Schedule compression and emerging waste in construction

an assessment of overlapping activities

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Published in:
Engineering, Construction and Architectural Management

DOI (link to publication from Publisher):
10.1108/ECAM-12-2022-1121

Publication date:
2023

Document Version
Accepted author manuscript, peer reviewed version

Salhab, D, Lindhard, S. M. and Hamzeh, F., (2023), "Schedule Compression and Emerging Waste in Construction: An Assessment of Overlapping Activities", Engineering, Construction and Architectural Management, Vol. Ahead of print, No. Ahead of print. https://doi.org/10.1108/ECAM-12-2022-1121

SCHEDULE COMPRESSION AND EMERGING WASTE IN CONSTRUCTION: AN ASSESSMENT OF OVERLAPPING ACTIVITIES

ABSTRACT

Purpose: Compressing the schedule by using overlapping activities is a commonly adopted approach for accelerating projects. However, this approach might channel a variety of risks into the construction processes. Risks imply waste; still, evaluating the effects of using overlapping activities on schedule quality has been a looming gap in construction research. Therefore, there is a need to study the quality of overlapping in terms of emerging waste and to demarcate the boundaries of the overlapping envelope.

Design/Methodology/Approach: This study presents a method for assessing the consequences of implementing overlapping activities in a schedule, on two types of waste namely waiting time and variation gap. A Critical Path Method (CPM) network including eleven activities is modeled stochastically where the durations of individual activities are sampled as Beta-distributions. Using Program Evaluation and Review Technique (PERT) assumptions to calculate the schedule dates, the network is simulated for various amounts of overlapping and the corresponding waste is quantified each time.

Findings: Results show that not only the returns on overlapping are diminishing after a certain overlap percentage, but also waste in the production system increases. Particularly, results reveal that compressing the schedule leads to a decrease in variation gaps, but at the same time, it leads to a larger increase in waiting times, which creates more waste.

Originality: The presented study shows through simulation how overlapping activities affects productivity by identifying wastes. It shows that despite the apparent gains, overlaps should be used with caution, and while considering the side-effects of increased waste which introduces a need for increased managerial awareness.

Keywords: Scheduling, Schedule compressing, Overlapping activities, Waste, Simulation.

1 INTRODUCTION

At times, specific factors compel project management to compress the schedule and reduce project duration. Among the diverse techniques for accelerating construction projects, compressing the schedule by overlapping activities remains one approach widely adopted by practitioners. Schedule compression is a managerial tool used by professionals to ensure that a project is completed within a predefined schedule. Overlapping is a process of executing two or more sequential tasks in a partially overlapping manner with respect to time. Constructors faced with the need to accelerate a construction schedule are confronted with extreme difficulties, especially when dealing with unplanned compression. Unplanned compression refers to compression that was not anticipated nor planned prior to starting construction and that results from changes in original planned work scope or schedule (Mansur *et al.*, 2006). Although the practice of overlapping activities has been applied in fast-tracking, large-scale, and complex construction projects (Srour *et al.*, 2013), significant schedule overlapping might deteriorate the construction operations' performance for these activities (Moon *et al.*, 2015). Risks such as overcrowding the site (Igwe *et al.*, 2020), increased rework (Hazini *et al.*, 2013), and frequent claims (Moazzami *et al.*, 2011) are associated with overlapping activities, leading to waste. Such risks are likely to stem from initiating the successor activities with missing data and incomplete information (Hazini *et al.*, 2013). In fact, the U.S. Federal Facilities Council released a technical report stating that 33% of projects adopting schedule compression have claims, compared to 7% claims by projects following conservative schedules (Moazzami *et al.*, 2011). Specifically, when overlapping many activities, inevitable issues related to resource availability arise (Moon *et al.*, 2015), not to mention productivity losses resulting from congestion. Overcrowding the site, which occurs because of changing start dates of certain activities, is a potential risk. Shifting some activities

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to occur simultaneously with others might lead to congestion if the workspace requirements for these activities overlap as well. Consequently, safety and productivity are impacted. In fact, the Occupational Safety and Health Administration (OSHA) stated that 75% of struck hazards, which are among the deadliest hazards in construction, are due to spatial-temporal collisions (Igwe *et al.*, 2020). Moreover, overlapping might be less efficient than expected because variations in outputs of predecessors will probably cause rework in successor activities, thereby extending the duration of the latter (Hazini *et al.*, 2013). Indeed, rework and change orders occur at a higher frequency in fast-track projects. In addition, it is challenging to specify the optimal strategy for compressing a construction schedule, and the decisions made for accelerating a project might be associated with loss rather than benefit (Hazini *et al.*, 2013).

Having said all this, decisions pertaining to selecting overlapping activities and the degree of overlapping must be carefully made, especially since compressing a schedule creates waste. However, no study has been found to evaluate the quality of overlaps in terms of emerging waste that is detrimental to the production system as discussed earlier. It is important to assess waste in order to ensure that the compressed schedule is efficient and effective. Assessing waste can help identify opportunities to streamline the schedule and eliminate unnecessary tasks. By doing so, the project team can reduce the overall duration of the schedule and ensure that resources are being used effectively. This can help reduce costs and improve the quality of the final product. In addition, identifying waste can help the project team focus on activities that are critical to the project's success and prioritize these activities accordingly. This can help ensure that the project stays on track and meets its deadlines. Therefore, this study employs simulation to tackle the effect of compressing the schedule on two types of waste, which are waiting time and variation gap. Waiting time is a type of waste that occurs when subsequent work waits behind its scheduled start date, due to previous work being completed behind schedule. A variation gap consists of untapped potentials, which occur when activities are completed or have the potential to be completed ahead of schedule (Salhab *et al.*, 2022). The scientific contribution of this study lies in presenting a method for evaluating schedule robustness in terms of waste created when implementing overlapping. Additionally, this study contributes to the industry by assisting site managers when making decisions regarding shortening project duration through applying activity overlapping. Understanding the effects of schedule compression provides a basis for rational decisions. To deliver the purpose of the study, the suggested approach was tested on a hypothetical CPM network consisting of eleven activities that was adopted from a previous study. The network is stochastically modeled in MATLAB, where activity durations are taken as beta-distributions rather than deterministic values. The schedule is compressed in three phases, starting with a 25% overlap percentage between select activities, then 50%, and finally 75% overlap percentages. The analysis is further elaborated in the discussion section, and findings are recapitulated in the conclusion section.

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2 LITERATURE REVIEW

Some researchers have suggested that overlapping is harmful to the production system, while others have defended its use. For instance, Lu *et al.* (2022) conducted interviews and archival research to analyze schedule compression practices through a qualitative case study method on two hospital projects. Their results recommend that successful practices heavily depend on the participants' and organization's high capacity, as well as innovations in technology and management. Bharadwaj *et al.* (2019) discussed the factors leading to the need for compressing schedules, along with an overview and comparison of different compressing techniques. The authors state that schedule compression techniques entail additional costs in increments of 0% to 5%, additional resources in increments of 5% to 10%, a compression degree in increments of 15% to 20%, and medium calculation efforts. Ballesteros-Pérez (2017) presented a stochastic model for accelerating construction schedules through overlapping. The suggested model is advantageous with respect to (1) calculating the exact costs resulting from activity overlapping and (2) minimizing the subjectivity of input data. Garrido Martins *et al.* (2017) posited that activity overlapping creates risks that impact project duration and the adopted construction strategy. They used Monte Carlo Simulation (MCS) to simulate various overlapping levels while incorporating the probability of occurrence and the impacts of several risk factors. On the other hand, Abuwarda and Hegazy (2016) presented a computational model for translating flexibility in the relationships between tasks into modified task start and finish dates, thereby accommodating the overlapping needed for schedule crashing. Gwak *et al.* (2016) proposed a computational model that allows formulating a global solution for accelerating a project while respecting project constraints such as duration and budget. In their model, concurrency attributes of activities are considered for calculating the amount and cost slope of rework. More importantly, the study presented a mathematical formula for computing the exact rates of activity overlapping remuneratively. Moon *et al.* (2015) argued that overlapping activities can be detrimental to project performance, so they implemented a systematic methodology for simulating construction schedules to optimally constrain the overlapping activities. All overlapping tasks are shifted in day units, either forward or backward within the calculated total float, until an optimal schedule with minimum overlap is reached. Their results showed a 32.84% decrease in the schedule overlapping ratio. Hazini *et al.* (2013) provided a detailed discussion on and a comprehensive comparison of three schedule compressing strategies, which are crashing, substitution, and overlapping. The study further included a practical method for combining these strategies to optimally shorten the project duration at the least cost increase. Grèze *et al.* (2012) presented a scheduling heuristic model to shorten project duration through performing overlapping between activities without violating precedence and resource constraints. They stated that overlapping causes rework activities, which are added as an increase in duration of the downstream overlapping activities. Therefore, their method used an objective function to achieve an appropriate tradeoff between the reduction in project duration and the additional costs incurred by rework. Similarly, aiming to optimize overlapping between tasks to achieve a balanced time-cost acceleration, Dehghan *et al.* (2011) developed a genetic algorithm designed to allow the cost of overlapping to change proportionally to the degree of overlapping. Bogus *et al.* (2005) suggested a planning framework to assess overlapping in terms of the strategies used, overlap degrees, and outcomes of overlapping dependent tasks. To do so, they formulated a decision algorithm;

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however, it requires input information that might be difficult to acquire. In addition to extra costs for design and construction, overlapping dependent tasks might cause rework. Considerations that must be addressed when seeking overlapping include specifying the dates of overlapping, degree of overlapping sequential tasks, and strategies to adopt in achieving this overlapping (Bogus *et al.*, 2005).

