Research Article

Model and Algorithm for Dependent Activity Schedule Optimization Combining with BIM

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The project duration can be shortened by overlapping construction activities. However, the continuous changing of the environment tends to cause problems such as rework and the failure of the overlapping plan. In order to solve these problems, communication strategies for the overlapping of dependent activities are first introduced and optimized from a revenue perspective. We first consider the different maturities of upstream activity before and after the overlapping, the downstream sensitivity which is decided by involving communication strategies, and the learning and error-correcting ability of workers. Then, the overlap and communication strategies are decided by calculating the maximum revenue using Monte Carlo simulation and MATLAB based on overlap cost, communication cost, rework cost, and reward amount. Finally, the algorithm and BIM are combined to provide a visual overlap plan and dynamic control platform framework. This research is valuable for practitioners as it provides a dynamic overlap plan which can maximize the revenue in changing the environment and ensure the duration of the project. This research also provides researchers a new insight into combining overlap problems and BIM technology.

1. Introduction

Compressing project duration, one of the most important ways to optimize project schedule and obtain the investment benefits [1–3], has been intensively investigated. Compared with other compressing technologies, overlapping has characteristics of high efficiency and low cost, which has attracted increasing attention in recent years [4–6]. However, if applying overlapping strategy between two activities in an unappropriated time, for example, the upstream activity information is incomplete, the resources are in a shortage, or the working surface is insufficient, it is likely to increase the risk of rework [2, 7, 8], cost [9], and the failure of schedule plan [2, 7]. Furthermore, it will reduce the potential revenue of the project entering the market. Therefore, it is important for companies chasing investment return to increase the resilience of schedule plan to the dynamic environment and maximize the revenue.

Activities in projects can be roughly divided into three types [10]: independent, dependent, and interdependent. Between independent activities, changes in each activity will not affect each other, as shown in Figure 1(a). Changes in upstream activities between dependent activities (Figure 1(b)) will cause rework of downstream activities, which will bring the delaying and resource crisis, and finally disturbing the schedule plan. If two activities are interdependent (Figure 1(c)), not only can the changes in upstream activity bring the rework risk of downstream activity, but also the changes in downstream will cause the delay of upstream activity; that is, the iterative influence. Therefore, for the activities which can influence each other, namely, the latter two types, controlling the amount of change or reducing the impact of them is a critical factor for project success.

The research aiming at solving such problems mainly focuses on the degree of dependence between activities; that is, the impact of changes in one activity on another activity. Information sensitivity modeling [2, 11–15] and DSM matrix [16–18] are the two key methods for this category. However, most of them neglected that the
activity maturity is various according to time [13, 15, 19], which is an important prerequisite for subsequent analysis. So, if simply assuming that the maturity speed of an activity is fixed, the subsequent results will be quite different from reality. Meanwhile, we should also note that for the dependent activities, the construction of one activity will inevitably affect the maturity of the already-constructed activity. More studies on such impact are crucial to gain realistic results.

The occurrence of changes is uncertain. Obtaining information in advance or promptly is the key to depress the impact of change. Loch and Terwiesch [12] proposed that the pre-communication before overlapping can reduce the possibility of change. Yang et al. and Srour et al. [2, 20] suggested that meetings should be held during the overlapping to share information. These methods have been paid off. But the quantification of change is still lacking to make precise schedule plans. Li proposed that information sharing can benefit the whole supply chain and all members [21]. Gurevich et al. proved that the collection and distribution of accurate, reliable, and timely information related to the states of the processes and products are essential [22]. Therefore, multiple and dynamic communication can be performed to share information during the overlapping between dependent activities.

Implementing multiple projects simultaneously is common, and many constraints, like resources, working face, and duration, need to meet to make the schedule plan. As projects are temporary and unique and the communication between different stakeholders is complex, the schedule plan heavily depends on the individual ability of project managers. Therefore, how to realize the dynamic, intelligent, and visual schedule and how to provide a shared platform for stakeholders to communication become key problems to be solved.

The main direction of information exchange is from upstream to downstream [11], so this paper only considers the information transmission (Figure 1(b)) without considering the further impact of downstream activities on upstream activities. And the activity that starts earlier is defined as “upstream activity” and the latter is referred to as “downstream activity.” The project has many objects, like the shortest duration, the least rework time, the lowest cost, or the largest revenue. We know that these goals are hard to be realized at the same time. Therefore, in this paper, we set the maximum revenue as the only goal. Also, the duration and rework will be considered to provide targeted advice to companies with different preferences. There are three main research questions in this paper:

1. How to measure the maturity of upstream activities more realistically?
2. How to deal with frequent changes during the construction process to develop a more effective schedule?
3. How to achieve a more intelligent schedule?

