Alternative Scheduling and Planning Processes for Hybrid Offsite Construction

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Abstract

Offsite construction has gathered momentum in recent years due to its improved performance in terms of project cost, schedule, quality, environmental impact, and safety. Offsite prefabricated systems vary depending on the size of prefabricated components, which affect the need for onsite construction. These systems include categories such as modular, panelized, prefabricated, and processed materials construction. Each category has its own unique practices and can be blended with other categories in a "hybrid" offsite construction system. Several research studies have introduced scheduling and planning techniques for panelized and hybrid offsite construction using BIM and simulation tools. This paper thus presents an alternative BIM-based integrated framework for modelling and planning of hybrid offsite construction projects. BIM software (eg. Vertex BD) is used in the proposed framework for automating the data exchange between BIM model and the proposed method for scheduling of hybrid construction system. The objective of the proposed method is to develop a practical planning and scheduling alternative at the components level for offsite hybrid construction project. The proposed method integrates the linear scheduling method (LSM) and the buffering techniques of the critical chain project management (CCPM) into a comprehensive BIM-based framework while considering uncertainty associated with activities durations. This paper first introduces the literature pertaining to planning, and scheduling techniques for offsite construction; then, it presents the proposed computational along with a case study to verify the efficiency of the proposed integrated framework. Finally, conclusions related to implementation of the proposed framework are summarized.

Keywords – BIM, Panelized Construction, Planning, Hybrid Offsite Construction Introduction.

1 Introduction

Offsite construction and prefabrication facilitate the work simultaneously on offsite and on-site deliverables which may reduce considerably project schedule. Reduction in schedule leads to significant cost savings due to the reduced need for expensive and labor intensive onsite operations.

McGraw-Hill smart market report [1] asserts that 67% of firms reduced project schedules using prefabrication and modularization, and 35% of firms experiencing decreases of four weeks or more. Offsite construction provides valuable assistance for tight scheduling where project deadlines are usually inflexible as the higher education buildings sector [1].

Two features of offsite and modular construction are controlling the determination of its appropriate scheduling techniques. . The first is the repetitive nature of manufacturing for offsite construction, and the second is the uncertainty and variability of these operations. Thus, the traditional scheduling techniques that depend on the critical path method (CPM) cannot be applied due to lack in satisfying the resource continuity constraint in repetitive projects [2].

The linear Scheduling Method (LSM) is an advancement of the traditional line of balance (LOB) technique [3] that is commonly used for scheduling of repetitive projects. LSM uses similar mathematics to LOB though it represents the activity as a single line rather than dual lines as in LOB. However unlike LOB, LSM allows for representing non-repetitive and non-typical activities in complex construction projects.

The (LSM) diagram outlines time along the horizontal axis and the number of repetitive units along the vertical axis. Hence, it would be a great alternative to schedule offsite and modular construction though a few methods incorporate uncertainty with LSM in the literature. The other alternative for LSM is the use of simulation engines due to its capabilities for considering the cycles of repetitive activities and uncertainty.

However, the simulation models require dedicated simulation professionals [4] and it is usually tailored based on the special needs and requirements of the project being considered. Other studies [5], [6] and [7] integrate simulation with Building Information Modelling (BIM) to automate quantity take-off data and to visualize offsite and modular construction activities. BIM assists in automating the quantity-take off for modular construction components including the properties of modules, openings, and framing. Such automation improves the accuracy of schedule that can be integrated with other techniques to produce 4D and 5D schedules.

2 Literature Review

Limited number of scheduling techniques has been developed for off-site or modular construction projects. In this respect, the review focuses on three perspectives; linear scheduling, critical chain project management, and off-site construction scheduling.

2.1 Linear Scheduling Method (LSM)

The linear graphical techniques were used as early as 1929 on the empire state building, and then it was developed by the Goodyear Company in the 1940s and expanded by the US Navy in the 1950s [3]. Since the early 1970's, many variations of linear scheduling methods have been proposed with different names [2], [8], [9], [10], [11], [12], and [13].

LSM has a different approach to identify the critical path of activities due to resource continuity constraint.