Overlapping schedules have also been applied to the design phase. For instance, in identifying the shortest overlapping schedule for the design phase in fast-track projects, Srour *et al.* (2013) proposed a four-step scheduling framework that considers the exchange of information among various project tasks using a dependency structure matrix (DSM). The approach allows sequencing and quantifying the magnitude of overlaps among different design disciplines. The approach was verified by testing it on a real case study, and the results showed that the model can be used to generate short schedules for the design phase of fast-track mega projects. Bogus *et al.* (2011) proposed that overlapping activities could create risks, although such overlapping reduces project duration and possibly the overall cost. They suggested that an interaction occurs between the upstream and downstream activities in a schedule, which depends on (1) the way information emerges in upstream activities and (2) the degree of sensitivity of downstream activities towards this evolving information. In other words, a greater risk exists when an upstream task processes information slowly, but the downstream task is robustly sensitive to variable information, and vice versa. As a result, risk might be expressed in the form of rework or re-executing parts of the downstream task. Therefore, the authors developed a simulation model that tests the effect of strategies, including overdesign, early release, and diverse percentages of overlapping, on the possible rework risk. They concluded that decision-makers generate more systematic decisions pertaining to task durations and overlaps when using the presented approach.

Alternatively, another widely adopted approach for compressing construction schedules is time-cost tradeoff (TCT). TCT is practiced by crashing activity durations (e.g., adding more resources or operating overtime), which drives direct costs to increase (Nasiri and Lu, 2019). The goal of such analysis is to identify the shortest possible duration at a minimal cost. A variety of researchers have proposed different algorithms to optimize TCT analysis. Tomczak and Jaskowski (2020) presented a schedule crashing optimization approach by relocating resources from non-critical tasks to critical ones through changing the crew composition. The model was able to shorten project duration by 7% without hiring additional resources, and by 27.7% with employing more resources, but with incurring 40% additional subcontracting costs. Moreover, Nasiri and Lu (2019) proposed a novel framework for optimizing TCT using a technique that merges path-float with integer programming. In this technique, only the critical path fraction of the network is considered in each cycle, narrowing the search space.

Table I summarizes findings and contributions from different schedule overlapping studies. The majority of these studies revolve around a similar objective, which is shortening the project duration at the minimal possible cost. Others focus on optimizing the combination of different schedule compression techniques. However, they do not consider evaluating the quality of overlapping in terms

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of emerging waste in the schedule. Tasks in a network are interdependent in a way that altering one activity impacts its dependent activities. Although a variety of applications and purposes justify the use of overlapping schedules and their impact on rework, as Table I shows, no study has been found to address how compressing activities affects waste in a schedule by creating variation gaps and waiting times. Thus, in this study, the effect of overlapping activities is evaluated by examining two types of waste, namely waiting time and variation gap, which are detrimental to the production system and should therefore be avoided. Scrutinizing such effects help the project planners and schedulers make more informed decisions when implementing schedule overlaps, especially since activity overlaps can lead to undesirable effects such as overcrowding a site and adding rework. Also, most schedule compression studies, including those involving TCT, integrate cost with time while seeking optimal solutions to balance both. Decisions pertaining to TCT analysis are generally complex, prompting planners to choose suitable resources for each activity and select corresponding equipment, technology, methods, and crew size. Reaching an optimal solution in TCT is a tedious and difficult task, especially since many possible permutations exist (Hegazy, 1999). Thus, the method presented allows examining the effect of compressing a schedule without considering cost and by investigating multiple overlap percentages. In other words, the method combines variation with compression to examine whether the returns of compressing the schedule are diminishing, even if cost is not considered. Additionally, not only critical activities are compressed, but other activities that have a significant influence on project duration are identified using the Spearman coefficient and compressed accordingly. In brief, this paper presents a method to test the robustness of a schedule when overlapping activities in terms of the effect on waste, which can be used by project managers to evaluate different alternatives for better project performance.

Table I: Summary of previous research.

Study	Finding/Contribution	Domain
Lu *et al.* (2022)	Successful schedule compression practices depend on organization's high capacity.	General
Bharadwaj *et al.* (2019)	Schedule compression increases costs in increments of 0% to 5%, and resources in increments of 5% to 10%.	
Ballesteros-Pérez (2017)	There is a physical-like obstacle indicating that it is improbable to reduce a schedule by over 25% of its initial length when using overlapping.	
Martins *et al.* (2017)	Compressing a sample project indicates a 21.4% chance of achieving a shorter duration than the original one, implying a high probability of 78.6% that implementing the fast-track approach will be unsuccessful.	
Abuwarda and Hegazy (2016)	Decisions pertaining to overlapping and crashing can be optimized using the proposed model which showed through a case study an 18% decrease in project duration at no extra cost.	
Gwak *et al.* (2016)	The model efficiently pinpoints the precise global overlaps between activities and creates a compressed schedule that meets the project's requirements for both budget and duration.	
Moon *et al.* (2015)	Schedule overlapping ratio can be decreased by 32.8% using total float, entailing potential increase of resource utilization efficiency, flow continuity, and job logic.	

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Hazini *et al.* (2013)	By identifying the most effective combination of accelerating and overlapping techniques, the model can shorten the project duration by 16% while maximizing monetary benefits.	
Grèze *et al.* (2012)	Rework activities resulting from overlapping are appended to downstream tasks and the resource consumption remains constant during project execution.	
Dehghan *et al.* (2011)	By increasing the extent of overlapping, it is possible to attain greater benefits while simultaneously reducing the project duration.	
Bogus *et al.* (2005)	The input requirements for analytical approaches involved in schedule overlapping include schedule, assessment of upstream and downstream activities' evolution and sensitivity respectively, overlapping cost, and overlapping risk of rework.	
Srour *et al.* (2013)	An overlapping scheduling algorithm is created to compute the most concise (overlapped) possible design phase schedule based on interrelationships between design disciplines. This algorithm integrates information exchange with task durations	Design
Bogus *et al.* (2011)	Utilizing simulations to model concurrent engineering activities through overlapping activities is a reliable method. The simulations provide details regarding the likelihood of rework by examining diverse combinations of evolution, overlapping strategy, sensitivity, and the percentage of overlap between the upstream and downstream activity.	
Tomczak and Jaskowski (2020)	The proposed approach makes it possible to decrease a project's baseline time by 27.7%, albeit at a cost of a 40.0% rise in subcontracting expenses. Such a notable reduction in project duration may be advantageous in projects with strict timelines, as well as situations in which the planner needs to compensate for delays to evade steep contractual penalties.	TCT
Nasiri and Lu (2019)	The study presents a novel computing framework for optimizing TCT which utilizes a method based on path-float and integer programming (IP). The path-float analysis enables the project duration to be reduced during each crashing cycle, whereas IP is incorporated to identify the critical path(s) activities to shorten and the extent of duration reduction.	

3 METHODOLOGY

The methodology used in this study is a computational simulation approach that involves building a stochastic simulation model using MATLAB to examine the effect of compressing the schedule by overlapping activities. The simulation model is based on a network of activities with uncertain durations, which are modeled using a beta distribution. Previous studies identified the beta distribution as the most suitable method for simulating production (Lindhard *et al.*, 2019; Nguyen *et al.*, 2013). To achieve this, best-case (a_i), most-likely (m_i), and worst-case (b_i) duration parameters are first defined for each activity (i). Then a beta distribution is generated based on the specific duration parameters (best-case, most-likely, worst-case) to represent the probability density function. The simulation runs involve stochastically generating durations based on the beta distributions and updating the schedule after a delay is encountered. In each run, the summed mean durations (t_e) and

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variances (V) are calculated for each path using Equation 1 and Equation 2 from PERT (Andiyan *et al.*, 2021).

$$Mean\ (t_e) = \frac{a_i + 4 \times m_i + b_i}{6} \quad (1)$$

$$Variance\ (V) = \left(\frac{b_i - a_i}{6}\right)^2 \quad (2)$$

The methodology involves conducting multiple simulations with varying degrees of overlap in four phases and identifying key activities that have the greatest impact on schedule duration. To do this, first, the initial network with no overlap is simulated. Then, to identify where compressing will have the most impact, and consequently, to know where to intervene, key activities that have the greatest impact on schedule duration are identified using the Spearman coefficients (Salhab *et al.*, 2022). Thus, Spearman coefficients of the activities' impact on total duration were calculated. The schedule was compressed by planning for pairs of activities to be completed in parallel, making the execution phase of key activities overlap with their successor activity. In the next three simulations, the compression is carried out gradually with a 25%, a 50%, and finally a 75% overlap, respectively. In each run, waiting times and variation gaps were quantified. Overall, this approach involves using computational models and simulation techniques to investigate the effects of schedule compression on waste reduction in construction projects. The methodology is summarized in Figure 1.