To solve the above problems, we firstly simulate the start-up time of downstream activity as 0-1 uniform distribution and construct the corresponding maturity model of the upstream activity according to the start-up time of overlapping. Then, we introduce the dynamic communication during the overlapping, supplemented by the team error correction ability, and learning coefficients to modify the reworked model. Finally, Monte Carlo is used to simulate different communication strategies, and the algorithm is applied combined with BIM to show the different duration, rework time, and revenues for different overlapping and communication strategies. We argue that our study contributes to theory and practice in three ways. Firstly, the important premise for the schedule is revised, that is, the different upstream activity maturity in different periods, which provides a more realistic basis for later research. Secondly, we propose a dynamic communication strategy to cope with the complex and unpredictable changes. Finally, this paper provides the stakeholders with a visual and intelligent communication platform to develop schedule plans, which greatly reduces the difficulty and workload of schedule development.

This article is organized as follows. Section 2 presents the referential background. Section 3 describes the mathematical models in detail and makes basic assumptions. Simulation is performed in Section 4. In Section 5, we perform the example, the combination of algorithms and BIM, and the sensitivity analysis. Finally, the article ends with conclusions, contributions, limitations, and future research.

2. Literature Review

2.1. Dependent Activities. Krishnan et al. [11] firstly defined the dependence and influence relationship between activities by using “evolution” and “sensitivity” and assumed that the
evolution of upstream information obeyed nonhomogeneous the Poisson distribution. Since then, plenty of researchers have put forward different standards and influencing parameters for that. Carrascosa et al. [23] used “variability” and “influence” to measure the dependence between activities for the coupling of concurrent engineering design activities. Peña-Mora and Li [24] developed a fast-tracking framework based on activity generation rate, upstream reliability, and downstream sensitivity. They pointed out that the level of work reliability was determined by three factors: the effect of learning reliability, employee’s experience, and schedule pressure. The downstream sensitivity was decided by the validity of inspection and the number of upstream activity segments. Bogus et al. [25] also discussed the influencing factors of these two parameters in design activities but put forward different opinions. They pointed out that the degree of design optimization, constraint satisfaction, external information conversion, and standardization were the key factors affecting the evolution degree of upstream activities while activity constraints, input variables, and design integration level were the key factors affecting the sensitivity of downstream activities. Loch and Terwiesch [12] suggested that the reliability of upstream activities should be measured by the number of errors that occurred in the specific period of upstream activities. Some other scholars used the DSM matrix to study the dependence between elements in the system [16–18].

The theme of information interaction has been addressed in different ways. Loch and Terwiesch [12] pointed out that overlap would bring more revenue if uncertainty could be solved earlier. Srour et al. [20] identified that more frequent meetings could reduce rework time. They also proposed that the team would apply the best communication strategy without considering the cost of it. With the goal of maximum cost savings, Yang et al. [2] determined the optimal communication times and intervals in R&D activities.

Although considerable progress has been made about the quantification of interactivity dependencies and the interaction of information in the R&D area, there are still some gaps when applied to the construction area. And it is assumed that the overlap start-up time is fixed when studying the information interaction, which makes it difficult to adapt to dynamic scheduling.

2.2. Maturity. “Maturity” was first reported by the College of Engineering, Carnegie Mellon University [26]. Then, there has been a continuous studying about it and research gradually developed a proper term in the engineering project management maturity model about it [27]. So far, the different project management maturity models [27, 28] can be roughly divided into the following three main categories: (1) focus on project management process, (2) focus on the technical process of project development achievement, and (3) focus on organizational maturity in a broader sense [29]. Görög [30] reviewed these maturity models and proposed a framework for evaluating relevant maturity models based on the broader concept and the viewpoint of organizational project management maturity. He pointed out that a more appropriate maturity model would help different projects and organizations improve their management and practical abilities.

However, these studies on maturity are based on project level, project planning level, or organizational level, which is a macroevaluation index of project success. The project, which is composed of many activities, needs to be measured from the activity level to achieve the overall success.