Several methods have been introduced for identifying the controlling activity path (e.g. critical path) for linear schedules based on: controlling sequence of activities [14], controlling points concept [2], resource continuity constraint [15], and time and distance constraints [16]. However, these methods didn't consider the uncertainty associated with linear scheduling. In this respect, Schoderbek and Digman [17] integrated the LOB and the program evaluation review technique (PERT) into one scheduling method to account for repetitive activities and uncertainty. Dressler [18] considered uncertainty for a project by assigning probability distributions to each project segment however this approach requires complex linear programming methods to develop a schedule. Other researchers developed simulation-based methods [19], [20], and [21] and fuzzy set-based methods [22] and [23] to account for uncertainty associated with linear scheduling. However, these methods either depend on data availability, third party software, or tailored for a specific type of repetitive projects.

In a recent study, Slorup [24] suggested the application of critical chain buffer management theory in location-based management to account for uncertainty in linear scheduling without providing any formulation for this concept. The critical chain project management (CCPM) incorporates the critical chain scheduling technique which was introduced in 1997 as an application of the Theory of Constraints (TOC) by Goldratt [25]. The critical supply chain is first identified as the longest chain of activities that determines the project total duration based on availability of resources and durations of activities. Goldratt [25] introduced an aggressiveness procedure that reduces the activities durations confidence level from 95 to 50 percentile. The project buffer consists of the deducted durations of critical chain while, the feeding buffer consists of the deducted durations of non-critical chains as shown in Figure 1. A recent comprehensive review conducted by Ghaffaria et al. [26], highlights 21 aspects related to CCPM and outlines the research potentials in CCPM area.

2.2 Scheduling of offsite construction

Lack of tools that allows for modeling of uncertainty associated with linear scheduling led researches to develop simulation based methods for off-site construction [5], [27], and [28]. Other studies [6] and [7] integrate the Building Information Modelling (BIM) with simulation to facilitate the quantity take-off data for construction project scheduling.

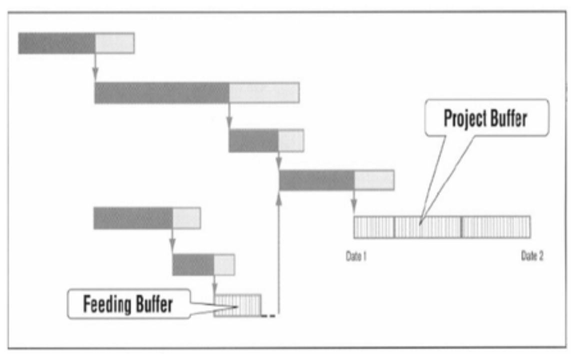

Figure 1: CCPM network with project and feeding buffers [24].

The main limitation identified based on the literature review is the lack of scheduling tools that utilize the linear scheduling under uncertainty for offsite construction projects. Thus, this paper presents a generic scheduling methodology for manufacturing of hybrid and modular offsite construction based on the LSM while considering the uncertainty associated with productivity of crews involved in the manufacturing process using the CCPM buffering technique.

3 Proposed Methodology

The proposed methodology utilizes the critical chain buffer management theory proposed by Slorup [24] to model the uncertainty associated with linear scheduling for manufacturing of offsite construction wall panels. The aggressiveness of CCPM eventually leads to shorter schedules while LSM visualizes the repetitive manufacturing processes.

The proposed framework depends on BIM for automating the data collection, then the collected data is used to generate the linear schedule. A set of assumptions are considered in the proposed methodology as follows:

1- Each of the manufacturing processes (or stations) has one fixed crew with a given productivity rate.
2- Each of the manufacturing processes is considered continuous due to the use of racks that reduce the variability in productivity rates of panels.
3- The manufacturing of panels follows the sequence of on-site erection.

The proposed methodology consists of four main phases: 1) Building Information Modelling (BIM) , 2) Automated data collection, 3) Calculation of activity (i.e. panel manufacturing) duration under uncertainty, and 4) Generation of linear schedules.