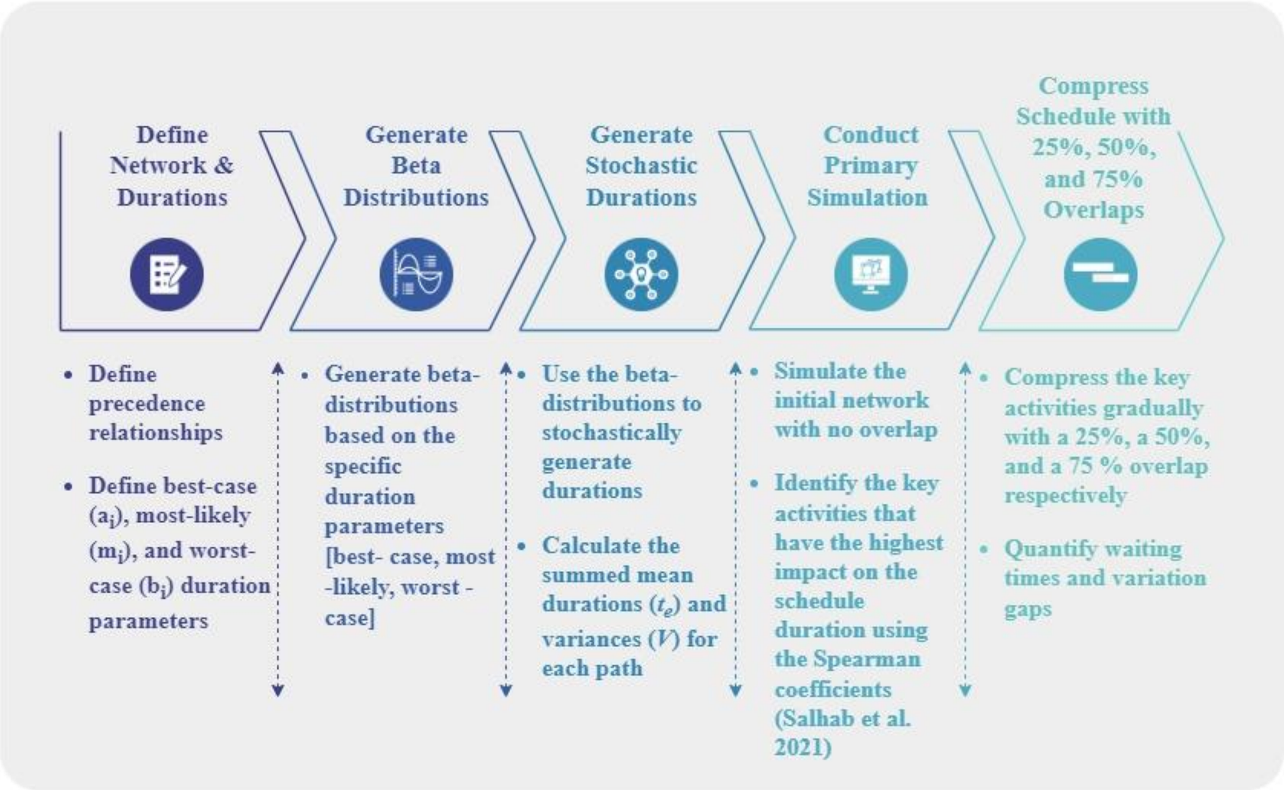

Figure 1: Diagram of the proposed research methodology

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3.1 Methodology Assumptions

Some assumptions have been adopted to fulfill the purpose of this study. First, the beta-distribution represents the duration of the activity under a fixed set of production assumptions where differences in durations are caused by variations in labor productivity (Arashpour and Arashpour, 2015). If the production assumptions change, such as by adding more laborers, the entire probability distribution function changes, and new beta-distributions must be generated.

Second, during the simulation runs, each stochastically sampled duration is compared to the corresponding mean duration (representing the scheduled duration), and the one with the largest value is selected. Selecting the larger value as the activity duration means that the activity cannot be completed ahead of schedule. This assumption is based on on-site experience: when planning upcoming work, a contractor prioritizes tasks by matching workload with capacity, while re-evaluating the durations and criticality. When an activity is evaluated as potentially being completed ahead of schedule, resources are often moved to more critical activities, which in turn reduces the chance of completing an activity early. Moreover, when an activity is actually completed ahead of schedule, the project management team usually receives this information too late, making it impractical to coordinate with the contractors coming next. Therefore, during the project, the simulation model is formulated in a way that updates the schedule after a delay is encountered. This reflects that site management continuously conducts scheduling and re-scheduling to keep track of project progress (Laufer and Tucker, 1987).

Third, there are two reasons for selecting the three percentages of 25%, 50%, and 75%. Firstly, numerous runs (100,000) are conducted for each step of overlap, and the complexity increases with each run which adds plenty of extra calculations per run. This requires a huge computational effort to run and re-run all simulations and issue corresponding outputs for a specific percentage. Since the study presents a hypothetical example intended to show the impacts of schedule compression on waste, it is presumed that the selected three percentages are enough to deliver the purpose. Secondly, it is desirable to see a difference in outcomes so that the results can be clearly compared, leading to useful analysis. Thus, being not too close to each other's, the selected percentages should allow such kind of analysis, as they cover a wide range of the solution space.

Fourth, in the simulation, each activity is divided into four sub-activities. Unique distributions are then created for each sub-activity while ensuring that the summed durations follow the distribution function of the whole activity. Afterwards, interrelationships are encoded, which include dependencies between activities and sub-activities. Performing schedule compression through overlapping leads to an increase in interdependencies between parallel activities, making the activities vulnerable to deviations in durations. Since waiting time is a type of waste that occurs when schedule delays for one task create schedule delays for subsequent tasks, this waste is dependent on the interrelationships between activities in a network (Lindhard, 2014). Variation gaps are similarly dependent on interrelationships between activities, since they represent the time gap between actual or potential completion dates and the dates of starting subsequent activities. Therefore, to determine

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the activities' start dates and to calculate waste, the relationship between the simulated duration and the planned schedule is established.

In the following sections, the model is applied to a predefined network and the results are discussed.

4 MODEL APPLICATION

4.1 Network Information

The proposed model was applied to a predefined network of activities, shown in Figure 2, which is adapted from a study by Nicholas and Steyn (2008). The simulated network consists of eleven activities labelled *A* through *K*. As mentioned, calculating the mean durations and variances requires specifying the best-case, most-likely, and worst-case parameter durations. In a simulation run, the total duration of the project is determined by identifying the critical path. Table II summarizes these parameters along with the calculated mean duration and variance for each activity. The activities highlighted in light red in Figure 2 represent the critical path.

Table II: The basic characteristics to the activities (A–K) in the network diagram. Variance and mean are calculated using traditional PERT formulas. A similar table can be found in Salhab et al. (2022).

