represents a fundamental transition for building design and construction. These innovations are more than just evolutions; they represent an overhaul of the philosophy behind construction, oriented towards greater efficiency, sustainability, and resilience (Attajer et al., 2022). At the core of this transformation lies the increasing complexity of construction projects. This complexity, characterized by a diversity of components and actors- ranging from materials and equipment to operators, supervisors, and engineers - requires continuous coordination to successfully complete a project (Muñoz-La Rivera et al., 2021). Moreover, the strong interconnection between these elements increases the vulnerability of construction sites to disturbances and their propagation, whether technical, human or logistical, underlining the need for innovative and effective disturbance and risk management strategies (Afzal et al., 2021). These new strategies require continuous monitoring and anticipation throughout the project lifecycle, particularly during the construction phase.

The sources of disturbances are multiple and varied, ranging from the intrinsic characteristics of the construction project (e.g., technical specifications, dimensions, and architectural elements) to more operational aspects (e.g., equipment failures or delays in material supply) (Kikwasi, 2012). These factors impact the continuity of activities, risking the construction value chain and, consequently, the successful delivery of projects (e.g., delays, and increased cost). The fundamental question that emerges from this issue is therefore how these disturbances propagate through the various elements of a construction site and what strategies can be implemented to evaluate and mitigate their impacts? Despite the considerable efforts made in the literature (Love & Matthews, 2020), the dynamic

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analysis of disturbances and their propagation during project execution remains an open problem. To address this challenge, it is essential to develop tools and methodologies capable of acquiring and analyzing real-time data, detecting potential disturbances, and assessing their impact.

In this context, the concept of Smart Construction Sites (SCS) emerges as a promising solution. By equipping construction sites with advanced technologies — such as Automated Guided Vehicles (AGV) for material transport, robots dedicated to specific tasks like painting, welding, and finishing, or autonomous cranes offering increased precision — construction projects benefit from increasing automation in operation execution. Thus, the adoption of these technologies allows for real-time monitoring and tracking of all activities on the site (Rao et al., 2022). This ability to collect and analyze information continuously offers an unprecedented opportunity to detect and assess disturbances and their propagation as they occur on the site.

The main objective of this paper is to develop a framework for the characterization of disturbances and their propagation in SCS. Furthermore, we use a discrete event simulation using FlexSim to model and analyze a SCS process and operations. With advanced visualization and analysis capabilities (Attajer et al., 2021), FlexSim is used to create detailed, realistic scenarios to assess the impact of disturbances on SCS performance, and to test various mitigation strategies prior to their implementation in the field. Several works have used FlexSim software in the construction industry, as illustrated in this review article (Dziadosz & Kończak, 2016).

The structure of the paper is organized as follows: Section 2 presents a review of the literature on the propagation of disturbances in SCS. Section 3 details the proposed framework for characterizing disturbances and their propagation through the components of SCS. Section 4 illustrates an instantiation through a case study conducted using simulation. Section 5 concludes the article by suggesting future directions for research.

2 RELATED WORKS

Disturbance management represents a significant challenge in the execution of construction projects, given the inherent complexity of operations and the interconnection of components (Peñaloza et al., 2020). Understanding the propagation of disturbances and their overall impact offers valuable insight into the complexity of managing construction projects. However, the lack of detailed analysis on the use of advanced technologies to dynamically monitor and analyze this propagation on the overall project performance, such as delays, represents a challenge (Meszek et al., 2019). SCS constitute a new area of investigation for proactive and real-time disturbance management, but this requires further exploration (Peñaloza et al., 2020). In the literature, several works have proposed frameworks for the classification of disturbances. The distinction between high-impact and low-frequency disturbances, often likened to the "*ripple effect*" in the supply chain domain, and those of low impact and high frequency, provides a first layer of complexity in the management of disturbances (Dolgui et al., 2020). This classification highlights the need for a nuanced approach in the evaluation of disturbances, where the focus is not only on their direct impact but also on their frequency and propagation through the project.