At the activity level, Zhang et al. [19] introduced the concept of “product maturity” to describe the information completeness in the process of upstream product evolution. Xu et al. [31] used “technology maturity” to characterize whether the technology reached the expected conformity level in the process of risk assessment of the system. And “integration maturity” was proposed to express the matching degree among subsystems in the complex system while “system maturity” is the combination of the above two maturities. Yin et al. [32] studied “information maturity” in the iteration model of coupled activities in the development process. He and Chang [33] used “manufacturing maturity” to achieve the classification of maturity.

The studies above only classified maturity or developed relevant key indicators but did not provide any information about the quantification of maturity. To resolve such problem, Wang and Lin [15] expressed the degree of information evolution in the design phase by the percentage of knowledge accumulated or developed activities completed at a given time. Sacks et al. [34] proposed to measure the degree of work package readiness by maturity to arrange daily work plans in the completion and visualization process of production plans. However, this study did not consider the key issue that downstream activities will have an impact on upstream maturity.

2.3. BIM and Schedule. BIM (building information modeling) is an information technology, which is regarded as a potential tool to solve construction problems. Also, the enriched information of BIM satisfies the needs of schedule generation [35]. Dave et al. [36] pointed out that with its data-rich models, BIM can provide both product and process-related information across the whole building lifecycle. Also, its visual nature makes it an ideal platform for information deliveries to workers at all stages. Attempts to study the schedule-related problems based on BIM have been carried out in recent years.

Fan et al. proposed a model by which they can automatically link the cost and schedule data from their linkage to BIM elements [37]. Similarly, Chen presented a BIM-based method to automate the generation of schedule considering four factors, namely, problem type, emergency level, the distance among components, and location [38]. Unlike them, H. Hamledari establishes an approach to incorporate progress data into 4D BIMs automatically. Their work relies on nonproprietary IFC, which makes BIM using more realizable [39].

Furthermore, much research concentrates on the combination of BIM and other technologies. Li et al. used RFID
to capture the real-time data to support the supervision and enhance schedule performance based on BIM. Their work primarily revolved on the schedule delay problems [40]. Sacks et al. [34] integrated Kanban theory in lean construction with BIM, named KanBIM; they defined it as the BIM-enabled pull flow construction management software system based on the Last Planner System. Their work revolved primarily on the requirements for the KanBIM system, namely, process visualization, product and method visualization, computation and display of work package, and task maturity, to support for planning, negotiation, commitment, and status feedback, implement pull flow control, maintain workflow and plan stability, and formalize experimentation for continuous improvement. Gurevich and Sacks [22] proposed that the trade crew leaders’ task selection behavior is positively affected by the use of the prototype KanBIM production control system.

3. Models of Multiple Communication-Rework Activities Results

3.1. Related Concepts, Symbols, and Model Assumptions. Before building the model, we need to elaborate on the concepts, assumptions, and symbols related to dependency activities. Frequent exchange of the design information in the overlapping process enhances the controllability of concurrent engineering [41]. Therefore, to deal with changes and reduce the risk of rework, we propose communication behavior occurring not only during the overlapping. After each communication, changes in upstream activities within the communication interval may lead to rework in downstream activities. So there may exist many reworks during overlapping after each communication. Undoubtedly, the length of rework time is related to the amount of change in upstream activities, the sensitivity of downstream activities, and the communication interval, which will be explained specifically later in Section 3.4.

The communication between upstream and downstream activities is represented by a directed graph with arrows. As shown in Figure 2, the one-way arrow represents the behavior of information sharing, called maturity transmission. The width of the shaded rectangle indicates the rework time and the total length of the rectangle shows the overall duration of activities. We set the starting time of upstream as the time origin and express all the time points on the horizontal axis. And the main symbolic variables involved in the model are shown in Table 1.

To effectively analyze the impact of multiple communication between upstream and downstream activities on rework time and final revenue, it is necessary to clarify the boundary and preconditions. This paper proposes the following assumptions:

1. This paper mainly talks about the one-way information transmission from upstream to downstream, so the rework of upstream activities is no longer considered. And it is assumed that the upstream activities can be finished.

2. The first communication occurs at the beginning of the overlap, which will not lead to rework.

3. The last communication occurs when upstream activities are completed.

4. Communication does not take up construction time.

The optimization is conducted with the maximum total revenue as the objective function; the purpose of the later simulation is to determine (1) the start time of overlapping, (2) the best communication time, and (3) the frequency of communication under the given duration of upstream and downstream activities and the decision-making time to lay the foundation for the further investigation.