Activity	Best case (a)	Most likely (m)	Worst case (b)	Variance (V)	Mean (t_e)
A	7	14	21	5.44	14
B	6	15	30	16.00	16
C	2	5	8	1.00	5
D	1	4	7	1.00	4
E	3	12	21	9.00	12
F	7	10	13	1.00	10
G	5	7	9	.44	7
H	2	4	6	.11	4
I	1	6	11	2.78	6
J	1	5	9	1.78	5
K	1	4	7	1.00	4

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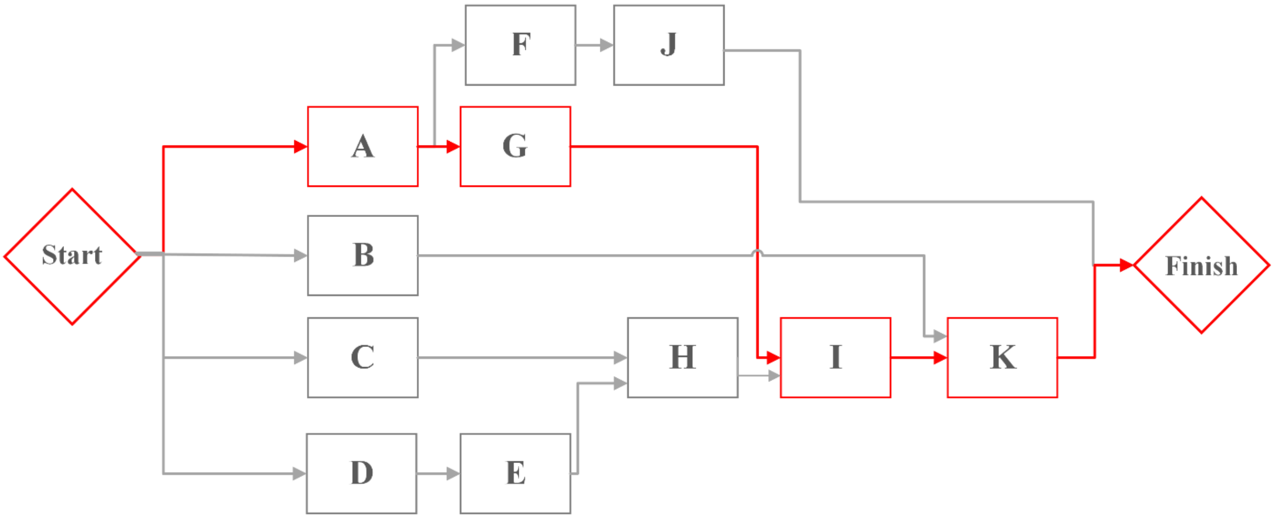

Figure 2: Network diagram based on the diagram defined in Nicholas & Steyn (2008).

Due to the interrelationship between the 11 activities in this study, five different paths existed, as illustrated in the network diagram (Figure 2). These five paths are: A-F-J, B-K, A-G-I-K, C-H-I-K, and D-E-H-I-K. The duration of the entire project, which is identified through the longest of the five paths, was calculated by summing the durations of individual activities along each path. In this case study, the target deadline of the project was set to 33 days, which is 6.5% longer than the critical-path duration of 31 days. In each simulation run, the path durations were compared to the deadline in order to identify the likelihood of meeting the deadline.

This study examined the effects and side effects of using overlapping activities. In each simulation run, activity durations and time wastes in the network were calculated. Through the simulation, five possible paths were examined, and the probability of each path exceeding the deadline was calculated.

4.2 Effects of Compressing the Schedule

As mentioned, compression is conducted by scheduling activity pairs to be performed in parallel. Thus, pairs of activities were created based on network characteristics where the activities subsequent to A, E, I, and K were identified. Because K is a subsequent activity to I, this results in three pairs: AG, EH, and IK. AG and EH are located on two different primary paths. Therefore, to prevent the other primary path from becoming critical, AG and EH were compressed simultaneously. IK lays on both paths (A-G-I-K and D-E-H-I-K); thus, compressing IK affects the two near-critical paths identically. IK was compressed separately.

Schedule compression was examined in two scenarios:

(1) Scenario 1: AG and EH were compressed, with A and E identified as the important activities. Both A and E are long activities with great variation. The effect of the compression on project duration is dependent on one another. Thus, to achieve the desired effect, both A-G-I-K and D-E-H-I-K needed to be shortened simultaneously despite the great variation in A and B.

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(2) Scenario 2: IK was compressed, with I and K identified as important activities in relation to project duration. Both I and K are short activities with less variation compared to A and E, but their direct effect on duration is stronger because they exist on the two primary paths.

In each scenario, four simulations were conducted. First, the initial network with no overlaps was simulated, and then, the schedule was compressed by 25%, 50%, and 75% overlap.

4.3 Model Verification and Validation

Model verification entails checking whether the model is built correctly with no errors, while model validation ensures that the model built is the correct one for the case at hand. Sargent (2010) recommended several tests for model verification and validation. Of those, both *static* and *dynamic testing* were selected to verify the model proposed in this study. Static testing was performed through walkthroughs and traces, where small 10 run simulations were used to continuously check for errors and compliance. Dynamic testing was conducted by varying input and checking if output makes sense. The model was running error free and generating expected output. As for model validation, a *face validity* test was adopted. This test requires experts or people knowledgeable about the subject to ensure that the model or/and its behavior are rational (Sargent, 2010). To do so, the group working on this study was divided into two: one building the computational model and one checking its logic without bias to ensure that the model is based on accurate assumptions and relevant variables. The second group consulted in face validation consists of subject matter experts in the field of planning and scheduling. The experts reviewed the model and provided feedback on whether the variables and equations used in the model accurately reflect how overlapping affects waste. The following section presents the results, providing insight into the study's outcomes.

5 RESULTS & ANALYSIS

5.1 Results

The paths, their summed mean durations, and their summed variances are shown in Table III. The mean durations reveal that A-G-I-K is the critical path, while A-F-J and D-E-H-I-K are near-critical paths.

Table III: The five paths in the network diagram, their summed mean duration, and their summed variance. A similar table can be found in Salhab et al. (2022).

Activities	Summed mean duration	Summed variance
A-F-J	29	8.22
B-K	20	17.00
A-G-I-K	31	9.66
C-H-I-K	19	4.89
D-E-H-I-K	30	13.89

The project durations and related probabilities are shown in Figure 3(a). Figure 3(b) shows the project's summed waiting time, while Figure 3(c) shows the project's summed variation gaps.

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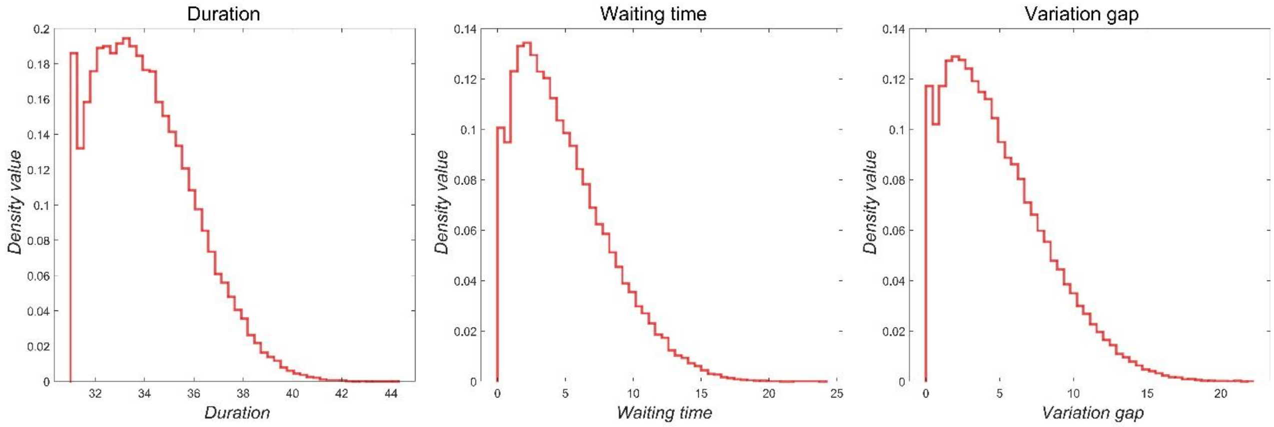
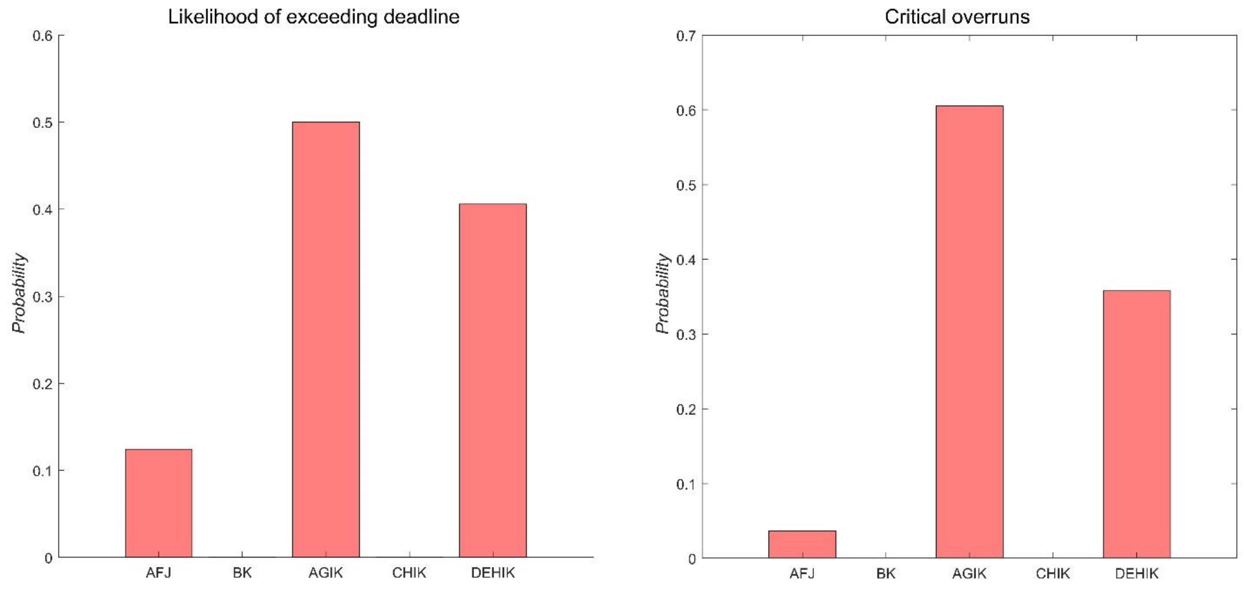


(a) **(b)** **(c)**

Figure 3: Schedule performance. (a) Probability density function related to project duration. (b) Probability density function related to the project waiting time. (c) Probability density function related to the variation gap at project level.