3.1 Building Information Modelling (BIM)

The project is modelled using BIM software (e.g. Vertex BD Pro 2016 22.0) that facilitates the modelling with automatic framing capabilities. The BIM model allows for generation of database that includes; property (e.g. Dry wall), dimensions, list of components (e.g. Openings), and the sequence of on-site erection of each panel. Figure 2 presents the interconnections between the BIM model and the project database.

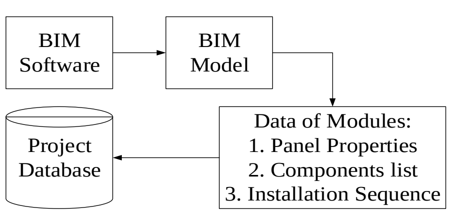

Figure 2: The interconnections between the BIM model and the project database.

3.2 Data Collection

The data collection has two main levels; 1) Project database generated from BIM model and 2) Data for productivity rate of crews involved in the manufacturing processes. The framework of the data collection is presented in Figure 3.

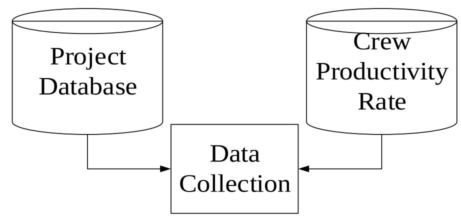

Figure 3: The framework of the data collection.

3.3 Calculation of Activity Duration

Each manufacturing process has "n" number of activities where n represents the number of panels. Each process has one fixed crew with a given productivity rates per the net area of panel which is referred to Average Productivity Rate (APR) in the remaining part of this paper. The activity duration for a given confidence level (CL) percentile (e.g. 50 percentile) is calculated as follows:

$$D_{i,j}(CL)= Area_i \,/\, APR_{i,j}(CL) \tag{1}$$

Where,
Di,j(CL), represents the duration of panel "i" in process "j" with given confidence level "CL"
Area i, represents the area of the panel i
APRi,j(CL), represents the average panel productivity rate .

3.4 Generation of Linear Schedule under Uncertainty

The proposed method considers the linear schedule at 50 percentile as the basic schedule. However, the uncertainty associated with the linear schedule is modelled using time buffer for each activity at each process. The buffer formula, as shown in Eq. (2), follows the Root Square Error Method (RSEM) [26]. The buffer of each panel "i" at process "j" with a confidence level "CL" is calculated as follows:

$$Buffer_{i,j}(CL)=\sqrt{\sum_{1}^{i}(D_{i,j}(CL)-D_{i,j}(50))^2} \quad (2)$$

Where,
Bufferi,j(CL), represents the uncertainty associated with the duration of panel "i" in process "j" with a confidence level CL.

It should be noted that the CL=50 results of buffer =0 which means that the scheduling with 50 percentile represents the basic linear schedule. However, a higher confidence level generates a buffer to be added to the duration of 50 percentile as presented in Eq. (2).

The linear schedule of a given process "j" can be generated using start and finish dates of each panel "i" which can be calculated using Eq. (3) and (4) respectively. Figure 4 shows the schedule of one process with multiple level of confidence (e.g. 85 percentile).

$$SD_{i,j}(CL) = FD_{i-1,j}(CL) \quad (3)$$

$$FD_{i,j}(CL) = FD_{i,j}(50)+ Buffer_{i,j}(CL) \quad (4)$$

Where,
FDi,j, SDi,j represent respectively start and finish dates of panel "i" at the process "j"

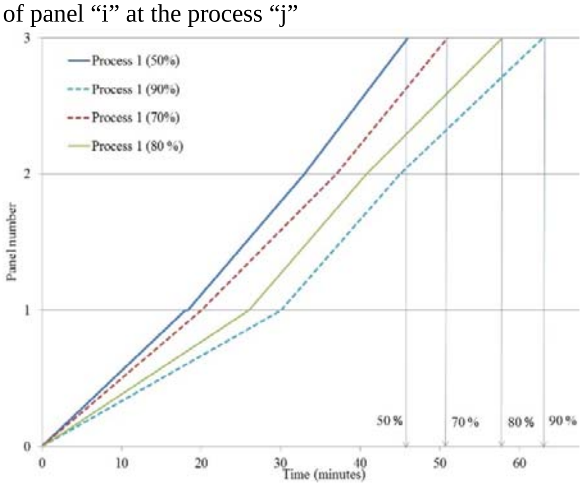

Figure 4: Various confidence rates for one manufacturing process.

