Leadership in Sustainable Infrastructure

Leadership en Infrastructures Durables

Vancouver, Canada

May 31 – June 3, 2017/ *Mai 31 – Juin 3, 2017*

LEAN SCHEDULING OF REPETITIVE LOW INCOME HOUSING USING COLD FORMED STEEL

Saad, Dina A.[1,4], Masoud, Mohamed[2] and Osman, Hesham[3]
[1,2,3] Structural Engineering Department, Cairo University, Egypt
[4] d.atef.saad@gmail.com (corresponding author email)

Abstract: Construction of low-income housing is a tremendous challenge for governments to meet the increasing demand especially in developing countries. A fast and cost-effective construction process, therefore, is needed. To meet these requirements, light cold-formed steel (CFS) framing systems have been used as an alternative to traditional systems. Low-income housing projects usually consists of typical residential units located close to each other. The construction of such units, accordingly, is a repetitive process that requires repetitive scheduling to maintain work continuity and reduce idle time. For a large-scale residential project, conventional repetitive scheduling of the entire project as one big batch would lead to large work-in-progress inventory, potential delay due to discovered defects, and waste of time due to the waiting time between trades to finish the entire batch. Due to the analogy between manufacturing and construction processes, this paper discusses the application of batching and pull-production concepts of lean manufacturing in the repetitive scheduling of low-income housing projects to accelerate the construction process and reduce cost. A case study of 200 residential units, has been used to examine the impact of both concepts. From the results, it has been noticed that scheduling the project using pull scheduling and 10 batches, has reduced project duration, cost, and work-in-progress inventory as opposed to conventional scheduling which uses a single batch of 200 units. As such, this research demonstrates the benefits of applying lean manufacturing principles in construction of repetitive residential units and encourages further investigation of other potential lean concepts.

Keywords: Linear, Economical, Repetitive, Light-weight buildings, Fast Construction, Pull Scheduling

1 INTRODUCTION

Construction of affordable residential housing for the increasing low-income population has been a tremendous challenge for governments especially in developing countries. In Egypt for instance, 100,000 units on average are required every year in Greater Cairo based on the expected population growth rates. 20% of this demand is needed for low-income housing (Colliers, 2015). Thus, a fast and cost-effective construction technology is required to provide affordable housing with high performance. Among the advances in the construction systems that satisfy these requirements, cold-formed steel (CFS) framing system (also known as light gauge steel) has been recently used as an economical solution. Compared to the traditional reinforced concrete building systems in Egypt, CFS framing system has prevailing advantages including: light weight, high strength-to-weight ratio, high durability, and sustainability due to its high recycled content. Moreover, the panelized CFS members shortens the construction cycle allowing faster completion (SFIA, 2017; Abu-Hamd, 2015).

In Egypt, low-income housing units are often offered in the form of a development of hundreds of identical residential buildings, located very close to each other. Thus, they are repetitive units advancing in a horizontal direction. This type of repetitive units are often called non-linear or discrete repetitive units (Hegazy and Kamarah, 2008; Harris and Ioannou, 1998). Moreover, using the CFS framing system, the construction of a building is often a repetitive process of erecting CFS walls and slabs, and cladding using either gypsum or ferro-cement boards (Abu-Hamd, 2015). The utilization of the standard critical path method (CPM) for scheduling such repetitive construction projects suffer from many drawbacks including: non-efficient representation of the repetitive tasks across the repetitive units, inability to represent neither the location of the scheduled work nor the crews' productivity rates necessary for achieving optimum performance (Hegazy and Kamarah, 2008). Accordingly, to maintain continuous flow of resources across these discrete repetitive units and reduce idle time, repetitive scheduling technique (line of balance scheduling, LOB) is required.

