A CONTINUOUS FLOW SIMULATION MODEL FOR PROBABILITY REPETITIVE PROJECTS

Weizhuo Lu and Thomas Olofsson (Luleå University of Technology)

ABSTRACT
Continuous flow is one of the main focuses of scheduling repetitive projects. Construction practitioners and researchers have proposed approaches to maintain continuous flows. However, many of these approaches only consider deterministic activity durations or have some other methodological limitations. Accordingly, a continuous flow simulation model is presented in this paper in order to overcome aforementioned limitations. The proposed model integrates simulation and buffering to consider the probability of activities durations and for proper sizing of buffers. Instead of having the same activity duration distribution on different units as is common, the proposed model allows for different activity duration distribution between units. The proposed model is tested and validated on a case study and the results show that the model can provide practical contributions in scheduling that effectively maintain continuous flow for probability repetitive project. Possible further research directions in this regard are also discussed in the paper.

1. INTRODUCTION
Repetitive projects are common in construction where similar units require repetitive work from unit to unit. Typical repetitive projects include multi-story buildings, housing projects, highways, and tunneling projects. For such projects, the objective of scheduling methods focus on maximizing flow continuity by enabling crews to finish work in one unit of the project and then move promptly to the next in order to minimize interruptions.

A major in-depth study of seven Swedish construction projects reveals that only 15-20% of a construction crew's time is spent on direct work. Approximately 45% is spent on indirect work. The remaining 35% is spent on interruption, waiting, etc., i.e. a complete waste of time (Josephson, 2005). Productivity related studies also indicate that crew interruption in construction ranges from 20% to 45% (Thomas, 1991).

Flow continuity provides room for an effective resource utilization strategy by minimizing interruption. Some researchers involved in the construction industry have identified the benefit of continuity in recent years (Rongyau and Kuoshun, 2006; Vanhoucke, 2006). Yang (2002) used simulation to show the cost savings gained through continuous flow to be 30% for the small case project.

Many scheduling technologies, such as Line of Balance (LOB) and Repetitive Scheduling Method (RSM) have been proposed to maintain continuous flow for repetitive project. These repetitive scheduling techniques are deterministic methods in which activity durations are represented by a single number. The single number alone is insufficient to capture the behavior of actual construction for the probability of flow productivity (Tommelein et al, 1999). Accordingly, these deterministic methods could not provide practical scheduling for probability repetitive project.

This paper presents a continuous flow simulation model to provide practical contributions in scheduling that effectively maintains continuous flow for probability repetitive project. The next section discusses the literatures that are most relevant to this research project. The third section proposes a continuous flow simulation model for probability repetitive projects, which integrates simulation and buffering to consider the probability of activities...
durations and for proper sizing of buffers. The case study is presented in the fourth section. The last section describes key conclusions and opportunities for future research.

2. STATE-OF-THE-ART REVIEW

This section of the paper first reviews the existing approaches for repetitive project scheduling. Followed by the detailed description of construction simulation model developed so far, this section highlights two simulation models for getting continuous flow under probability activities duration and points out the limitations of them. Finally, to make a clear understanding of research project, buffers are also discussed.

2.1 Repetitive Project Scheduling

Construction projects that are generally characterized as repetitive projects may be divided into two categories: (1) nonlinear project that are repetitive due to a uniform repetition of a unit work throughout the project (e.g., high-rise buildings and multiple housing construction); and (2) Linear projects that are repetitive due to their geometrical layout rather than uniform repetition of a unit work (e.g., highway, pipeline and railroads projects) (Hegazy and Wassef, 2001). El-Rayes and Moselhi (1998) distinguish between typical and atypical repetitive activities. Typical repetitive activities are characterized by identical durations over all units, while atypical repetitive activities assume variation of duration from one unit to another. This variation can be attributed to variations in the quantities of work encountered or crew productivity attained in performing the work of these units.