3.2. Maturity Model of Dependent Activities Based on Overlapping Time. The inherent uncertainty of construction keeps its construction process in dynamic changing. Every activity is restricted by constraints such as information, materials, equipment, space, and safety requirements. If the impact of these constraints on activities can be evaluated, activities can be arranged effectively. In this paper, activity maturity is used to express the release state of constraints, that is, the state of activity readiness.

Different vendors have different capabilities, and the reliability of resource provision also varies. The magnitude of reliability value will affect activity maturity [34]. According to the speed of evolution, activities can be roughly divided into two types [13, 15, 19]. (1) Early progress is rapid, but closing activities are cumbersome and take more time \((0 < \alpha < 1)\), as shown in Figure 3(a). (2) In the early stage, a lot of preparatory activities are needed, so the progress of the activities is slow. With the completion of preparatory activities and the continuous supply of resources, the degree of activity completion begins to rise rapidly \((\alpha > 1)\), as shown in Figures 3(b)

The start-up of downstream activities will affect the maturity of upstream activities, so this paper divides the change of the maturity of upstream activities into two parts according to whether the downstream activities start or not. We then measure the variability of material supply with the help of vendor reliability and define the evolution speed of upstream activities as the maturity evolution coefficient.

3.2.1. Maturity Model of Upstream Activity before Overlapping. Before overlapping, the degree of upstream maturity is only relevant to the construction time, the total duration, the reliability of vendors, and the character of itself. So the maturity evolution coefficient of upstream activities is defined as follows:

\[
m_1 = \left(\frac{t - t_F}{D_1}\right)^a P_k, \quad t_F < t < t_0,
\]

where \(t\) is a time variable and the previous equation can be used to measure the maturity from the decision time \(t_0\) to the start time of overlapping \(t_F\), which is also the range for \(t\). We assume that the maturity speed of upstream activity is fast in the early stage, so \(0 < \alpha < 1\). However, when
Figure 2: Multiple communication-rework mode.

Table 1: List of the main symbols.

<table>
<thead>
<tr>
<th>Variables</th>
<th>Meaning</th>
</tr>
</thead>
<tbody>
<tr>
<td>(D_1)</td>
<td>Upstream duration</td>
</tr>
<tr>
<td>(D_2)</td>
<td>Downstream duration</td>
</tr>
<tr>
<td>(\alpha)</td>
<td>Characteristics of upstream activities</td>
</tr>
<tr>
<td>(P_k)</td>
<td>The reliable of vendors</td>
</tr>
<tr>
<td>(t_p)</td>
<td>Decision time</td>
</tr>
<tr>
<td>(t_i)</td>
<td>Communication time</td>
</tr>
<tr>
<td>(t_0)</td>
<td>The start time of overlapping &amp; the first communication time</td>
</tr>
<tr>
<td>(Q_j)</td>
<td>Time interval between two adjacent communications</td>
</tr>
<tr>
<td>(n)</td>
<td>The amount of communication intervals</td>
</tr>
<tr>
<td>(M_t)</td>
<td>Maturity of upstream activity at t-time</td>
</tr>
<tr>
<td>(m_1)</td>
<td>The maturity evolution coefficient of upstream activities before overlapping</td>
</tr>
<tr>
<td>(m_2)</td>
<td>The maturity evolution coefficient of downstream activities after overlapping</td>
</tr>
<tr>
<td>(S)</td>
<td>Downstream sensitivity</td>
</tr>
<tr>
<td>(B)</td>
<td>Team error correction ability</td>
</tr>
<tr>
<td>(y)</td>
<td>Learning coefficient</td>
</tr>
<tr>
<td>(r_i)</td>
<td>The rework time caused by the change of upstream activities in the adjacent two communication intervals</td>
</tr>
<tr>
<td>(R_t)</td>
<td>The total rework time</td>
</tr>
<tr>
<td>(D_s)</td>
<td>The total duration</td>
</tr>
<tr>
<td>(D_s)</td>
<td>The shorting duration</td>
</tr>
<tr>
<td>(D_l)</td>
<td>The overlapping time</td>
</tr>
<tr>
<td>(c_r)</td>
<td>Unit rework cost</td>
</tr>
<tr>
<td>(c_o)</td>
<td>Unit overlapping cost</td>
</tr>
<tr>
<td>(c_a)</td>
<td>Unit reward amount</td>
</tr>
<tr>
<td>(c_c)</td>
<td>Unit communication cost</td>
</tr>
<tr>
<td>(I)</td>
<td>The total revenue</td>
</tr>
<tr>
<td>TC</td>
<td>Communication frequency</td>
</tr>
</tbody>
</table>