In conventional repetitive scheduling, activities follow technical precedence constraints and resource availability constraints, while maintaining continuous flow of resources from one unit to another. To avoid convergence of activities with different production rates, activity with higher production rate than the preceding activity is controlled by the finish of the last unit in the preceding activity, as shown in Figure 1(a) for activities A and B (Harris and Ioannou, 1998). Utilizing the conventional repetitive scheduling for constructing large number of repetitive non-linear units; however, may lead to large work-in-progress inventory in terms of idle unfinished units, and waste of time for the working trades due to waiting for completion of the preceding activities for the entire units. Accordingly, some research efforts introduced intentional breaks to work flow of converging activities to reduce project duration, as shown in Figure 1(b). For linear projects, like highways and pipelines, these work breaks may result in higher costs due to the idle time experienced by the heavy equipment on site (Bakry et al., 2014). For non-linear repetitive projects consisting of repetitive building units, having these work breaks between batches of reasonable number of units can potentially expedite the construction process (Shim, 2011; Sacks and Goldin, 2007).

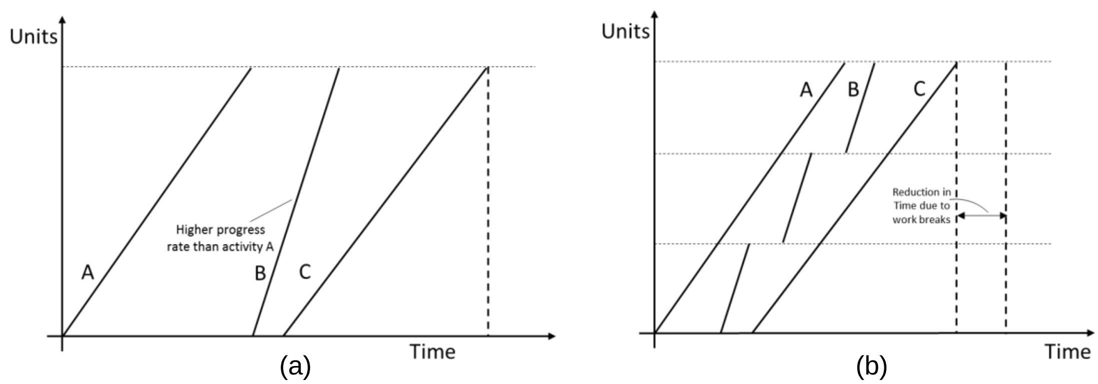

Figure 1: LOB charts using: a) Conventional scheduling; and b) Intentional work breaks

This batching concept is one of the main concepts of Lean manufacturing to reduce waste. Similar to manufacturing which is machine driven, construction is resource driven towards the completion of project. Due to the analogy between manufacturing production of repetitive units, and the construction of repetitive building units (Tommelein, 1998), delivering repetitive units; therefore, can benefit from the lean principal of batching to accelerate the construction process and reduce the associated costs.

2 APPLICATION OF LEAN PRINCIPLES IN CONSTRUCTION

Lean construction is the "continuous process of eliminating waste, meeting or exceeding all customer requirements, focusing on the entire value stream and pursuing perfection in the execution of a constructed project" (CII 2004). According to Lean principles, there are 7 types of wastes that need to be minimized in any given manufacturing process (Tommelein, 1998): Overproduction, Waiting, Unnecessary Transport, Extra processing, Inventory, Unnecessary Motion, and Defects. From the lean production techniques to reduce waste in general are: Pull production and Batch production. In the next subsections, a description of these two concepts is provided, and their application in the construction environment.