In case of a manufacturing process with multiple stations, start and finish dates of activities with a confidence level of 50 percentile are calculated using Eqs. (5) and (6) respectively.

$$SD_{i,j}(50) = Max\ [FD_{i,j-1}(50), FD_{i-1,j}(50)] \quad (5)$$

$$FD_{i,j}(50) = SD_{i,j}(50)+ D_{i,j}(50) \quad (6)$$

Start date of first activity within process "j" is calculated using Eq. (7) as follows:

$$SD_{1,j}(CL) = Max\ [SD_{1,j}(50), FD_{1,j-1}(CL)] \quad (7)$$

For the succeeded activities of process "j", start and finish dates with a given confidence level (e.g. 80 percentile) are calculated using Eqs. (8) and (9) respectively.

$$SD_{i,j}(CL) = Max\ [FD_{i-1,j}(CL), FD_{i,j-1}(CL)] \quad (8)$$

$$FD_{i,j}(CL) = FD_{i,j}(50)+ Buffer_{i,j}(CL) \quad (9)$$

The proposed methodology generates two linear schedules for each process as shown in Figure 5. The first represents the linear schedule of each process at confidence level of 50 percentile, while the second represents the linear schedule of each process at a given confidence level. Thus, the proposed methodology illustrates graphically the manufacturing processes of all panels (or modules) at any confidence level (e.g. 85 percentile).

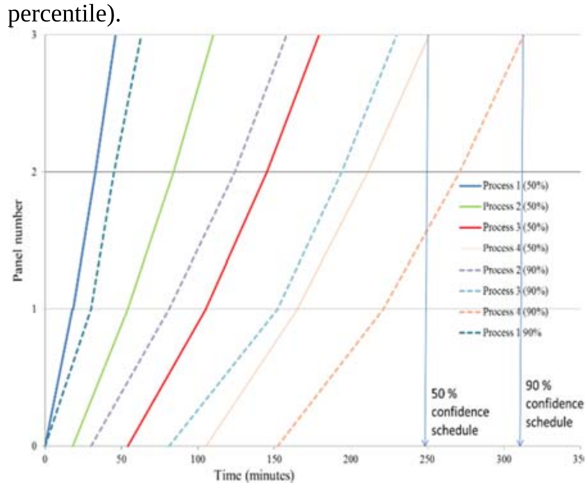

Figure 5: The two curves for each manufacturing process.

The proposed method utilizes the procedure developed by Harmelink [14] for identifying the critical segments within each process. This procedure is based on two main steps, the upward pass and the downward pass.

Step1: Upward pass

The upward pass begins with "the origin activity" which is the first activity/process. While the second activity/ process is named "the target activity" as shown in Figure 6. Harmelink [14] indicated that the controlling activity path occurs where activities/processes are closest to each other. The upward pass determines the potential controlling segments by identifying the least distance (LD) between the origin activity/ process and the target activity/process. The intersection between LD and origin activity is named critical vertex as shown in Figure 6. The LD interval is a potential controlling link between the origin and target activities/ processes as shown in figure 6. This step is repeated until all the potential controlling segments and links are identified.

Step2: Downward pass

The downward pass is equivalent to the backward pass in CPM scheduling, which identifies the activities that in case of delay extend the duration of the project. It starts at the end of last activity/process in the project until the potential controlling link is reached. The segments between these two points belong to the controlling activity path, and the potential controlling link between the last two activities/processes is a controlling link.

The project buffer is then added at the end of controlling activity path by considering the variability of the critical activities/panels only. The project buffer can be calculated using Eq. (8).

$$\text{Project Buffer} = \sqrt{\sum_{k=1}^{k=n} \left(D_k(CL) - D_k(50)\right)^2} \quad (10)$$

Where,
n, represents the number of activities on the critical path
k, represents the couple (i, j) that indicates the critical activity "i" within process "j".