Additionally, previous studies have addressed other classification criteria related to the sources of disturbance: internal or external. For example, (Zhang & Yu, 2021) addressed external disturbances specific to the supply chain of off-site prefabricated construction components. Furthermore, recent works (Meszek et al., 2019) has highlighted the significant, financial and temporal, impacts of internal sources of disturbances. However, there is a lack of a more generic approach that can carefully examine and consider both internal and external types of disturbances and their management in a broader context. Many studies tend to handle disturbances in an isolated manner, without exploring their propagation or examining how SCS technologies can be used to anticipate and mitigate these effects in real time (Meszek et al., 2019). A few proactive approaches aimed to identify the impact of disturbances have been proposed. For example, (Zarghami & Zwikael, 2023) suggested a methodology focusing on assessing the probabilities and consequences of disturbances, highlighting the necessity of preparation and planning in risk management. Its integration into SCS management systems could offer effective means to predict and respond efficiently to disturbances, leveraging advanced analytical capabilities to optimize resource allocation and minimize delays. At the same time, the use of system dynamics and neural networks to anticipate delays brings an advanced technological dimension to disturbance management (Zhao et al., 2022). While the reviewed research provides valuable insights, literature highlights the lack of the capability of SCS to manage disturbances proactively and in real time.

3 PROPOSED FRAMEWORK

Before addressing the modelling of disturbance propagation within SCS, it's crucial to understand and characterize disturbances.

3.1 Characterization of Disturbances

To structure and classify disturbances in the context of SCS, we propose a framework articulated around four main dimensions: the impact, frequency, nature, and source of disturbances.

Impact of Disturbances: The impact of disturbances on the activities of construction sites varies considerably, directly influencing the continuity of operations, costs, and project delay. This dimension is detailed into three levels of impact: high, medium, low.

High Impact: These disturbances can cause considerable delays or significantly increase project costs, while having a profound impact on the organization and planning of the construction site. For example, a major design or sizing error in the BIM plan might require significant revisions, thereby causing delays and additional cost.

Medium Impact: These disturbances affect the project but can be managed or corrected with minor adjustments. For example, a delay in the delivery of materials can affect the schedule without necessarily risking the overall project delay.

Low Impact: These disturbances have minimal, if not negligible, impact on the project and can generally be resolved without requiring significant adjustments. An example could be a temporary equipment breakdown, quickly repairable and need systematic maintenance actions (Attajer et al., 2019).

Frequency of Disturbances: The frequency of disturbances refers to the likelihood of occurrence within the system. Three levels of frequency are considered in our paper: very likely, likely, unlikely.

Very Likely: These disturbances are frequent and can be anticipated. For example, minor delays in the delivery of materials are common, as are issues related to the management of spare parts inventories for equipment used during construction.

Likely: These disturbances occur occasionally and must be considered in planning. Unfavorable weather conditions, for example, can temporarily affect outdoor activities and therefore require anticipation.

Unlikely: These disturbances are rare and unpredictable. For example, the discovery of an archaeological site on the construction area could require work to be paused for evaluation and taking specific measures to preserve the historical site, leading to a significant delay in the progress of the construction.

Nature of Disturbances: Before exploring the different types of disturbances that can affect a construction site, it's essential to understand the nature of these disturbances. They can be classified based on their familiarity and occurrence in previous projects, as well as their specificity and novelty.

Known & Common: These disturbances are well identified and have been encountered in the past. Due to the experience gained, it is often possible to anticipate them, such as seasonal fluctuations in productivity due to weather conditions. Moreover, some disturbances are recurrent and common, like noise from site activities, requiring the adoption of measures such as time restrictions for noisy work.

Known & Specific: These disturbances refer to identified and documented events, often related to specific technical or organizational aspects. Due to their predictable nature, these disturbances can be proactively managed. Examples include delays in the delivery of essential materials like concrete or foundations, errors in labor scheduling, or initial design errors.

New & Specific: Disturbances not previously experienced can arise due to various factors such as the introduction of new technologies, regulatory changes, or unprecedented conditions. For example, the Covid-19 pandemic perfectly illustrates this type of disturbance, having forced the construction industry to adapt its working methods and implement strict health measures. T1hese new disturbances often require a significant adaptation period, due to the lack of prior experience, and can extend project durations.

Source of Disturbances: Identifying the sources of disturbances that affect construction sites is crucial. In this paper, we distinguish between internal and external disturbances.

Internal: These disturbances typically originate from the project itself, the organization responsible for its completion, or the construction processes and resources involved. Changes in key personnel, such as resignations or retirements of skilled collaborators, can significantly influence the progress of the project.