2.1 Pull Production

Pull scheduling in construction originated from Pull production in lean manufacturing. Previously, manufacturing was dominated by push production to serve mass production and satisfy the economies of scale. Due to the witnessed fast changes in the end user requirements, manufacturers in mass production had to choose between the risk of pushing the partially completed products to the market which may not receive demand as before, or the risk of terminating the whole production and scrapping the uncompleted products. In pull production, the market needs pull the production instead of pushing products to the customer. Thus, it helps reduce the waste of overproduction and inventory. In construction, some efforts used the concept of pull production in different ways (CII, 2004). For example, Tommelein (1998) investigated the application of the pull concept to better coordinate between site, fabricators, and designers to improve construction process performance. Sacks and Goldin (2007) used pull scheduling to pull the construction of apartments which their design requirements are completely identified by the client to avoid any latent design changes. Sivaraman and Varghese (2016) used the pull production concept to properly plan fast-track construction projects. Such that, the construction downstream requirements are transferred to the upstream design and procurement teams in order to pull the delivery of only the needed design drawings and material. Sacks and Partouche (2009) used the pull strategy to reduce Work-in-Progress (WIP) by pulling the resources to work in any spaces that have already started work rather than allocating them to new spaces. Yang and Ioannou (2001) developed a pull-system algorithm to maintain work continuity and eliminate gaps between activities in repetitive construction projects. Such that upstream activities would not start sooner than needed to ensure work continuity. Activities that start in units without being needed are considered as overproduction waste (Ward and McElwee, 2007). Accordingly, an activity can pull all of its predecessors to reduce cycle time for a given unit, and reduce having queues of idle work (Ballard 2001). For example, in Figure 2, activity C has been shifted forward due to an unforeseen interruption, therefore, it will pull the preceding activities A and B to eliminate gaps and ensure work continuity in a given unit. In this research paper, this latter use of the pull concept in scheduling is further investigated on delivering low-income housing, as discussed later.

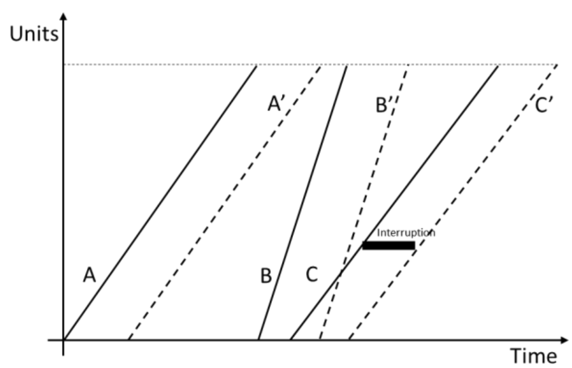

Figure 2: LOB chart showing Pull-production effect on work continuity (based on Yang and Ioannou, 2001)

2.2 Batch Production

To accommodate the lean thinking of pull production, products are manufactured in small lots/batches to allow rapid response to the market needs (CII, 2004). The conventional process of having products manufactured in large batches at one process within a plant and then queued for the next process leads to many manufacturing problems, such as bottlenecking and large inventories from high WIP levels (CII, 2004). Having batches smaller in size can help eliminate many of the aforementioned waste types. For instance, it will reduce over production by producing the appropriate volume of work for the next process to continue steadily, and thus eliminating waiting. Also, it can help recover defects earlier with minimal economical loss (Ward and McElwee, 2007).

Some research efforts tackled the batching concept in repetitive construction projects due to the analogy between the production of repetitive units in manufacturing, and the deliverance of repetitive units in construction (e.g., floors in high-rise buildings, units in development housing, pavement sections in linear highways, etc.). For instance, Ward and McElwee (2007) investigated the impact of reducing the batch size on the total duration of completing the finishing works of repetitive rooms in a given building floor. Shim (2011) examined, as well, the impact of having matched batch sizes on reducing the project duration in repetitive construction projects using Monte Carlo simulation.

Delivering construction projects using batches not only reduces the project duration, but it helps reduce WIP inventory and reduce the impact of having defected work. Once a defected work is detected in a given batch, it will be fixed before proceeding with the next batch, thus avoiding the rework of the entire project (Shim, 2011). WIP inventory can be described as work that has already been processed but not finished yet, awaiting for further processing either in idle or in active status. WIP in construction can be an activity waiting for completion of preceding activity, resources to be available, or information. Also WIP can be in terms of unfinished unit (Building floor, road section, room) which its construction is not yet completed. Reducing WIP inventory is necessary to reduce cycle time, waste, non-value movement of resources, and potential mistakes from being inactive or waiting in idle for a long time (Santos et al., 2000).