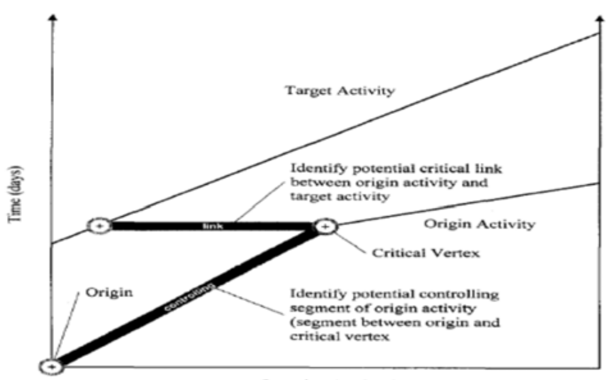

Figure 6: Potential controlling segments [14].

4 Case Study

A hypothetical case study was modelled on Vertex BD for three identical hybrid construction units including 45 panels with different dimensions and properties. A hybrid unit consists of bathroom modules combined with panelized construction forms the hybrid units shown in Figure 7. The bathrooms modules are fabricated as separate units of four panels, while the rest of units are panelized construction.

Vertex BD was used to generate the BIM model that includes panels of the three hybrid units as shown as an isometric view in Figure 8. The project database that includes list of components (panels and modules), properties of each components, and the sequence of installation on site. The net area is calculated based on the dimensions generated from Vertex BD. Figure 9 shows panel framing generated by Vertex BD which illustrate panel dimensions, components, and openings. The productivity rates for four different manufacturing processes (e.g. assembly, framing, etc.) for 3 different groups of panels based on their respective net areas as shown in Table 1. The panels are categorized into three categories; the first represents the panels which have net area less than 60 square feet, the second represents the panels which have net area between 60 and 90, and the third represents the panels which have net area higher than 90 as shown in Table 1. Accordingly, the productivity rates vary from panel to another as shown in Table 1.

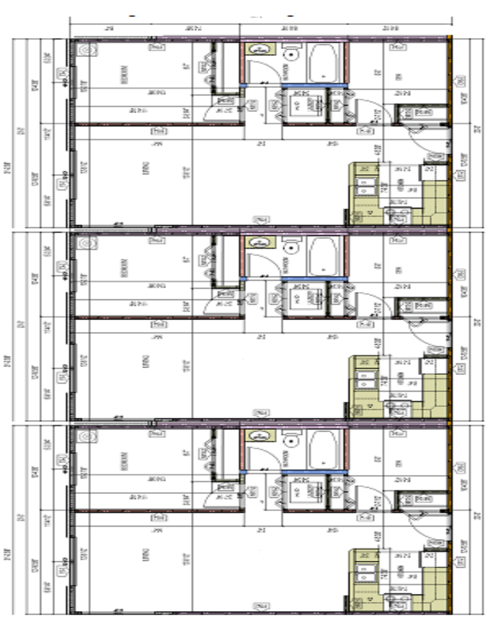

Figure 7: BIM model plan view using Vertex BD.

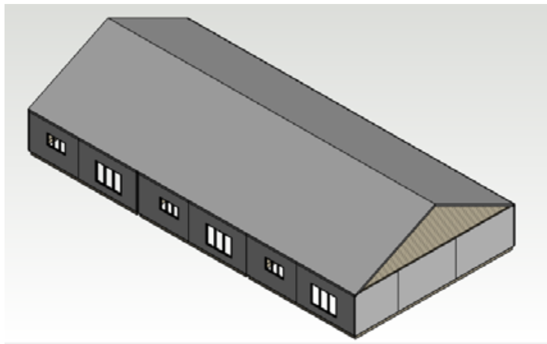

Figure 8: Isometric view of the BIM model

date and time buffer of each module or panel (i.e. activity). The required calculations for panel durations and buffers are shown in Figure 10. Then, the basic linear schedule for all manufacturing processes is generated using Eqs. (1) - (6) as shown in Figure 11. Then the second linear schedule with 90% confidence rate is generated for all manufacturing processes using Eqs. (7) - (9) by considering all the necessary buffers to account for uncertainty associated with production of panels. The 50 percentile basic schedule and the 90 percentile schedule are shown in Figure 11as the solid and dashed lines respectively.