External: These disturbances are caused by factors outside the project and organization. The location of the construction site in an urban area, for example, can pose challenges to material deliveries' accessibility, with potential delays due to traffic constraints, parking restrictions, or congestion. Moreover, introducing new safety or environmental standards, may require adaptations in the planning and execution.

Relationships Between Dimensions: High-impact disturbances are often unlikely and can occur as a result of exceptional events. These disturbances can be of a new and specific nature and originate from either external or internal sources. In contrast, low-impact disturbances are often high-frequency, such as minor delays in material delivery, and are generally well-known and can occur regularly throughout the project. These disturbances, resulting from predictable circumstances, often involve minor operational adjustments and can originate from both internal and external sources. Recognizing and understanding the relationships between these various types of disturbances is essential. This understanding not only allows for anticipating events that may affect a project but also for developing adapted and effective management strategies, thus optimizing the site response to disturbances. Figure 1 offers a schematic representation of the different dimensions characterizing disturbances, as well as the interdependent relationships between these dimensions.

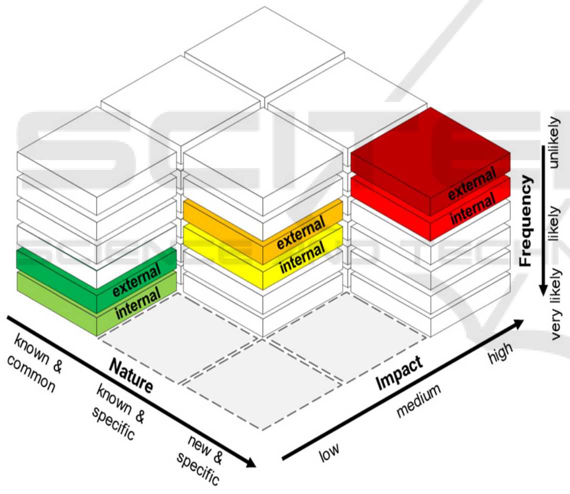

Figure 1: Overview of the dimensions of disturbances and their interactions.

3.2 Propagation of Disturbances

The links between components on a SCS are often characterized by functional and operational interdependencies. For example, the use of an autonomous crane to move essential materials creates an operational dependency between the crane and the construction activities that require these materials. In this interconnected system, a breakdown of the crane can lead to significant delays in the progress of the site. If other equipment or activities directly depend on this crane for their operation, their productivity could be severely affected. For instance, operators might find themselves unable to mount prefabricated structures or move materials to specific areas of the site. Moreover, the malfunctioning crane could block access to certain areas, obstructing the movement of materials and personnel, while posing a potential safety risk on the site. When a system (components – links) consists of several interconnected components through links, any disturbance in one of these components can potentially propagate through the network and impact other connected components. When a component is disturbed, this can trigger a chain reaction that propagate through the links to adjacent components. The propagation of the disturbance can occur in various ways depending on the system nature and the characteristics of the disturbance. In some cases, a disturbance may remain isolated, affecting a single network component without notable consequences on the entire system. However, in other cases, an initial disturbance can lead to cascading failures, disturbing the overall functioning of the system. This situation is often triggered by operational disturbances affecting the construction process. For example, a delay in material delivery may initially affect a single construction process step. Nevertheless, this initial disturbance can quickly propagate further downstream, affecting other components that depend on the delayed materials for their operations. This type of cascading propagation, which reduces the performance of affected components, is similar to the "*Bullwhip*" effect observed in supply chains. Furthermore, some disturbances have the potential to affect the entire construction network structure, causing a critical decrease in the overall system performance. These major disturbances, such as natural disasters or systemic failures of key technologies, can paralyze the entire construction process. This phenomenon, is similar to the "*Ripple*" effect in supply chains, demonstrates the propagation of an initial disturbance through multiple levels or components of a system, exacerbating the overall impact on the project (Dolgui & Ivanov, 2021).