Having demonstrated the benefits of batching and pull scheduling, this paper describes the application of both concepts in the construction of a condominium of repetitive residential buildings located close to each other, and their impact on the construction plan and schedule.

3 CASE STUDY

The case study is a development project of 200 low-income residential buildings. Each building consists of a basement and 5 typical floors. The structural skeleton consists of slabs and walls made of CFS panels. Ferro-cement boards are used for flooring tiles and for interior and exterior cladding of walls. Each floor consists of 32 and 15 CFS walls and slabs, respectively. Construction activities of any typical floor include: erection of CFS walls and slabs; installation of the services rough-ins; and erection of Ferro-cement boards for floorings, interior walls, and exterior walls. Resources involved in the construction process are: crew of semi-skilled workers and assistants for erection of CFS and Ferro-cement boards, drill machine, and mobile crane and its associated crew. The crane is used to lift the CFS panels to their designated locations, and holds the panels until they are partially bolted. The objective in this case study is to complete the construction of the 200 units with the least total cost and duration to meet the increasing demand on low-income housing in Egypt. Total cost includes direct costs associated with the resources utilized, and indirect costs which include fixed and variable costs function of the project duration. To investigate the potential benefits of using the batching and pull scheduling concepts, the project is scheduled using both concepts, and the results will be compared against the schedule generated using the conventional scheduling method.

3.1 Schedule Development

The detailed steps for developing the schedule are as follows:

1. Identify construction activities within each repetitive building unit.
2. Identify the logical sequence between activities – To accelerate the construction process, CFS walls and slabs will be erected concurrently with a lag between them to allow for assembling each slab on its supporting walls. Accordingly, while developing the construction schedule of the CFS

framing system, the erection of walls and slabs has been combined into one core activity to eliminate gaps in the schedule, and thus reduce the overall project duration.

3. Identify the quantity of work, and crew formation and productivity for each activity – For the CFS related activities, the crane operation has higher productivity than the CFS crew, thus, the crane can stand idle which is considered ineffective due to its high daily cost rate. Therefore, an analysis of the cycle time of each resource has been carried out, as shown in Figure 3, to determine the optimum number of cranes and crews that reduces idle time, and project duration and cost.

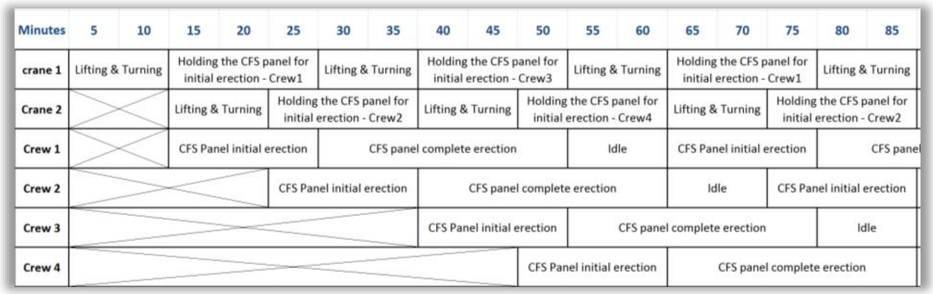

Figure 3: Portion of the resources cycle time analysis

4. Calculate the duration of each activity using the information in the previous step, and the direct cost of each activity considering the resources utilized in each

5. Calculate the progress rate of each activity across the building units in terms of no. of units per day, as follows:

   [1] $\text{Progress rate of activity}_i = \dfrac{\text{Number of crews across units}}{\text{Activity's duration}}$

   The progress rate identifies the slope of the activity's LOB. If the progress rate of a given activity is higher than the preceding activity's rate, as previously discussed, then the start of the activity is constrained with the end of the preceding activity, and vice versa.