The simulation results show that A-G-I-K is the path that most often exceeds the deadline, with a likelihood of 50.04%. Path A-G-I-K was expected to be an important path because it was identified as the critical path using the PERT method. After path A-G-I-K, paths D-E-H-I-K and A-F-J have a likelihood of exceeding the deadline of 40.41% and 12.36%, respectively. These findings are shown in Figure 4(a), which shows how often each path is critical. The most critical paths are A-G-I-K (critical in 60.83% of cases), D-E-H-I-K (35.41%), and A-F-J (3.74%).



(a) **(b)**

Figure 4: Network paths. (a) Likelihood of path exceeding deadline. (b) Number of critical overruns per path. A similar figure can be found in Salhab et al. (2022).

Table IV shows the Spearman coefficients calculated for this study. Based on the Spearman coefficients, the activities having the most impact on project duration are A, E, I, and K, which is consistent with calculations confirmed by Salhab *et al.* (2022). Therefore, the schedule compression was carried out beginning with these four activities.

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Table IV: Spearman coefficients expressing the activities' impact on total duration. A similar calculation can be found in Salhab et al (2022).

A	B	C	D	E	F	G	H	I	J	K
0.48	0.00	0.00	0.10	0.46	0.02	0.11	0.03	0.43	0.02	0.26

5.2 Analysis

5.2.1 Effect on Duration

As expected, schedule compression was found to decrease project duration. When compressing both AG and EH, or IK, the project duration was reduced along with the standard deviation, while skewness (distortion of asymmetry) and kurtosis (weight of the tails) remained essentially unaffected. Thus, the compression did not affect the shape and asymmetry of the probability distribution function. The four moments of statistics are shown in Table V, while Figure 5 shows the probability density functions. Table VI shows the percentage decrease in mean durations at the project level.

Table V: The four moments of statistics at project level.

	Mean	**Std. dev.**	**Skewness**	**Kurtosis**
		0% overlap		
AG and EH	34.04	1.99	.641	3.037
IK	34.04	1.99	.631	3.003
		25% overlap		
AG and EH	31.61	1.77	.674	3.145
IK	32.53	1.85	.623	2.973
		50% overlap		
AG and EH	31.54	1.78	.698	3.162
IK	31.81	1.78	.637	2.980
		75% overlap		
AG and EH	31.53	1.78	.698	3.163
IK	31.57	1.76	.665	3.025

Table VI: Percentage decrease in mean durations at the project level.

	0–25% overlap	**25–50% overlap**	**50–75% overlap**	**Total**
AG and EH	7.14%	0.221%	0.0317%	7.39%
IK	4.44%	2.21%	0.754%	7.40%

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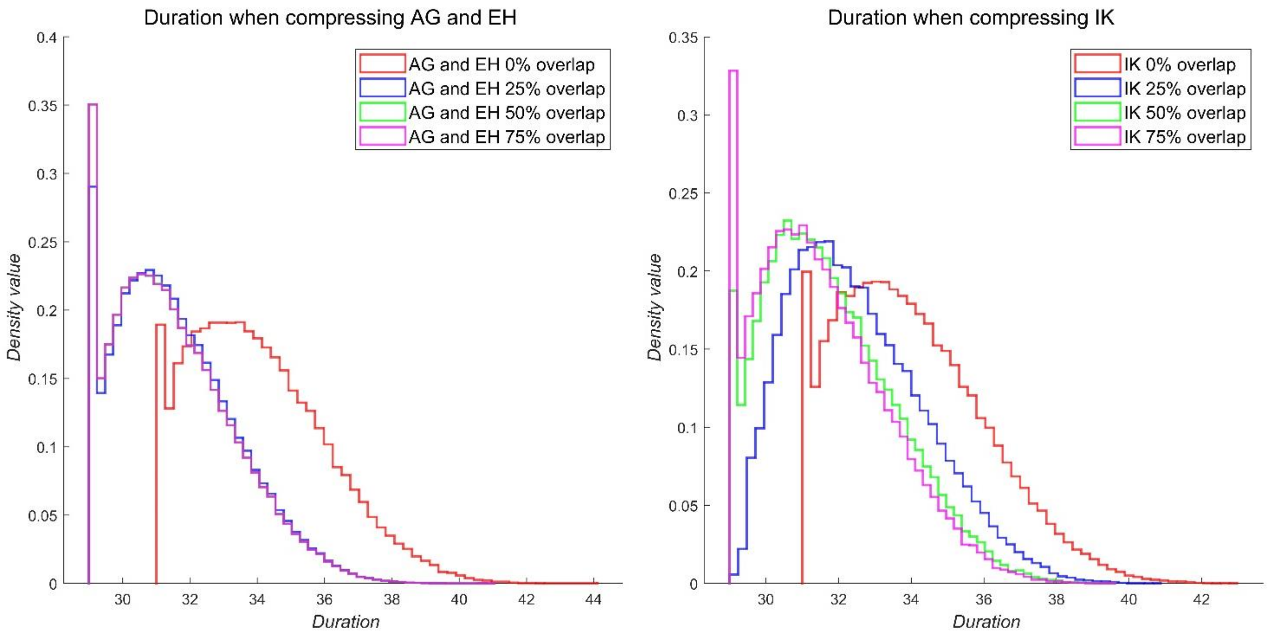

(a) **(b)**

Figure 5: Effect of compressing activities reflected by changes in work effort needed to complete the whole project. (a) Compressing AG and EH. (b) Compressing IK.

The comparison reveals a substantial effect when AG and EH have a 25% overlap, while no additional effect results from increasing the compression beyond this amount. As Table VI shows, a 7.14% decrease in mean duration at the project level is achieved when compressing AG and EH by 25%, whereas only a 0.0317% decrease is achieved when going from 50% to 75% overlap. In other words, after implementing all overlaps from 0% to 75%, around 97% (= 7.14% ÷ 7.39%) of the total decrease in mean duration was achieved when applying only 25% overlap for AG and EH. Similarly, when compressing IK, the effect gradually increases as the overlap is increased, but the major effect is witnessed when compressing IK by 25%. This finding is also evident when looking at the probability density functions in Figure 5.

Table VII shows the four statistical moments of the pairs AG, EH, and IK, while Table VIII shows the decrease in mean durations of pairs as a function of overlapping percentage.

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Table VII: The four moments of statistics at the activity level.

	Mean	Std. dev.	Skewness	Kurtosis
0% overlap				
AG	22.235	1.40	1.245	3.839
EH	17.360	1.74	1.351	3.954
IK	11.097	1.12	1.046	3.592
25% overlap				
AG	18.494	1.12	1.089	3.739
EH	14.382	1.66	1.394	4.150
IK	9.426	.94	.939	3.516
50% overlap				
AG	16.919	1.30	1.317	4.031
EH	14.257	1.73	1.372	3.978
IK	8.356	.90	.972	3.508
75% overlap				
AG	16.781	1.35	1.348	3.944
EH	14.257	1.73	1.372	3.978
IK	7.805	.97	1.264	3.840

Table VIII: Percentage decrease in mean durations at the activity level.

	0–25% overlap	25–50% overlap	50–75% overlap	Total
AG	16.8%	8.52%	.816%	26.2%
EH	17.2%	0.869%	0%	18.0%
IK	15.1%	11.4%	6.59%	33.0%

In short, there is a point at which overlapping activities become ineffective and can even lead to additional unnecessary costs. This point is known as the "point of diminishing returns." It means that is a limit to how much activity overlap can be used to shorten the project duration. Beyond this limit, the additional costs incurred outweigh the benefits gained from overlapping activities. If the project team tries to further shorten the duration, they may incur additional costs, such as hiring more workers or working overtime, resulting in increased project costs and reduced quality. Therefore, project managers must carefully analyze the project's critical path to determine the optimal amount of activity overlap required to shorten the project duration without incurring unnecessary costs.