Analyzing the modes of disturbance propagation in SCS reveals complex dynamics influenced by its dimensions. These elements interact to determine how a disturbance can influence the entire construction system. High-impact, new and specific, and unlikely disturbances are distinguished by their capacity to cause significant effects across the entire construction process network, thus generating the "*Ripple*" effect. Their unexpected and specific nature means they are not easily anticipated by standard risk management practices. When such disturbances occur, they can rapidly propagate through the construction network interdependencies, affecting not only immediate operations but also the overall project performance. In contrast, disturbances that are very likely, of low impact, and of a known and common nature tend to be well understood and manageable. These disturbances, like minor delivery delays or short and predictable work interruptions, can be mitigated through standardized operational procedures. Their low impact means they can be addressed without significantly disturbing the entire construction network. Generally, these events remain isolated to the component or process step initially affected, without significant propagation. Medium-impact, medium-frequency, and known nature disturbances can trigger the "*Bullwhip*" effect. This implies a chain propagation due to the complexity of interdependencies. A typical example could be a cumulative delay in a project phase that, while initially modest, amplifies through subsequent stages due to operational adjustments. These disturbances require careful management to limit their amplification and minimize downstream impacts.

Figure 2 illustrates the conceptual framework developed to analyze disturbance characteristics within SCS. This model aids in identifying the nature, impact, frequency, and source of disturbances, as well as understanding their mode of propagation and effect on the performance and continuity of operations in construction sites.

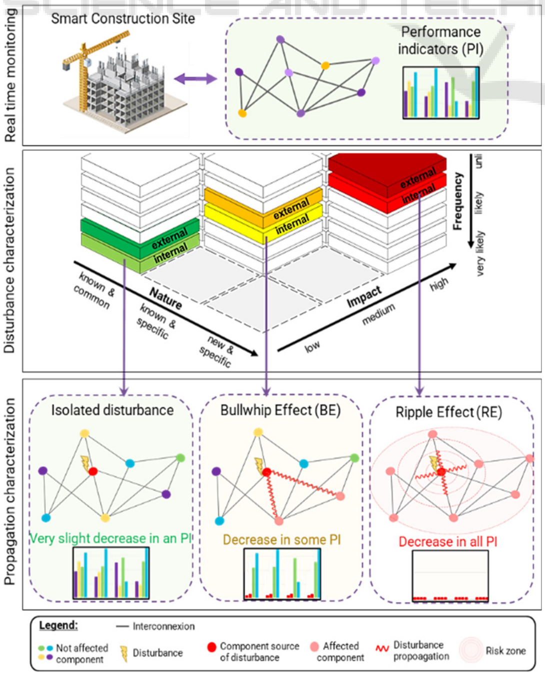

Figure 2: Framework for disturbance analysis: characterization and propagation.

4 CASE STUDY

Our case study focuses on the execution of the first phase of construction of a building. The objective of this phase is to construct five first-floor walls of the building under construction. This project is modeled in FlexSim simulation software v.24.0.1. The model and the data are available on request. The process begins with the arrival of bricks. Upon their arrival, a forklift transports the bricks to a first storage area. This initial step ensures that the necessary materials are gathered and ready for the next operation. an AGV transports autonomously the bricks from the first storage area to a second zone. This latter is positioned closer to where the construction work is carried out, thus optimizing the process by reducing the material transport time. An autonomous crane uses the bricks from the second storage area to precisely build the walls. As the crane progresses in the construction, an autonomous robot takes over to complete the finishing touches. Throughout this process, an operator supervises the construction operations. This supervisor has the capability to take manual control of the crane in case of failure.

4.1 Scenario Without Disturbances

This section evaluates the model through a series of simulations to understand how the system operates in the absence of disturbances, and to establish a baseline for construction performance. Figure 3 illustrates various key indicators collected during the simulation, offering a detailed overview of the SCS operations. The first diagram presents the work progress. There is a linear progression during working hours, with notable stops at break times (12-14h) and outside working hours (17h-8h). This observation highlights the system efficiency during active periods, while respecting the need for breaks for human supervisor and environmental noise-related constraints. The second diagram shows the operating cycle of the autonomous crane (i.e., number of operations per hour). We notice that this indicator drops to zero outside working hours, as expected. During active hours, performance fluctuations are observed, mainly due to changes in trajectory when moving from one wall to another, which implies a variation in the distance between stock 2 and the wall under construction. The third diagram illustrates occupation status of four components: forklift, AGV, crane, and robot. The different states of occupation reveal that the construction site resources are not fully utilized. The highest utilization rate observed for the robot is 39%, indicating that activity interruptions (breaks, end of the day) and the arrival of materials limit their efficient use.