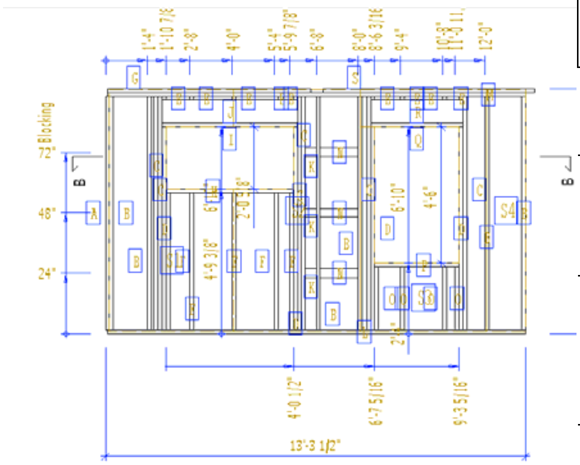

Figure 9: panel layouts generated by Vertex BD.

Table 1 Panel groups productivity rates

Panel Group	Net area (S.F)	Productivity rate (50 %) S.F/min		Productivity rate (90 %) S.F/min	
1	0:60	Process 1	4	Process 1	2.5
		Process 2	2	Process 2	1.1
		Process 3	1.5	Process 3	1
		Process 4	1.3	Process 4	0.9
2	60:90	Process 1	5	Process 1	3
		Process 2	2.5	Process 2	1.5
		Process 3	1.75	Process 3	1
		Process 4	1.5	Process 4	1
3	90:150	Process 1	6	Process 1	3.5
		Process 2	3	Process 2	2
		Process 3	2	Process 3	1.5
		Process 4	1.8	Process 4	1.6

The net area is calculated based on the panels dimensions acquired from the project database generated by Vertex BD. An EXCEL based tool is generated to facilitate the calculations of duration, start date, finish