To facilitate scheduling the project, a spreadsheet that formulates all the aforementioned steps has been developed, as shown in Figure 4. The columns in the figures shows: number of crews travelling across the units in each activity (once a given activity is completed in a certain floor, the crew moves to the same floor in the next unit), the daily and total cost of each activity considering the resource utilized, the activity's duration to complete a single unit, the progress rate of the activity (slope), the start and end times of the first and the last unit in the project, and the start and end times of any selected unit of choice in the project. The total cost and duration of the project depends on the progress rates of the activities and the interrelation between them, thus, it depends on the number of crews identified for each activity. To determine the optimum project total cost and duration, an optimum combination of crews is needed. To facilitate finding the optimum solution, a lookup table of the direct cost associated with each crew number for each activity has been constructed a shown in Figure 4. To solve this combinatorial problem, an optimization algorithm has been developed using genetic algorithm and has been solved using Excel Add-in evolutionary solver. The optimization parameters are as follows:

Objective Function: is set to minimize the total cost of the project including direct and indirect cost.

Decision Variable: X_i, which is the number of crews moving across the units for each activity (i).

Constraints: Number of crews should not exceed the available number of crews.

No. of crews travelling across units

Progress rate of the activity (#units/day)

Start and end times of any building unit in each activity

Activity	Crews	Cost		Unit	Slope	Unit 1		Unit 200		Unit	X = 140
		Cost/day	total	Duration		Start	End	Start	End	Start	End
Excavation	4	1,260	767,340	3	1.33	0	3	149	152	104	107
P.C. for foundation	4	8,100	3,288,600	2	2.00	53	55	152	154	122	124
R.C. Strip Foundation	5										
Foundation Insulation	4										
Backfilling	3										
GF Slab on grade	4										
GF CFS walls and slabs	2										
GF services	3										
GF exterior ferrocement boards	3										
GF Ceiling ferrocement boards	3										
GF interior ferrocement boards	3										
GF finishing	3										

Activity List	Number of Crews X	Duration	Slope	DC associated with numer of crews X			
				1	2	3	X
Excavation	2	3	0.67	774,063	851,469	928,876	1,006,282
P.C. for foundation	1	2	0.50	3,317,413	3,649,155	3,980,896	4,312,637
R.C. Strip Foundation	3	6	0.50	20,733,833	22,807,216	24,880,600	26,953,983
Foundation Isolation	2	3	0.67	289,966	318,963	347,960	376,956
Backfilling	2	3	0.67	1,597,273	1,757,000	1,916,728	2,076,455
Slab on grade	5	10	0.50	1,419,116	1,561,027	1,702,939	1,844,850
Ferrocement tiles	3	6	0.50	10,505,142	11,555,656	12,606,171	13,656,685
CFS walls and slabs	2	4	0.50	63,428,942	69,771,837	76,114,731	82,457,625
services	3	12	0.25	13,269,653	14,596,619	15,923,584	17,250,549
exterior ferrocement boards	2	2	1.00	7,961,792	8,757,971	9,554,150	10,350,330

Lookup table of the direct cost associated with each crew number for each activity