Flow continuity improves the overall productivity of construction works due to: (1) minimizing their idle time during their frequent movements on site; and (2) maximizing their benefits from learning curve effects (El-Rayes and Moselhi, 2001). The application of network scheduling techniques, such as the critical path method (CPM), to repetitive projects has long been criticized for their inability to maintain continuous flow in scheduling (Adeli and Karim, 1997). Recognition of the drawbacks of traditional CPM in scheduling repetitive projects has led to the development of several scheduling methodologies, such as, line of balance (Arditi and Albulak, 1986), Repetitive Scheduling Method (Harris and Ioannou, 1998), Repetitive non-serial activity scheduling (Hegazy and Wassef, 2001) and non-unit based repetitive project scheduling (Rongyau and Kuoshun, 2005), to name but a few.

Arditi et al. (2002) refer to those alternative scheduling techniques, developed over the last 30 years, by the generic term of ‘linear scheduling methods’ and claim that those methods have proven to be well suited for projects of a repetitive nature. Kenley (2004) points out that the repetitive scheduling methods strongly suggest locations or places and, consequently, he introduces the comprehensive term of ‘location-based scheduling’ (LBS). As a result of two decades of research and development, a comprehensive line-of-balance-based planning, scheduling and control system, has been developed and implemented among main contractors in Finland (Seppänen and Aalto 2005).

Nonetheless, many of these scheduling methodologies only consider deterministic activities durations and activities durations represent with a single number. The single number only represents an average and the actual production rate will vary (e.g., with some standard deviation if a Normal distribution appropriately characterizes variation) because of variation in the weight and size of components, ease of reach and access to their final installation location, fabrication and erection tolerances, skill level of the workers etc. (Tommelein et al, 1999).
2.2 Construction Simulation

Discrete-event simulation has been used as a tool for scheduling since the development of CYCLONE (Halpin, 1977). Ever since, the application of simulation to support decision making in construction management was popularized. The CYCLONE framework provided the foundation for construction simulation researchers to develop a number of construction simulation tools in the past 25 years. Martinez and Ioannou (1999) examined the characteristics of discrete-event simulation systems used in construction and grouped them into three general approaches, i.e. activity scanning, event scheduling and process interaction. They claimed that activity scanning is the natural and effective approach for modeling complex construction operations in detail. Hajjar and AbouRizk (2002) proposed Simphony which allows for the creation of new special purpose simulation (SPS) tools in the form of modeling element templates and provides a highly flexible, yet user-friendly, environment for the simulation modeling process.

González et al. (2008) developed a discrete event simulation approach to design work-in-progress (WIP) buffer for repetitive project. Discrete-event simulation software, Extend™, was selected to perform simulation modeling. Figure 1 illustrates the simulation modeling architecture for two linear sequential processes, which is made up by two kinds of hierarchical blocks: processes and WIP Buffer. Inside these blocks, there are individual blocks, logical decision processes and stochastic inputs (e.g. process duration or production rate). For the simulation modeling architecture, work units as houses or floors for building projects are the entities flowing through the system from INPUT to OUTPUT states. However, with proposed Extend™ simulation model, units must follow the same distribution types during process. This practice ignores the difference between typical repetitive activity and atypical repetitive activity (El-Rayes and Moselhi, 1998).

![Figure 1. Simulation modeling architecture showing two linear sequential processes and the corresponding WIP buffer (González et al., 2008).](image)

Ioannou and Srisuwanrat (2006) presented a sequence step algorithm developed in Stroboscope simulation platform, as shown in Figure 2. The sequence step algorithm addresses for the first time the problem of scheduling repetitive projects with probabilistic activity durations while maintaining continuous resource utilization. The precedence relationship (link) between A and B is implemented through the semaphore (i.e., the logical start control) of the successor activity, B. In particular, the logical expression for the semaphore of activity B_CrewPerform compares the number of completed units in B_WorkDone to the number of completed units in A_WorkDone, as follows:

\[ B_{WorkDone}.CurCount < A_{WorkDone}.CurCount \]

Nonetheless, the proposed model relies on complicated semaphore to erect the logical relationship between activities, which is not very easy to use in practical simulation process.
Nasereddin et al. (2007) describe elements commonly found in modular manufacturing and summarizes an approach for automating the model development process using ProModel and Visual Basic. However, study reveals that construction-oriented resource-driven simulation platform is found to be more flexible and straightforward than manufacturing simulation platform (for example ProModel) in addressing construction systems (Ming and Lap-Chi, 2007).