Panel#	PanelName	Aggressive Productivity rate 50 %				Safe Productivity rate 90 %				Aggressive Duration				Safe Duration				NetSF	Buffer			
		Process1	Process 2	Process 3	Process 4	Process1	Process 2	Process 3	Process 4	Process1	Process 2	Process 3	Process 4	Process1	Process 2	Process 3	Process 4		Process 1	Process 2	Process 3	Process 4
1.0	bath	5.0	2.5	1.8	1.5	3.0	1.5	1.0	1.0	18.08	36.17	51.67	60.28	30.14	60.28	90.42	90.42	90.42	12.0	27.0	47.2	56.0
2.0		4.0	2.0	1.5	1.3	2.5	1.0	1.1	0.9	15.03	30.06	40.08	46.24	24.05	60.12	54.65	66.80	60.12	15.1	40.4	49.4	59.7
3.0		4.0	2.0	1.5	1.3	2.5	1.0	1.1	0.9	12.92	25.83	34.44	39.74	20.67	51.67	46.97	57.41	51.67	16.9	47.9	51.0	62.2
4.0		4.0	2.0	1.5	1.3	2.5	1.0	1.1	0.9	12.92	25.83	34.44	39.74	20.67	51.67	46.97	57.41	51.67	18.6	54.5	52.5	64.7
5.0	bath	5.0	2.5	1.8	1.5	3.0	1.5	1.0	1.0	18.08	36.17	51.67	60.28	30.14	60.28	90.42	90.42	90.42	22.2	59.6	65.2	71.4
6.0		5.0	2.5	1.8	1.5	3.0	1.5	1.0	1.0	12.02	24.05	34.35	40.08	20.04	40.08	60.12	60.12	60.12	23.6	61.7	70.1	74.1
7.0		4.0	2.0	1.5	1.3	2.5	1.0	1.1	0.9	12.92	25.83	34.44	39.74	20.67	51.67	46.97	57.41	51.67	24.8	66.9	71.3	76.2
8.0		4.0	2.0	1.5	1.3	2.5	1.0	1.1	0.9	12.92	25.83	34.44	39.74	20.67	51.67	46.97	57.41	51.67	26.0	71.7	72.3	78.2
9.0	bath	5.0	2.5	1.8	1.5	3.0	1.5	1.0	1.0	18.08	36.17	51.67	60.28	30.14	60.28	90.42	90.42	90.42	28.7	75.6	82.1	83.8
10.0		5.0	2.5	1.8	1.5	3.0	1.5	1.0	1.0	12.02	24.05	34.35	40.08	20.04	40.08	60.12	60.12	60.12	29.8	77.3	86.0	86.2
11.0		4.0	2.0	1.5	1.3	2.5	1.0	1.1	0.9	12.92	25.83	34.44	39.74	20.67	51.67	46.97	57.41	51.67	30.8	81.5	86.9	85.5
12.0		4.0	2.0	1.5	1.3	2.5	1.0	1.1	0.9	12.92	25.83	34.44	39.74	20.67	51.67	46.97	57.41	51.67	31.7	85.5	87.8	85.5
13.0	PT4 B	6.0	3.0	2.0	1.8	3.5	2.0	1.5	1.6	23.68	47.36	71.04	78.94	40.60	71.04	94.72	88.80	142.08	35.9	88.7	91.0	90.3
14.0	PT5 B	5.0	2.5	1.8	1.5	3.0	1.5	1.0	1.0	17.39	34.79	49.70	57.98	28.99	57.98	86.97	86.97	86.97	37.8	91.7	98.3	94.8
15.0	B10	6.0	3.0	2.0	1.8	3.5	2.0	1.5	1.6	24.25	48.51	72.76	80.85	41.58	72.76	97.02	90.95	145.53	41.6	94.9	101.2	95.3
16.0	B11	5.0	2.5	1.8	1.5	3.0	1.5	1.0	1.0	16.09	32.19	45.98	53.64	26.82	53.64	80.46	80.46	80.46	42.9	97.3	107.0	99.0
17.0	PT4 B	6.0	3.0	2.0	1.8	3.5	2.0	1.5	1.6	23.68	47.36	71.04	78.94	40.60	71.04	94.72	88.80	142.08	46.1	100.1	109.5	99.5
18.0	PT5 B	5.0	2.5	1.8	1.5	3.0	1.5	1.0	1.0	17.39	34.79	49.70	57.98	28.99	57.98	86.97	86.97	86.97	47.6	102.7	115.7	103.7
19.0	B10	6.0	3.0	2.0	1.8	3.5	2.0	1.5	1.6	24.25	48.51	72.76	80.85	41.58	72.76	97.02	90.95	145.53	50.6	105.6	118.2	104.2
20.0	B11	5.0	2.5	1.8	1.5	3.0	1.5	1.0	1.0	16.09	32.19	45.98	53.64	26.82	53.64	80.46	80.46	80.46	51.7	107.7	123.2	107.6
21.0	PT8	5.0	2.5	1.8	1.5	3.0	1.5	1.0	1.0	17.22	34.44	49.21	57.41	28.70	57.41	86.11	86.11	86.11	53.0	110.2	128.6	111.3
22.0	PT9	6.0	3.0	2.0	1.8	3.5	2.0	1.5	1.6	24.69	49.37	74.06	82.28	42.32	74.06	98.74	92.57	148.11	55.9	112.9	130.9	111.8

Figure 10: The calculations for panel durations and buffers

The generated schedules in Figure 11 presents the uncertainty associated with scheduling of panel manufacturing in a manner that enables project stakeholders to monitor and control each manufacturing process. Alternatively the project duration can be determined without the need for generating all the schedules at 90 percentile confidence level. The critical controlling activity path shown as a red arrow on Figure 10 was identified based on the procedure described in the methodology. Eq. (10) is used to calculate the project buffer which equals 147 minutes due to the variability of production rates of panels that belong to controlling activity path.