Figure 3: (a) Fast-moving activities in the early stages; (b) fast-moving activities in the late stages.
downstream activity begins to overlap, the degree of upstream activity cannot be measured only by those parameters above. So we should first calculate the maturity when overlapping occurs, which is shown as follows:

$$M_0 = \left[M_p + \left(\frac{t_o - t_p}{D_1}\right) P_0\right], \quad t_o \in \left(\max\{t_p, D_1 - D_2\}, D_1 - 1\right),$$  \hspace{1cm} (2)

where $M_p$ represents the maturity of upstream activity at the decision time $t_p$, which is a known constant and $t_o$ denotes the start time of overlapping. To avoid downstream activity ending earlier than upstream activity, the lower bound of $t_o$ is the maximum of the decision time $t_p$ and the difference between the duration of upstream and downstream and the upper bound is $(D_1 - 1)$.

3.2.2. Maturity Model of Upstream Activity after Overlapping. We regard the upstream activity maturity as “1”. If the accumulation of maturity is $M_0$ before overlapping, then $1 - M_0$ is the amount of change that may occur during overlapping. Therefore, the maturity evolution coefficient of upstream activities after overlapping is defined as

$$m_2 = \left(\frac{t - t_0}{D_1}\right)^\beta, \quad t_0 < t < D_1,$$

\hspace{1cm} s.t.

$$\int_{t_0}^{D_1} \left(\frac{t - t_0}{D_1}\right)^\beta \, dt = 1 - M_0,$$  \hspace{1cm} (3)

where $t$ is a time variable, and the range of it is from the start time of overlapping $t_0$ to the completion time of upstream $D_1$. $\beta$ is a variable to be determined, which varies with the start time of overlapping and is used to represent the evolution speed of upstream maturity after overlapping. Since the overlapping start-up time is not determined, the value of $\beta$ changes every time as it changes. And we will explain it in detail in Sections 4 and 5 during the simulation. Because of the relationship between $\beta$ and the overlapping start-up time, the impact of the starting of downstream on the upstream activity can be reflected, which makes our model more realistic.

3.3. Downstream Sensitivity. In this paper, we define “sensitivity” as the ability to resist the change, which means that minor changes can bring a large disturbance for the activity with high sensitivity, but for the activity with low sensitivity, even frequent changes will not necessarily cause rework [42]. So the lower the value of sensitivity, the better. As we said before, multiple communication is considered during overlapping to reduce that value. Also, the project is not only an inanimate object but is closely related to workers, which indicates that sensitivity is closely related to the characteristics of field workers. So we take into account two main parameters concerning workers, namely, team error correction ability and learning coefficient when modeling the sensitivity.

We defined downstream sensitivity as follows:

$$S = \frac{t_i}{t_0 + D_2} \cdot e^{(1 - y)} (1 - y)^i, \quad (i = 1, 2, \ldots, n),$$

\hspace{1cm} s.t.

$$t_i = t_{i-1} + Q_i,$$

$$\sum_{j=1}^{n} Q_j = D_1 - t_0,$$

where $t_i$ represents the time of each communication, and the frequency of it determines whether or not downstream activities can receive upstream changes in time. The earlier the communication is, the lower the sensitivity is [2, 12]. The rework is relevant to the evolution degree of downstream activities [12, 14] and the time of communication. The reduction of activity sensitivity is related to the team error correction ability [12], which is defined as $B$ ($0 < B < 1$). The greater $B$ is, the less sensitive it is. After each communication, the team will accumulate a certain ability to cope with change, which is defined as learning coefficient $y$ ($0 < y < 1$). So $S$ decreases $y S$ after each communication. The sensitivity changes to $(1 - y)S$ after the first communication, which will convert into $(1 - y)^2S$ after the second communication. So the sensitivity is $(1 - y)^iS$ after the $i$th communication.