5.2.2 Effect on Waste

Compressing the schedule by using overlapping activities increases the interdependency between the parallel activities and makes the activities vulnerable to variations in durations. Interruptions in the production flow can happen quickly when a subsequent activity is catching up with the previous activity, having to wait until enough work and resources are made ready and the working space is unoccupied. Problems with activities catching up with one another are evident under 'Mean waiting time during' in Table IX. As noted previously, waste is created when subsequent work either must wait or could have been initiated earlier. Therefore, the effect of compressing AG is evident when looking at G (effects of A on G) and I (effects of G on I). Likewise, the effect of compressing EH is evident when looking at H (effects of E on H) and I (effects of H on I). Finally, the effect of

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compressing IK is evident when looking at K (effects of I on K). K is the last activity, thus no waste occurs after K.

Table IX: Mean waste (waiting time and variation gap) at the activity level.

	Mean waiting time before	**Mean waiting time during**	**Total waiting time**	**Variation gap**
		0% overlap		
G	.959	---	.959	.955
H	1.232	---	1.232	1.225
I	.224	---	.224	.196
K	.685	---	.685	.674
		25% overlap		
G	.774	.000	.774	.727
H	.993	.329	1.322	.929
I	1.738	---	1.738	.007
K	.556	.000	.556	.513
		50% overlap		
G	.547	2.163	2.710	.494
H	.700	3.513	4.213	.630
I	2.500	---	2.500	.000
K	.401	.602	1.003	.342
		75% overlap		
G	.299	5.765	6.064	.260
H	.381	6.823	7.204	.314
I	2.495	---	2.495	.000
K	.285	1.722	2.007	.173

Waiting time before an activity starts represents delay, because the subsequent activity is prevented from starting as scheduled. Looking at Table IX, it is evident that compressing the schedule has a positive effect on reducing waiting time before G, H, and K. This can be explained by the fact that only a small part of the activity needs to be completed before the subsequent work can start. Variance in parts of activity durations will be less than variance in the entire activity. On the contrary, waiting time before I is increased, because initiation of I now depends on a combination of completing AG and EH, which magnifies the variances in activity completion times.

In Scenario 1, overall changes in waiting time are attributed to the combined effects of changes in G, H, and I, while in Scenario 2, they are attributed to the effects in K. Overall waiting time is depicted in Figure 6. The probability density functions reveal that in both scenarios, waiting time is increased, but the increase is much greater in Scenario 1, which is also expected based on the numbers in Table IX.

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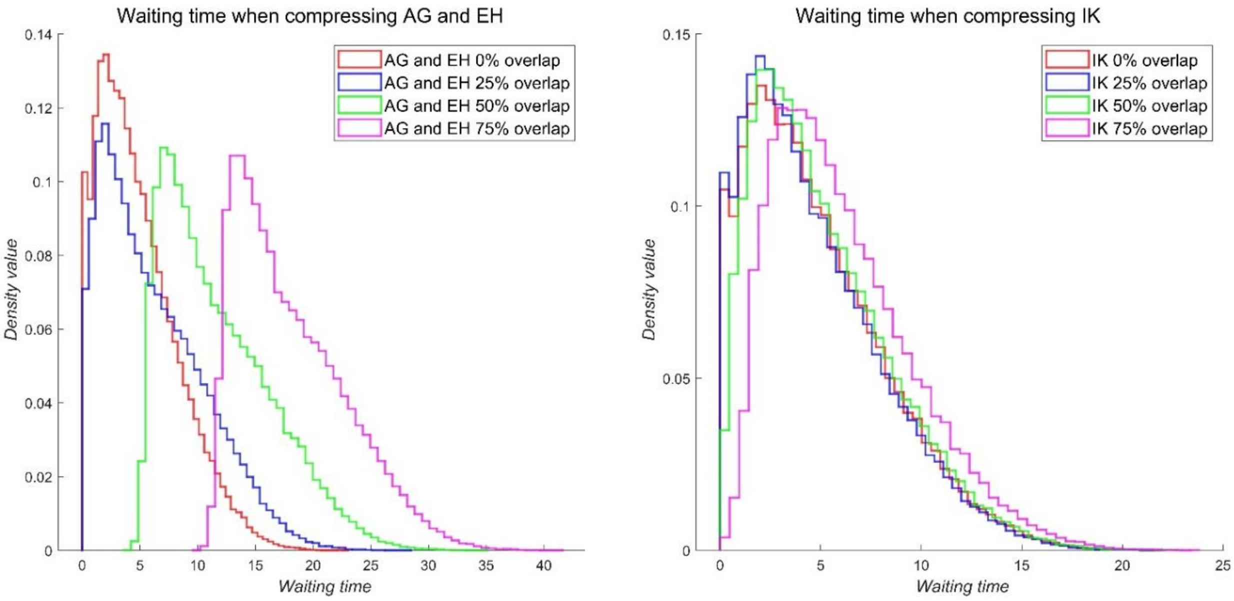
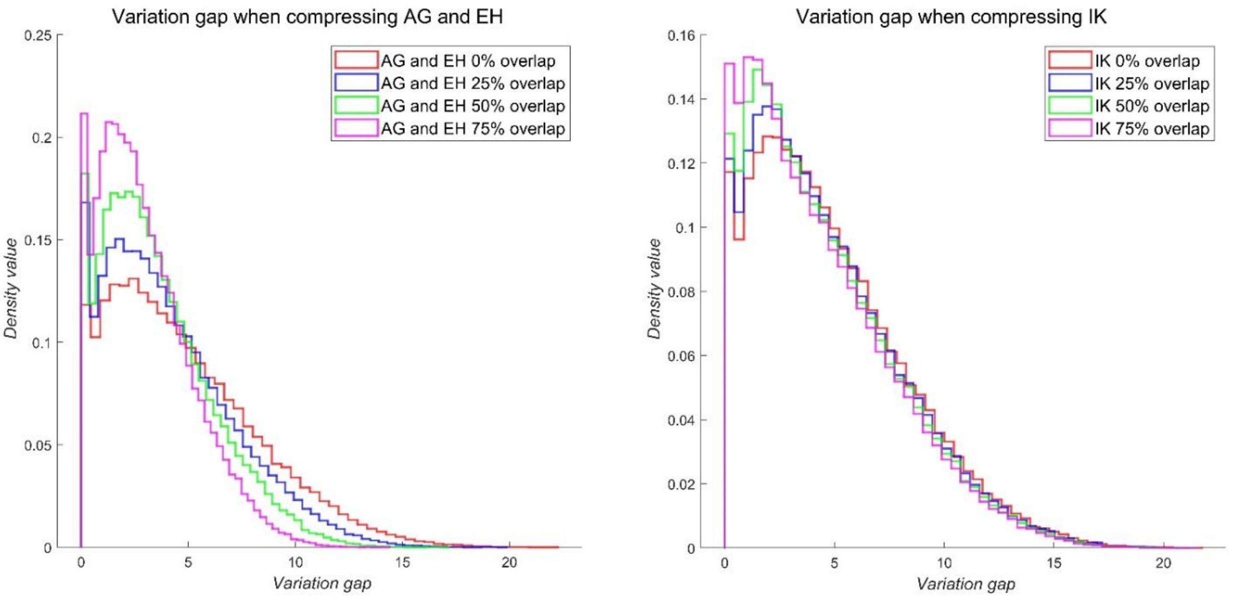


(a) **(b)**

Figure 6: Effect of compressing activities on waiting times. (a) Compressing AG and EH. (b) Compressing IK.

A variation gap before an activity represents a missed opportunity to initiate the activity prior to the scheduled start date. Variation gaps before activities G, H, I, and K are shown in Table IX. Variation gap decreases gradually when the schedule is compressed. Variation gaps are caused by variances in durations; the reduction is caused by the same phenomena as the reduction in waste before an activity can start. Thus, due to the overlap, only a smaller part of the previous activity needs to be completed, which reduces the amount of deviation. An exception is activity I; as activity I now depends on both AG and EH to finish early, the risk of a variation gap occurring rapidly decreases towards zero. The variation gap is depicted in Figure 7.



(a) **(b)**

Figure 7: Effect of compressing activities on variation gaps. (a) Compressing AG and EH. (b) Compressing IK.