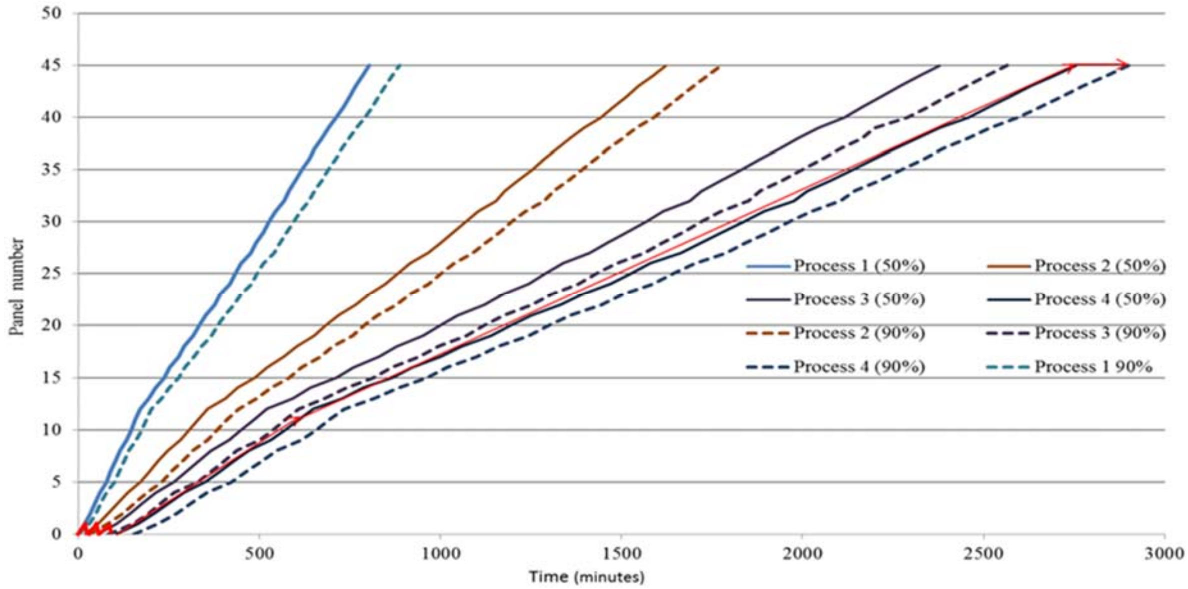

Figure 11: The 50% and 90% percentile schedules

All panels in the last process are critical because this process has the slowest productivity rate among all the four processes. By adding the calculated project buffer to the identified finish date for the last panel at the basic schedule (i.e. 50 percentile), the project total duration with 90 percentile confidence level is 2902 minutes. While, duration of the schedule at 50 percentile confidence level is only 2755 minutes.

5 Conclusion

The developed methods accounts for the uncertainty associated with the schedule of each activity. It also integrates between BIM and the linear scheduling method (LSM) to automate the data collection and the generation of linear schedule. Visualization capabilities of LSM allow the identification of controlling path. The developed method presents a generic alternative for scheduling of offsite construction projects that can be used by the manufacturing industry without the need for [1] a specific simulation model for each different production line. The developed method allows for generation of schedules at various confidence levels in a manner that supports the decision making procedure in selecting the best schedule for each project. The results of a case study shows that the linear behavior of manufacturing processes for offsite construction panels can be scheduled using LSM while considering the uncertainty associated with productivity rates. It also concluded that the automating procedure of linear scheduling method provides the manufacturers with an easy to use approach of planning for their manufacturing processes.

This methodology assumes the continuation of production for all stations based on unlimited storage capacity of racks between stations. This assumption prevents the identification of bottlenecks and starvations on any manufacturing production line. In this respect, future research in identification of bottlenecks and starvations in linear scheduling techniques is recommended.

Acknowledgements

The authors wish to thank Dr. Mohamed Al-Hussein from the University of Alberta, and the management team at Fortis Company in Edmonton, Alberta for their guidance and support in this research project.

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