3.4. Model for Multiple Communication-Rework. Rework can be expressed by multiplying the upstream changes and downstream sensitivity [11, 25]. Therefore, the rework time caused by the change of upstream activities in the adjacent two communication intervals is defined as

$$r_i = \left(M_{t_i} - M_{t_{i-1}}\right) \ast \frac{t_i}{t_0 + D_2} \ast \exp\{1 - B\} (1 - y)^i$$

$$\ast (t_i - t_{i-1}), \quad (i = 1, 2, \ldots, n).$$

The total rework time during overlapping can be calculated as

$$R_t = \sum_{i=1}^{n} r_i.$$  \hspace{1cm} (6)

Therefore, the total duration under overlapping strategy is expressed as

$$D_t = D_2 + t_0 + R_t.$$  \hspace{1cm} (7)

3.5. Model for Multiple Communication-Revenue. If communication costs nothing, frequent communication can significantly reduce the risk of rework. However, communication in actual construction process will take up time and resources. Therefore, we propose that unit communication
cost is $c_c$ and unit rework cost is $c_r$. Overlapping inevitably occupies more resources and needs more investment. Therefore, the cost of overlapping is higher than that of the flow process, we assume it as $c_l$. Also, overlapping can shorten the duration; we assume that the amount of unit reward is $c_a$. Therefore, the revenue brought by overlapping is the difference between the amount of reward and the cost of overlapping and communication.

The shortening duration is

$$D_s = D_1 + D_2 - D_l,$$  \hfill (8)

The overlapping duration is

$$D_l = D_1 - t_0,$$  \hfill (9)

The total revenue is defined as

$$I = c_a \cdot D_s - c_r \cdot R_t - c_l \cdot D_l - c_c \cdot (n + 1).$$  \hfill (10)

### 4. Simulation of Overlapping Based on Monte Carlo

To obtain the start-up time of overlapping, communication time, and communication interval at maximum revenue, we use the Monte Carlo to simulate the overlapping and realize the simulation by MATLAB 2014a. The input of the simulation model includes upstream and downstream activity duration, unit reward amount, unit communication cost, unit rework cost, and unit overlapping cost.

The simulation steps are shown below.

**Step 1.** Input values of parameters $D_1, D_2, t_p, c_a, c_r$, and so forth.

**Step 2.** Determine vendor reliability $P_{.k}$ based on the difference between the decision time and the start time of overlapping.

**Step 3.** Set the uniform distribution between the maximum difference of decision time and downstream activity duration and the one-day advance time of upstream activity duration as the simulation value of start-up time of overlapping.

**Step 4.** Calculate the value of $\beta$ corresponding to the overlapping start-up time simulated in Step 3 by calculus.

**Step 5.** Just like Step 3, set the uniform distribution between the maximum difference of decision time and downstream activity duration and the one-day advance time of upstream activity duration as the simulation value of communication time.

**Step 6.** Calculate the maturity evolution coefficient $b$ by the start-up time of overlapping (it varies with different start-up times of overlapping).

**Step 7.** Calculate the total rework time, the communication time, the start-up overlapping time, and so on when the revenue is maximum.

Because each cycle is independent of each other and communication time and overlapping time are determined randomly, the value of $I_{\text{max}}$ will not tend to be stable with the increase of the number of cycles. The purpose of this study is to obtain the maximum value of $I_{\text{max}}$. Therefore, the step size of the algorithm can be set to 5 and iterated many times. When its distribution tends to be uniform, we regard it as the final result.

### 5. Examples Verification and Analysis

Implementing the best overlap and communication strategy is conducive to overcoming the impact of dynamic factors on schedule in the construction process. To verify the scientific and the effectiveness of the model, two activities with the longest duration and the highest cost in [2] are selected for the example design and result analysis.

#### 5.1. Example Design

The parameters not involved in [2] are assigned. And the values of all parameters are shown in Tables 2 and 3.

The reliability of vendors is listed in Table 4 [34]. We can know that the reliability of vendors to deliver materials one day in advance is 11%, that of delayed delivery is 22%, and so on.

#### 5.2. Result and Analysis

The algorithm cycled 250 times and the maximum revenue of each 5 cycles is recorded. The distribution of the maximum revenue is approximately in line with the uniform distribution, and the change has tended to be stable according to Figure 4. $N_C$ is the amount of cycling. Therefore, the maximum revenue is 364.4653. The corresponding overlap and communication strategies are as follows: (1) the start-up time of overlapping is 11th day, (2) the amount of communication is eight, respectively, on the 11th, 16th, 19th, 22nd, 39th, 45th, 48th, and 50th days; and (3) the total rework time is 7 days. When the revenue is maximum, the relationship between the “downstream sensitivity” and the “communication strategy” is shown in Figure 5. The sensitivity shows a downward trend with the progress of communication. It may be because the construction team keeps learning from mistakes throughout the overlapping.