2.3 Buffer

Buffer is a common approach to handle variability and to shield production system from its negative impact. By using a buffer, a production process can be isolated from the environment and the process depending on it, and the negative impact variability can be reduced in the production chain (Koskela, 2000). Buffers can avoid loss of throughput, wasted capacity, inflated cycle time, larger inventory levels, long lead time and poor customer service shielding a production system against variability (Hopp and Spearman, 1996).

Buffers are understood as resource cushions, i.e. money, time, materials, space, etc., used to protect processes against variation and resource starvation (Alves and Tommelein, 2004). Buffers can be used to protect a system against variability through the use of inventory, capacity, time, or a combination of the previous. Hopp and Spearman (1996) define three generic types of buffers for manufacturing, which can be applied in construction.

1. Inventory: in-excess stock of raw materials, work in progress (WIP), and finished goods, located in the supply chain.
2. Capacity: allocation of labor, plants, and equipment capacity in excess so that they can absorb actual production demand problems.
3. Time: reserves in schedules as contingencies used to compensate for adverse effects of variability – float in a schedule is analogous to a buffer for time since it protects a critical path from time variation in noncritical activities.

The size of buffers should be carefully managed, if oversize, buffers are waste and can impede on the continuous flow principle. On the other hand, if not sufficient, crews cannot realize their full production capacity due to starvation of upstream resources causing interruptions in the production flow. Ballard and Howell (1995), in looking to apply just-in-time to construction, called for research into the sizing and location of buffers and argued that a schedule buffer should be placed at the end of unpredictable processes, with a buffer size based on the degree of uncertainties involved.
However, the size of a contingency buffer is normally decided based on individual experience and assigned in a uniform way (e.g., 10% of activity duration) instead of taking into consideration the characteristics of each individual activity (Park and Peña-Mora, 2004).

3. RESEARCH PROJECT

3.1 Research Objectives

The objective of this research is to propose a method to validate a continuous flow simulation model for a probability repetitive project. To reflect the variability of a crew's productivity on different units, varying activity durations from unit to unit are incorporated into the model. To facilitate implementation of the proposed simulation model, a hierarchical structure is applied to avoid a complicated simulation network. Also, through proper sizing of buffers using the proposed simulation model, the method could provide practical scheduling information for obtaining continuous flow in repetitive project.

3.2 Continuous Flow Simulation Model

After considering the review points in section 2, a continuous flow simulation model for repetitive projects is developed using Simphony, as shown in Figure 3. The proposed model, in which four crews (A, B, C and D) pass through four units (1, 2, 3 and 4), applies an hierarchical modeling method. The model consists of two levels of hierarchical structures. The parent level is shown in Figure 3 and every unit elements possess a child level sub-model, as shown in Figure 4. The parent level contains three types of elements explained as follows.

Figure 3. Continuous flow simulation model.

1. Crew elements represent available crews for the construction process. For example, four crews perform the construction activities on four units. Accordingly,
the model has four crew elements which represent these crews respectively, as shown in Figure 3. The user can specify the start times of a crew, which denotes the buffer for the crews. It must be emphasized that the size of buffers are measured from the start time of the project to the start time of a buffered crew. For instance, the start working time of crew B is set to 7, which means that crew B moves into the construction site 7 days after the project starts.

2. Unit element is the working unit required to be performed by the crews. With the progress of a project, crews need to flow through unit1, unit2, unit3 and unit4 sequentially. Unit elements have a children-level model describing the behavior characteristic of that unit, which are explained in detail below.