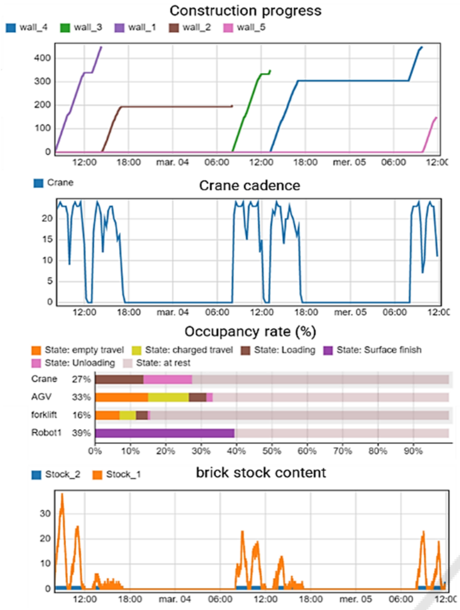

Figure 3: Key Indicators collected during the simulation without disturbances.

This suggests that the flow of materials, particularly the arrival of bricks, constitutes a critical bottleneck in optimizing the construction site. The final diagram in the Figure 3 presents the stock analysis which reveals that storage area 2 is frequently empty, indicating rapid use of bricks by the crane. This observation contrasts with stock 1, where materials may stay longer. The finding that stock 2 acts as a potential bottleneck suggests that increasing the quantity of bricks in this area could improve the crane utilisation and, consequently, the use of robot and progress of construction work.

4.2 Impact of an External Disturbance

This section analyzes the impact of an external disturbance, specifically an interruption in the brick supply, on construction operations. This disturbance, for 4 hours, had significant repercussions on work progress, resource utilization, and stock levels. Figure 4 illustrates collected indicators during the simulation with this disturbance.

Impact on work progress (First diagram in Figure 4): The effect becomes evident at the start of the second day. Wall 2, whose construction had begun on the first day, was only completed in the afternoon of the second day, contrary to the normal scenario where it was expected to be finished at the beginning of the day. This disturbance caused a ripple effect, impacting all components and delaying the construction of subsequent walls and extending the total duration of work to 73 hours and 54 minutes, compared to 51 hours and 48 minutes in the normal scenario without disturbances.

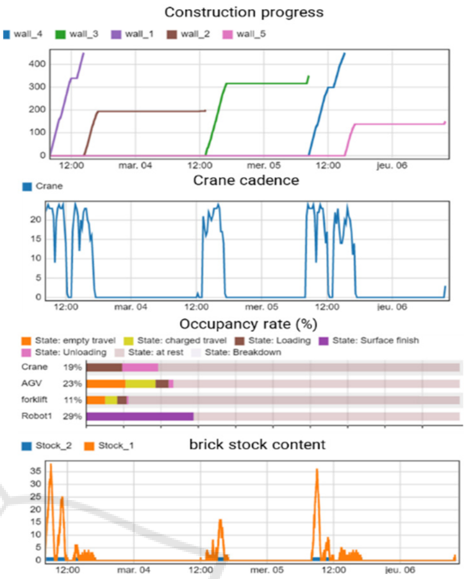

Figure 4: Key Indicators collected during the simulation with the external disturbance.

Impact on the crane operation (Second diagram in Figure 4): The operational rate followed the same pattern as in the normal scenario, with the exception of the inactivity observed during the morning of the second day due to the absence of bricks (i.e., disturbance impacts the crane efficiency). Furthermore, the crane was used throughout the third day and for a short period on the fourth day, showing an extension of the working time needed to compensate for the delay caused by the disturbance.

Impact on the resource utilization rate (Third diagram in Figure 4): Each component of the construction site experienced a decrease in utilization rate due to the half-day of inactivity and the extension of work beyond the initial schedule. This decrease directly reflects the impact of the disturbance on the overall efficiency of the construction site, highlighting the crucial role of continuous material supply in maintaining an optimal work operation.

Impact on stock levels (Final diagram in Figure 4): Stock levels were directly affected by the supply interruption. Stock_1 remained empty throughout the morning of the second day, leading to complete inactivity of the construction site during this period and justifying the decrease of resource utilization.

This observation confirms that material availability is a key factor for the continuity of operations.