Communication frequency ($T_C$) and the start-up time of overlapping ($t_1$) are two important factors affecting duration and the maximum revenue. The changing of the duration of the two activities with $T_C$ and $t_1$ is shown in Figure 6. The duration shows a downward trend with the increasing of $T_C$ and the decreasing of $t_1$. But when $T_C$ is 6 and $t_1$ is 11, the duration is the smallest, which indicates that the maximum number of communications does not lead to the minimum duration of the project.

As represented in Figure 7, when communication frequency is eight and the start-up time of overlapping is 11th, the revenue is maximized. (2) And the decrease in
communication frequency does not always lead to a decrease of revenue. These discoveries are different from the earlier conclusion that the more frequent the communication is, the less time it takes to complete the activity. Also (1) the decrease of rework time does not always lead to an increase in revenue according to Figure 8. On the contrary, (2) the moderate extension of rework time can increase the revenue when applying the best overlapping strategy. Therefore, the minimum rework time cannot be considered as the primary goal but the rework time should be relaxed to obtain as much revenue as possible.

5.3. Sensitivity Analysis and Discussion. To further explore the impact of communication cost, rework cost and overlapping cost on the optimal revenue, rework time, and communication times, sensitivity analysis of these three parameters was carried out.

Keeping other parameters unchanged and changing the unit communication cost, the results are shown in Figures 9 and 10. It is clear that, with the increasing cost of communication, (1) the number of communications first decreases, then increases, and finally decreases again; (2) the rework time first increases and then decreases, (3) while the maximum revenue has been on a downward trend. This shows that the unit communication cost has a significant impact on the target value, and the reduction of it can significantly improve the maximum revenue. But the number of communications does not necessarily increase, and the rework time is not positively correlated with it. Therefore, to improve the revenue, the communication cost needs to be reduced as much as possible. At the same time,
Figure 6: Communication frequency \((T_C)\)-the start-up time of overlapping \((t_1)\) – duration \((D)\).

Figure 7: Communication frequency \((T_C)\)-the start-up time of overlapping \((t_1)\) – revenue \((I_{\text{max}})\).

Figure 8: The start-up time of overlapping \((t_1)\) - rework time \((R_t)\) – revenue \((I_{\text{max}})\).
even if the cost of communication is low, it does not mean to increase the number of communications.

Figures 11 and 12 show that overlapping costs and rework costs have similar effects on communication times. (1) When their values are minor, the impact of cost changes on communication times is not significant enough. However, with the increase of unit cost, the impact is significant but shows an irregular trend. (2) Although the effect of rework cost change on rework time and maximum benefit is irregular, it has been always significant. (3) When the cost of rework and the rework time are relatively large, especially, the revenue is not in the smallest state. This is because dynamic and targeted overlapping and communication strategies offset the impact of these adverse factors. (4) The change of overlapping cost has a significant impact on rework time and return. Similar to the impact of communication cost on maximum return, the optimal return decreases with the increase of the overlapping cost. Therefore, a substantial increase in revenue can be achieved by reducing overlapping costs and communication costs. Figures 13 and 14 show that revenues are more sensitive to changes in overlapping costs, while the relative between revenues and the rework costs are irregular.

In terms of single factor, it can be known from the sensitivity analysis that (1) the communication cost and overlapping cost should be strictly controlled to achieve the improvement of revenue because their impact is significant. Therefore, more studies about ways to reduce those two costs, like applying information technology, should be conducive to create a collaborative platform that is easy to communicate and can be used to rationally plan resource allocation and utilization. (2) For the communication strategy, the results analysis and sensitivity analysis show that the rework cost and communication cost have no significant impact on the communication frequency, which also verifies our hypothesis that the communication frequency is affected by the interaction of activity start-up time, communication cost, and rework costs. Therefore, it needs a comprehensive strategy to finalize the project communication strategy. Neither should we increase the communication frequency because of low communication costs and high rework costs, nor should we reduce the communication frequency because of increased communication costs and reduced rework costs.