3. To collect cycle time in the model, CycleTime element is used to declare the collection of such statistics and distinguish it from other CycleTime elements. The declared CycleTime element can then be used by CollectStat elements to add observations to it. CollectStat elements add observations to the declared CycleTime elements.

The child level model consists of five modeling elements and two types of files, as shown in Figure 4.

![Figure 4. Child level continuous flow simulation model.](image)

Crew elements that flow through a unit element, by firstly passing the In0 element, which works as the input link from the parent-level model to the child-level model. Similarly, when crews flow out of the unit elements, they finally pass the Out0 element which works as the output link from the child-level model to the parent-level model. To use unit elements in the capture and release elements, the unit element need to be declared through the declare files, such as unit files. Once unit elements are declared, they can be captured or released by the capture or release element. In order to be processed by an activity element, the unit elements need to be captured by the capture element. The capture element declares the occupancy of unit elements for the activity duration specified in an activity element. After the crew flows through capture and activity elements, it is released by the release element and can be used by other capture
element. When several capture elements require the same unit element at the same
time, the set priority number determines the priority of that capture elements. The
higher the number of priority, the higher is the priority of occupancy of the unit element.
A crew file defines a waiting file for the crews. The activity element describes the activity
duration which follow a specified distribution, such as beta distribution or normal
distribution.

The whole process of simulation can be described as follows: when crews move in to the
construction site, all crews first wait in a crew file. All crews are related with a
corresponding capture element. The capture element with a highest priority number
captures the unit resource. The related crew flows into the unit element, processes the
activity on unit for the activity duration, and then releases the unit. Finally, according to
the priority number, remaining crews pass through unit elements sequentially. This
process continues until all the crew elements move out of the construction site.

Using the proposed continuous flow simulation model, schedules with proper sized
buffers for repetitive project can be generated. The flowchart of designing buffer size and
scheduling are illustrated in Figure 5:

![Flowchart of design buffer size and scheduling.](image-url)

Figure 5. Flowchart of design buffer size and scheduling.
Since the first crew has no precedence crew, it can be processed continuously. So at the beginning of the flowchart, the $i$ value with 2, which implies the successive crew of the first crew. The second step in the flowchart is assigning a deterministic buffer value to crews to start as soon a unit been released. As illustrated in Figure 6, when activities start as early as possible as is in typical in CPM, the difference in productivity between the activities in the deterministic scheduling observes interruptions. In order to eliminate the interruptions and ensure continuous flow, the start time of activities should be delayed by adding buffers between the activities, as shown in Figure 7. This situation is well suited for deterministic activity durations. While at the initial stage of a continuous flow simulation model, the deterministic buffer values can also be assigned to crews.

By running the simulation and collecting the statistics, the buffers can be adjusted. If crew 2 is interrupted, the buffer value can be incremented by 0.5 day, for each simulation, until no interruption exists for crew 2. When crew 2 maintains the continuous flow, the flowchart transfers to the next activity until all activities have been simulated. The schedule and buffer sizes ensure the continuous flow of crews.

![Figure 6. Initial scheduling of deterministic activity duration.](image)

![Figure 7. Continuous flows scheduling for deterministic activity duration.](image)

4. CASE STUDY

A repetitive project consisting of 4 units, with 4 activities, is used to test and validate the effectiveness of the proposed continuous flow simulation model. For repetitive project, the objective of scheduling such type project is to maintain work continuity. However, most case studies so far only consider deterministic activity duration. The case study of this section introduces probability of activity duration. Table 1 shows the activities and their duration distributions. The proposed continuous flow simulation model takes into
account not only optimistic activity duration but also pessimistic duration. The initial scheduling of the case study is shown in Figure 6.

Table 1. Activities and durations in case study.