4.3 Impact of an Internal Disturbance

This section analyzes the impact of an internal disturbance characterized by a two-hour crane malfunction at the beginning of the second day. Despite this disturbance, the overall progress of the construction remained unaffected (see the first diagram in Figure 5). The disturbance impacted the construction of the second wall, as it occurred early in the second day. This disturbance did not propagate across the subsequent construction activities due to the crane high capacity and the uninterrupted material flow from the source to stock_2, resulting in an accumulation of bricks in stock_2 awaiting crane repair. Once operational, the crane high capacity enabled it to quickly catch up on the delay, ensuring no downstream delay in construction activities and maintaining the project completion within the original calendar, which is 51 hours and 48 minutes. After the crane was repaired, its operational rate increased notably due to the accumulated bricks in stock_2 (see the second diagram in Figure 5), demonstrating the crane capability to compensate for the lost time. This scenario demonstrates that the perturbation has an isolated nature, as it did not significantly affect the utilization rates of other resources (see the third diagram in Figure 5).

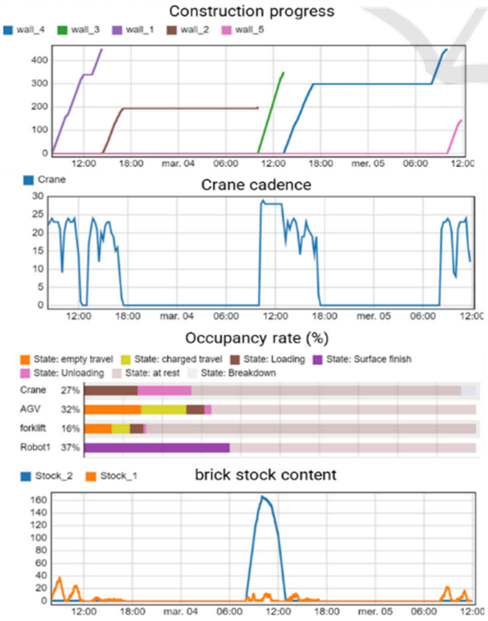

Figure 5: Key Indicators collected during the simulation with the internal disturbance.

4.4 Discussion

This case study illustrates how the nature, duration, and impact of disturbances vary their propagation effects within SCS. In the scenario related to a disturbance on the brick supply, this external event propagated through the system, causing a ripple effect. This disturbance affected not only the supply of materials but also the operational efficiency of key components, extending the total construction time significantly beyond the initial schedule. In contrast, the second disturbance, internal in nature, remained nearly isolated to a single system component without significant propagation. Despite temporarily breakdown of the crane, the system inherent capacity and uninterrupted material flow allowed for a quick recovery. Table 1 compares the different scenarios studied in relation to the total duration of the project and the propagation effects. In brief, this analysis underscores the critical role of disturbance characteristics in determining their propagation and impact within a SCS.

Table 1: Comparison of scenarios.

Scenario	Project total duration	Disturbance propagation
Normal operation	51 hours and 48 minutes	No disturbance
External disturbance	73 hours and 54 minutes	Ripple effect propagation
Internal disturbance	51 hours and 48 minutes	Isolated distrubance

5 CONCLUSION

The construction industry is transforming significantly towards Construction 4.0, integrating innovative technologies. Our study on Smart Construction Sites (SCS) highlights the complex dynamics of disturbances and their propagation, proposing a comprehensive framework. Our study on SCS highlights the complex dynamics of disturbances and their propagation, proposing a comprehensive framework. Our findings show that disturbance impact, frequency, nature, and source greatly influence their effects. Using FlexSim, we provided key insights into operational interdependencies and impact of disturbances on construction operations. An external disturbance, like a brick supply delay, caused a ripple effect, impacting material supply and operational efficiency, extending construction time. In contrast, an internal disturbance, such as a crane malfunction, remained isolated with minimal propagation due to the system's quick recovery capabilities. Several avenues for further research emerge from this study. Firstly, we need propose methodologies to evaluate and quantify the negative consequences of disturbance propagation to identify potential bottlenecks in construction operations. Secondly, quick decision-making strategies need to be developed, enabling just-in-time actions that can mitigate the effects of disturbances effectively. It is also essential to consider the technological capacity of SCS in our reaction strategies. For example, incorporating redundancy of critical elements or utilizing multi-task intelligent elements can significantly enhance the system's capacity to respond to disturbances. The comparison of these reaction approaches with existing risk management approaches in complex systems will provide valuable insights. Finally, real construction site implementation and experimentation are necessary to validate the findings and refine the proposed model.

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