Figure 4: Portion of the schedule spreadsheet and optimization setup

3.2 Batch-based Repetitive Scheduling vs. Conventional Repetitive Scheduling

Using the Batch-based scheduling method (BSM), the 200 building units are divided to 10 batches, each batch consists of 20 units. Once the crews of a given activity finishes work in a given batch, they move to the next batch considering the technical constraints with preceding activities. To determine the optimum number of crews across the units that minimizes cost and duration, the previously described optimization setup is used, resulting in a total project duration of 941 workings days and associated total cost of 1,112 million EGP. To evaluate the performance of the BSM, the conventional scheduling method (CSM) has been applied, as well, with the same number of crews. The resulting total project duration and total cost are 1,156 working days and 1,167 million EGP, respectively. This increase in duration and cost, using the CSM, is due to maintaining a continuous flow of resources throughout the 200 units as one single batch, and thus the flow is constrained with the progress rate of the converging activities for the entire 200 units, as shown in Figure 5. For example, the activity of installing exterior Ferro-cement boards to cover the exterior CFS walls succeeds the erection of CFS walls and slabs. However, the progress rate of installing the exterior Ferro-cement boards is higher than erection of CFS walls and slabs. Therefore, the start of the “Exterior Ferro-cement boards” activity is constrained with the completion of erecting the CFS walls and slabs in the 200th unit. This arrangement leads to an increase in project duration. On the other hand, using the BSM, converging activities are less constrained. Such that, the activity with higher progress rate can start earlier as its start is only controlled with the finish of the preceding activity in the last unit in the batch rather than the completion of the 200th unit, as shown in Figure 6 which shows only the optimum repetitive schedule plot for the first and last batch due to space limitation.

To further analyze the performance of both methods, the WIP has been calculated for both. In this paper, the WIP is represented using two different methodologies: 1) the cycle time that each unit consumes from the start to the end of its construction (Ballard, 2001), and 2) the number of unfinished units at any given point in time (Sacks and Partouche, 2009), as shown in Figure 7. It can be noted from Figure 7, that there is a recognizable WIP reduction due to using the BSM. For example in Figure 7(a), unit number 60 has a cycle time of 300 working days as opposed to 550 working days using the CSM. Also the number of units in progress at any point in time has reduced greatly. For instance at the 250th working day in Figure 7(b), the number of unfinished units are 160 units as opposed to 200 units using the CSM. However, it can be noticed from the chart in Figure 6, that as the work progresses in the later batches, gaps between activities are created (e.g., gap between backfilling and slab-on-grade activities). These gaps are considered one of the lean wastes that need to be eliminated to reduce construction cycle time of each unit, and the probability of having defects due to waiting idle for the next activity. Also it is considered as overproduction, which means executing unneeded activities that their succeeding activities are not ready to be executed.

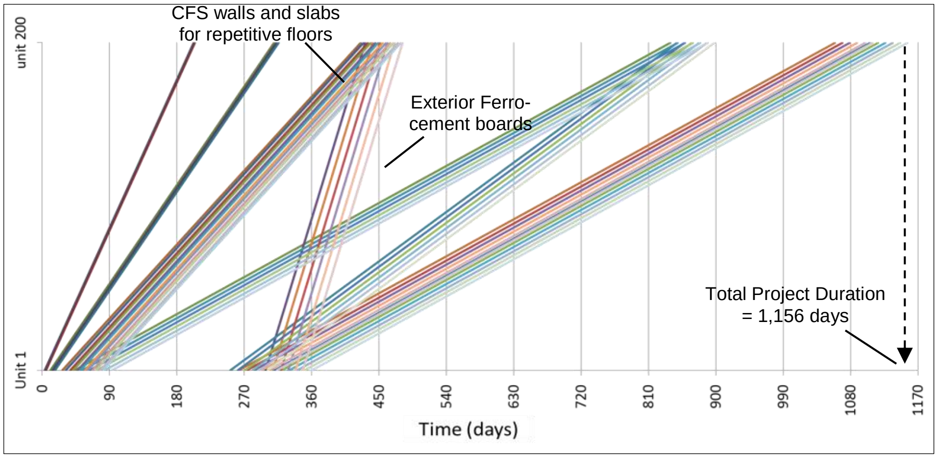

Figure 5: LOB chart using conventional scheduling method (CSM)