<table>
<thead>
<tr>
<th></th>
<th>Crew A</th>
<th>Crew B</th>
<th>Crew C</th>
<th>Crew D</th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>Unit 1</strong></td>
<td>Triangular(1.8,2,2.2)</td>
<td>Normal (1, 0.3)</td>
<td>Triangular(1.9,2,2.2)</td>
<td>Normal (1, 0.3)</td>
</tr>
<tr>
<td><strong>Unit 2</strong></td>
<td>Uniform (0.8,1.2)</td>
<td>Uniform (0.8,1.2)</td>
<td>Normal (1, 0.2)</td>
<td>Uniform (0.5,1.5)</td>
</tr>
<tr>
<td><strong>Unit 3</strong></td>
<td>Uniform (2.8, 3.2)</td>
<td>Triangular(1.7,2,2.2)</td>
<td>Normal (1, 0.2)</td>
<td>Uniform (1.8,2.1)</td>
</tr>
<tr>
<td><strong>Unit 4</strong></td>
<td>Normal (2, 0.2)</td>
<td>Normal (2, 0.1)</td>
<td>Uniform (0.8,1.2)</td>
<td>Normal (1, 1)</td>
</tr>
</tbody>
</table>

The numbers of simulation is set to 1000 within each simulation process and the initial sizes of the buffers are set to a deterministic value. The collected distribution of completion days is shown in Figure 8. Note that the confidence level of project completion due date (12 days) is below 20%. From the probability of activity duration, on unit 2, unit 3 and unit 4, there exist to some extent interruptions, as shown in Figures 9, 10 and 11. From observation of the simulation results, it should be emphasized that the buffer sizes and initial scheduling according to deterministic duration can not ensure the continuous flow of crews.

![Figure 8. Cumulative distribution functions of project duration.](image)

![Figure 9. Cumulative distribution functions of interruptions on unit 2.](image)
Figure 12 shows the interruption days on unit 4 when buffer B equals 5.5 and buffer C equals 6.5. There still exists interruption to some degree. However, comparing Figure 12 with Figure 11, the increase in buffer size alleviates the degree of interruption on unit 4. Application of the simulation model and following the flowchart of generation scheduling, the project distribution for case study is shown in Figure 13. Notice that in Figure 13, where the size of buffer B equals to 9.5 and buffer C equals to 13.5, the crews maintain a continuous flow during the whole construction process. The scheduling of project is shown in Figure 14. In contrast to Figure 8, the confidence level of project completion due date (19 days) is above 70%. 

Figure 10. Cumulative distribution functions of interruption on unit 3.

Figure 11. Cumulative distribution functions of interruption on unit 4.

Figure 12. Cumulative distribution functions of interruption on unit 4.

(Buffer B=5.5, Buffer C=6.5)

Figure 13. Cumulative distribution functions of continuous flow project duration.
The case study reveals that deterministic assigned buffer values to crews used in deterministic scheduling method of repetitive project can not maintain a continuous flow. For the interruption and probability during construction process, the confidence level of project completion due date is not satisfying. Application of the proposed simulation model, the generated scheduling of repetitive project with probability assigned duration values can better ensure a continuous flow during construction process. Furthermore, the confidence level of project completion according to scheduling is greatly enhanced.

5. CONCLUSIONS

Within the context of this paper, a new continuous flow simulation model for probability repetitive project is proposed. The proposed model integrates simulation and buffering to consider the probability of activity durations and for proper sizing of buffers. Instead of having the same activities duration distribution on different units as is common, the proposed model allows for different activities duration distribution between units. The proposed model applies a hierarchical modeling method which avoids a complicated simulation network and maintains continuous flow for probability repetitive project.

This paper investigates the relationship of time buffer with continuous flow. Future research in this regard will give insight into other type of buffers, such as WIP, CONWIP and capacity buffer and how to use these buffers to ensure the continuous flows. Note that strictly maintaining continuous flow induces prolong of project duration which causes the increasing of indirect cost, while maintaining continuous flow decreases direct cost. So there exit the trade-off between project duration and continuity in terms of cost. Detailed analysis of this trade-off will be focus of future work.

6. ACKNOWLEDGEMENT

The authors wish to acknowledge the postdoc scholarship of the first author, supported by Luleå University of Technology.

7. REFERENCES