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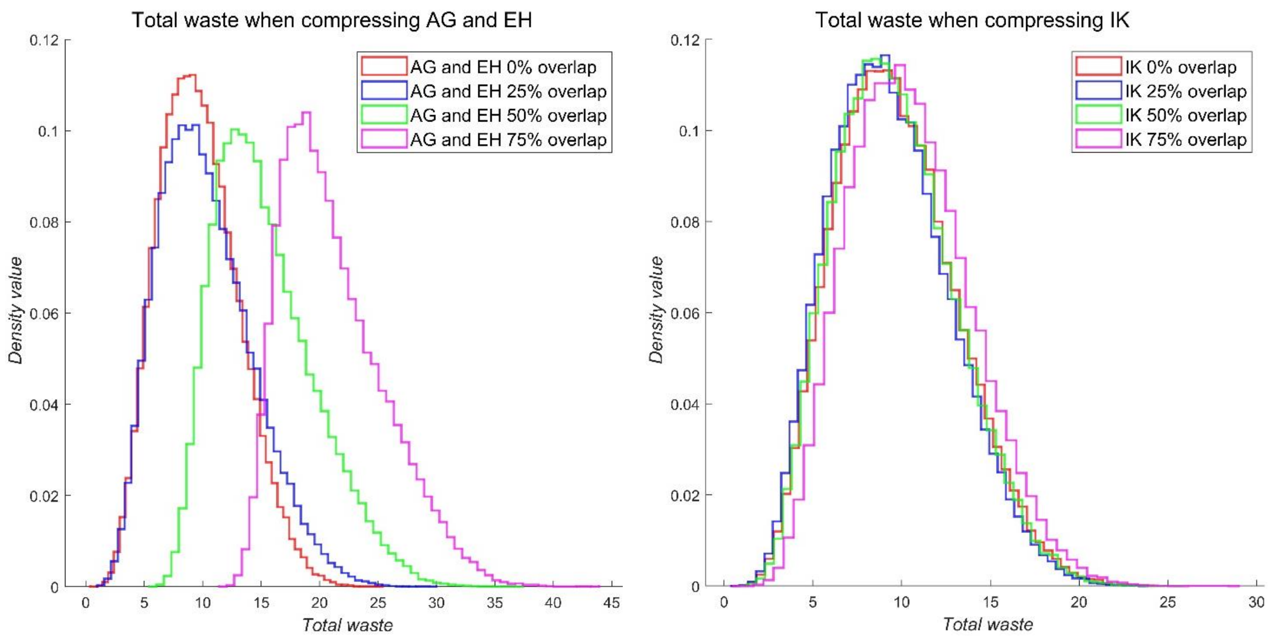
Table X illustrates the percentage change in total waiting time and variation gap when going from one overlap percentage to another, and specifically when going from 0% to 75% overlap as the last row shows. Even though the variation gap is reduced, the increase in waiting time is greater. For instance, Activity G experienced a 532% increase in total waiting time as compared to a 73% decrease in variation gap when going from 0% to 75% overlap.

Table X: Percentage change in waiting time and variation gap.

Overlap %	**% Change in total waiting time**				**% Change in variation gap**			
	G	**H**	**I**	**K**	**G**	**H**	**I**	**K**
0%-25%	-19	7	676	-19	-24	-24	-96	-24
25%-50%	250	219	44	80	-32	-32	-100	-33
50%-75%	124	71	100	100	-47	-50	-	-49
0%-75%	532	485	1014	193	-73	-74	-100	-74

Thus, when looking at the total wastes, compressing the schedule increases waste in the production workflow. The increase is much larger in Scenario 1. Generating greater waiting times is caused by two parallel pairs of activities, (AG and EH), with greater variance compared to the single pair IK with no subsequent activity in Scenario 2. Total waste is depicted in Figure 8.



(a) **(b)**

Figure 8: Effect of compressing activities on total waste. (a) Compressing AG and EH. (b) Compressing IK.

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Put simply, attempting to speed up the production process can lead to increased waste. This is because when a schedule is compressed, there is often a rush to complete tasks and meet deadlines, which can result in product errors or defects. These defects must then be corrected or scrapped, wasting time, resources, and materials. While it may seem counterintuitive, planning and executing a production schedule properly can lead to a more efficient and less wasteful workflow in the long run.

5.3 Summary

The effects of compressing the schedule can be explained by activity and network characteristics. The results of changing the percentage of overlapping are influenced by the lengths of activity durations. For instance, in Scenario 1, increasing the overlap in AG or EH from 0% to 75% results in reducing the mean of AG by 5.45 days, while the mean of EH is reduced by 3.10 days. The initial substantial effect is caused by differences in duration lengths between activities A and G, and activities E and H, respectively. The following observations are made:

- The mean of A is 14.95, while the mean of G is 7.27. A 25% overlap is around 3.74 days of A, corresponding to about half of the duration of G.
- The mean of E is 13.23, while the mean of H is 4.14. A 25% overlap is around 3.31 days of E, corresponding to almost the entire duration of H.

In Scenario 2, when increasing the overlap of IK from 0% to 75%, the mean of IK is reduced by 3.29 days. This reduction increases gradually as the overlap is increased. This gradual increase is caused by the durations of I and K being similar. The following observation is made:

- The mean of I is 6.68, while the mean of K is 4.41. A 25% overlap is around 1.67 days of I, corresponding to approximately one-third of the duration of K.

As the data in Table VIII clearly demonstrates, most of the decrease in mean durations are achieved by applying 25% overlap.

Another effect of compressing the schedule is that it changes the network characteristics and, thus, the likelihood of a given path becoming critical. This change in likelihood is illustrated in Figure 9. In Scenario 1, the durations of A-G-I-K and D-E-H-I-K are reduced, which increases the likelihood of other paths becoming critical. Figure 10 illustrates the frequency of each path being critical in the simulations, such as in path A-F-J. Moreover, because the duration is decreased more in AG than in EH, D-E-H-I-K also becomes more important compared to A-G-I-K. With 75% overlap, A-G-I-K almost never becomes critical. Even when two activities on the most critical paths are compressed, the effect is not identical. In Scenario 2, the durations of A-G-I-K and D-E-H-I-K are also reduced. Once again, AFJ becomes critical and determines the duration of the project. Because A-G-I-K before compression had the greatest risk of being critical, it experiences a greater reduction in criticality than D-E-H-I-K. In conclusion, both activity and network characteristics influence and provide an upper limit on the potential reduction in duration.

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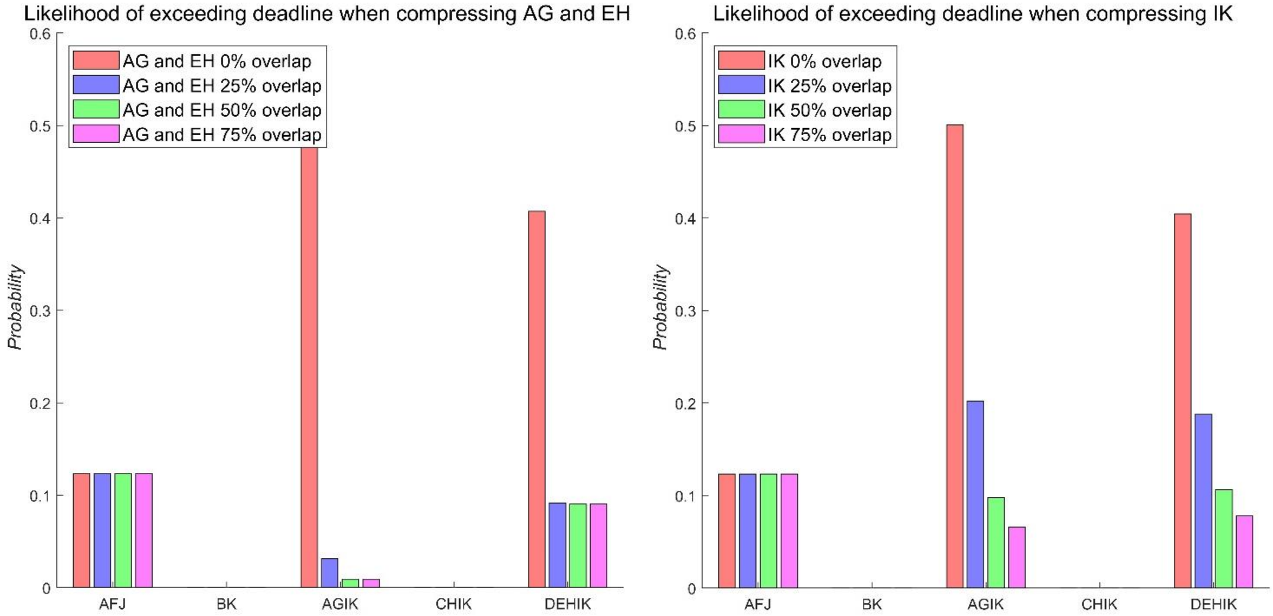
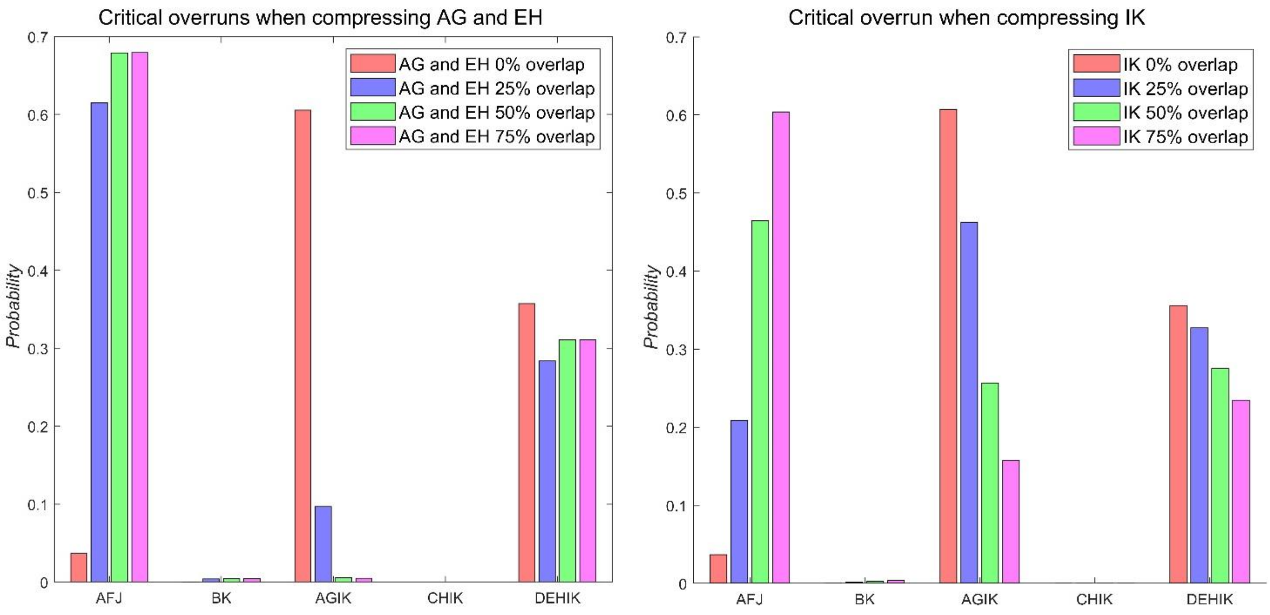