In terms of multiple factors, (1) revenue and rework costs and rework time do not present a strict positive correlation, which should be related to the introduction of communication during the overlapping. The transmission of information helps to eliminate understanding of the inconsistency of goals and improve the project performance. (2) There is a clear correlation between the duration and the number of communication times and the start time of the overlapping. When communication is frequent and the overlapping is started early in the activity, the duration has a significant downward trend. Although the overlap may lead to rework due to the uncertainty of the activity information, the frequent communication eliminates the uncertainty during the construction period, enabling the project to be completed smoothly and reducing the total duration.

However, it should be noted that only when these two factors change together can the shortening of the construction period be achieved. If only the communication frequency is simply increased, the duration cannot be minimized.

5.4. Algorithm and BIM. The algorithm in our paper can automatically give different communication and overlapping strategies and the corresponding revenue, duration, and rework time only by inputting the duration of dependent activities. But the intelligent schedule is hard to achieve by it because the visualization of the process is low. Considering the rich information of the BIM model and the dynamic communication platform, provided by BIM, where the stakeholders can have more easily access to negotiate with each other, our algorithm and BIM are combined to provide an intelligent control process for the development of schedule.
The process is shown in Figure 15. Firstly, the BIM modeler builds a 3D model and adds corresponding project information, such as duration and start-up time. Secondly, link the model to the on-site and marking the activities in construction with red, so that they can be easily distinguished from the activities that do not start. Thirdly, retrieve the supplier data in the database, which requires advanced storage. And calculate the upstream activity maturity by the above model and algorithm. Fourthly, we use yellow to indicate activities to be started and then calculate and display their overlapping strategy, communication strategy, and their corresponding benefits and duration. Finally, the project manager can select a suitable activity to arrange the schedule according to their before achieving the desired effect.

By associating the algorithm with BIM, the simulation of the activity can be carried out in advance, and the recommendations and references can be compared to develop the most suitable schedule. At the same time, the combination can provide a visual display platform for stakeholders to communicate progress issues and present the schedule information in a visual and easy-to-understand way. These reduce the communication barrier so that the negotiation can be achieved at a lower cost and faster way. What is more, the different colors help distinguish activities in different states, which provides an efficient understanding environment.
6. Conclusions

This paper focuses on making intelligent schedule for dependent activities by responding to ongoing changes with mathematical models and simulation, as well as advanced techniques. We firstly introduce the “maturity” variable to quantify the change and reduce it through multiple information sharing. The best communication and overlapping strategies are determined through Monte Carlo simulation with the consideration of workers’ characteristics. Finally, we built an intelligent control process with BIM.

The simulation results provide some interesting conclusions. For revenue, it is more sensitive to communication cost and overlapping cost than rework cost. Also, the increasing of rework time does not mean the decreasing of revenue. Similarly, more frequent communication would not bring in more revenue. For communication, it will not be more frequent due to lower communication costs when aiming at revenue maximizing. For duration, frequent communication cannot ensure the decreasing of rework, but the minimum duration can be achieved if limiting the overlapping and communication strategy at the same time.

This paper has some innovation points. Firstly, by considering the different characteristics of the activity during different periods and the start-up of overlapping, the maturity is measured more realistically, which provides an important basis for further analysis of changes. Secondly, we set the start-up time of overlapping and the communication time during the overlapping subject to random distribution, which makes our model and simulation more applicable. And the prediction of various overlapping and communication strategies and revenue can be achieved only by simple simulation. Thirdly, the characteristics of workers are fully studied. We model the “receiving information”, “transforming into one’s knowledge” and “correcting the error” process with the learning coefficient and error-correcting coefficient. Finally, algorithms and BIM are combined to provide a reference for intelligent schedule of process control.

The conclusions provide several important managerial insights. For the company that pursues revenue maximizing, it is of great significance to find a way to decrease the cost of overlapping and communication. They should introduce more advanced technologies (like BIM) to achieve efficient communication. However, for the company that has a tight schedule, it is more important to value the combined application of overlapping and communication strategies to meet the requirements of duration while ensuring a certain degree of revenue. There also exist some limitations in this paper. The conducted model is based on certain specific assumptions, which may differ from reality. Much empirical research should be conducted to verify these assumptions. Besides, the strategies putting forward in this paper lack a quantitative measurement of the dynamic environment. The following studies should focus on this problem from the perspective of information entropy.

![Figure 15: An intelligent control process for the development of schedule.](image-url)
Data Availability

The data supporting this simulation is from previously reported studies and datasets, which have been cited.

Conflicts of Interest

The authors declare no conflicts of interest.

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References