(a) **(b)**

Figure 9: Effect of compressing activities on the likelihood of exceeding the deadline. (a) Compressing AG and EH. (b) Compressing IK.



(a) **(b)**

Figure 10: Effect of compressing activities on the number of critical overruns per path. (a) Compressing AG and EH. (b) Compressing IK.

In summary, when activities in a project are scheduled to occur at the same time or overlap with each other, it can cause delays in the completion of the critical path. This is because overlapping activities can cause resources to be spread too thin, resulting in decreased efficiency and productivity. For example, if two activities are scheduled to occur at the same time and both require the same limited

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resource, such as a specific piece of equipment, one of the activities will likely be delayed while waiting for the resource to become available. As a result, the critical path may shift to include the delayed activity, resulting in an extended project duration. Additionally, overlapping activities can cause confusion and miscommunication among team members, leading to errors, rework, and further delays. Therefore, it is important for project managers to carefully plan and coordinate activities to avoid overlapping and ensure that the critical path remains on schedule. This may involve adjusting timelines or resource allocation to avoid conflicts and maintain productivity. By doing so, project managers can keep their projects on track and minimize the risk of delays and cost overruns.

6 DISCUSSION: DEMARCATING BOUNDARIES OF OVERLAPPING ENVELOPE

Koskela (2004) discussed the eighth category of waste, which is making-do. This type of waste occurs when an activity is started without at least one standard input, or when an activity continues to be executed despite the unavailability of at least one standard input, such as materials, tools, machinery, personnel, instructions, or external conditions. In this situation, the start date of succeeding activities may be shifted to overlap with preceding activities, leading to making-do waste. Uncertainties in the inputs are more likely to emerge as the total waiting time increases. Similarly, Ronen (1992) stated that working with an incomplete kit, such as missing information, documents, drawings, or components, causes longer lead times. Since lead time is crucial for achieving both tactical and strategic benefits for the company, it is essential to use techniques that can minimize it (Ronen, 1992). All that being said, decisions pertaining to the amount of overlapping should be well studied, as overlapping may lead to potential rework and other risks. A schedule could foster untapped potential for specific overlapping opportunities without causing any issues. For instance, there may be opportunities to overlap certain activities without creating space conflicts or other issues, which, if not utilized, may result in lost opportunities for improving project performance. Generally, construction scheduling assumes a specific relationship between tasks, with a fixed lag duration. This representation is rigid, because it overlooks the possibility of flexible relationships, known as "soft relationships" between the activities. Soft relationships can be helpful because they provide a range of overlapping options to be used when accelerating a schedule (Abuwarda and Hegazy, 2016). Usually, generating good-quality schedules necessitates schedulers to possess comprehensive knowledge that allows them to identify and mitigate risks (Hong *et al.*, 2021). However, the generated construction schedules do not undergo quality assurance, which implies that schedules may include hidden random activity overlapping. When starting with a tight schedule that contains a significant amount of overlapping, it lacks flexibility for implementing further overlapping if future adjustments are needed. At the same time, conservative schedules that contain lots of buffers raise the concern of why the buffer is not being exploited for the benefit of the project. Such analysis is not commonly conducted. Typically, the general practical guidelines for planning and scheduling address considerations such as specifying scheduling methodology, scheduling software, performance measures, and control procedures. Other approaches exist, such as the one adopted by the Defense Contract Management Agency (DCMA), which set a 14-point assessment strategy as a step towards schedule quality analysis. The 14 assessment metrics are logic, leads (negative lags), lags, relationship types, hard constraints, high floats, negative floats, high durations, invalid dates, resources, missed

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tasks, critical path test, Critical Path Length Index (CPLI), and Baseline Execution Index (BEI) (Winter, 2011). For example, the recommendation for the "relationship types" metric is that 90% of activities should have a finish-to-start (FS) relationship. However, the strategy has no provisions regarding the amount of activity overlapping that should be present in a schedule. Therefore, emphasizing the importance of finding the boundaries of the overlapping envelope, this study raises the following question: What are the lower and upper overlapping boundaries within which neither untapped potentials nor considerable risks occur? In other words, zero overlapping leaves untapped potentials, while too much overlapping creates waste and contributes to risks.

On a final note, when implemented on a project, the process suggested in this study must be monitored throughout construction. As a project evolves, relationships between tasks become clearer, and the links may undergo adjustments. Having more realistic relationships is crucial for scheduling to avoid reworks. This can be achieved through pull planning or phase scheduling in which various project participants engage in specifying hand-offs between subcontractors, thereby generating a schedule that covers individual project phases (Hamzeh *et al.*, 2012). Subsequently, assessing waste in a schedule is more accurate when the schedule is continuously updated to reflect the nature of construction.

7 CONCLUSIONS, LIMITATIONS, & RECOMMENDATIONS

Schedule compression is a commonly adopted method for speeding up projects. Aside from the risks associated with the method, its effectiveness requires evaluation. This paper presents two types of waste found in schedules, which are waiting time and variation gap, and illustrates a method for evaluating the effect of compressing the schedule on both waste types. Results showed that compressing the schedule beyond a certain overlap percentage threshold, specifically 25%, does not significantly shorten project duration but increases the total waste in the production system at the same time. An increase of up to 1014% was witnessed in total waiting time of an activity when going from 0% to 75% overlap, whereas the variation gap of the same activity decreased by 100%. Moreover, the tested network showed that one path has a 60.83% chance of being critical, another has a 35.41%, and a third one has a 3.74% chance. Hence, non-critical paths could become critical and they should be more closely monitored while performing overlapping. Altering the criticality of paths through consuming floats while compressing showed an increase in waiting time waste. When used by practitioners, the proposed method will guide them on which activities to compress and by how much while minimizing overall waste generated and risks created in the production system. The presented results appear to be notable findings, but they cannot be generalized since a hypothetical example was used to test the model. However, the study has potential, and it brings awareness to the issue of waste accompanying schedule compression. It forms a starting point for further research in this area.

Acquiring activities' three-point estimates can be challenging, because such data might not be readily available or easily accessible, and obtaining it can be experience-based which is characterized by subjectivity. Moreover, as the complexity of the network increases, conducting such an analysis requires additional analytical efforts and computational capacities. Additionally, schedule quality

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analyses are rarely conducted, especially scanning for overlaps in a schedule. Therefore, it is recommended in future studies to take this methodology further into a tool that automatically scans schedules for existing overlapping, if any, and determines the optimal range of overlapping within which there are neither untapped potentials nor considerable risks. Furthermore, as the study goal is to showcase the amount of waste that compression creates in a schedule, it presented a hypothetical example to deliver its purpose while excluding the cost aspect. A simple schedule abstraction case showed embedded waste, so how about real projects where one might find different kinds of issues and challenges? The results from the study open new horizons to explore; therefore, it is recommended for future studies to incorporate cost and other aspects into the model. Finally, to minimize waste when overlapping activities, it is essential to plan and manage the overlapping activities carefully, with a focus on communication, coordination, and collaboration. This can help ensure that everyone involved in the project understands their roles and responsibilities, and is working together towards a common goal of minimizing waste.

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