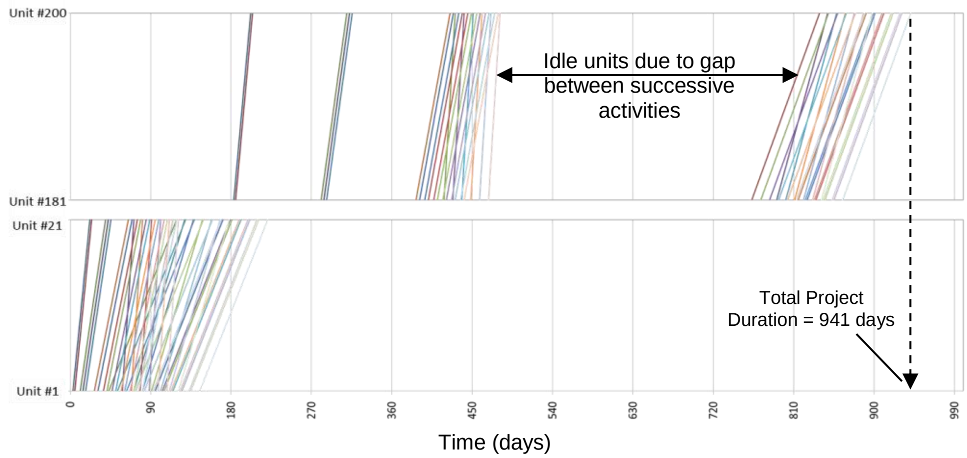

Figure 6: LOB chart for first and last batch using Batch-based scheduling method (BSM)

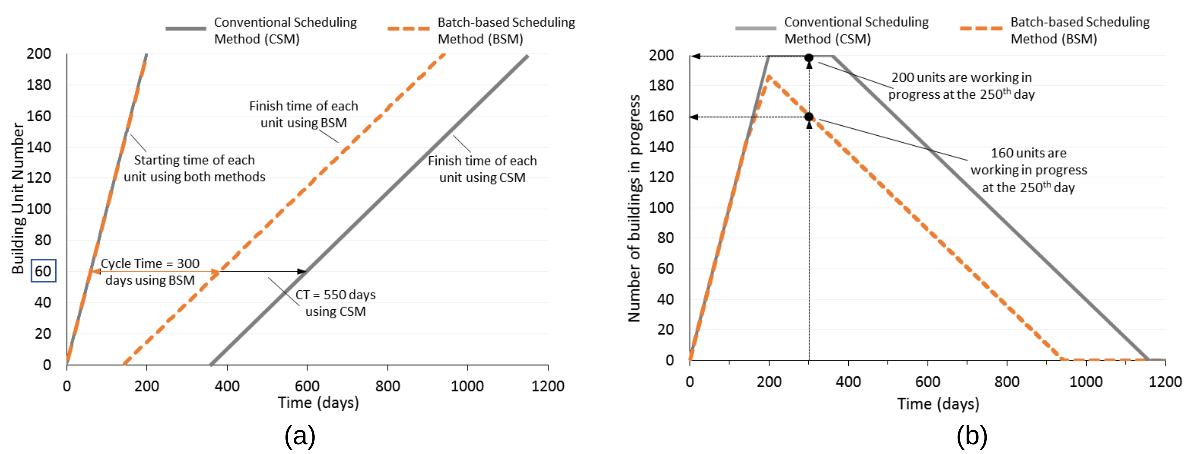

Figure 7: WIP charts using Batch-based Scheduling method in terms of: (a) Unit's construction cycle time, (b) Number of unfinished units at any point in time

3.3 Pull-Batch-based Repetitive Scheduling

To maintain work continuity and eliminate gaps between activities in any given unit, the pull-scheduling concept of Yang and Ioannou (2001) has been applied to the schedule generated using the batching concept. Such that downstream activities are formulated to pull upstream activities whenever there is gap. Accordingly, the schedule demonstrated in Figure 6, can be considered as Push-based scheduling such that activities are pushed to start as early as possible (Sacks and Partouche, 2009). Applying pull concept to this schedule, the last activities in any given unit will pull all the preceding activities to achieve minimum construction cycle time considering logical constraints between activities. Figure 8 shows the enhanced schedule using the pull scheduling technique. It can be noted that this technique results in the same project duration, however, it eliminates gap between activities, thus, reduces WIP inventory.

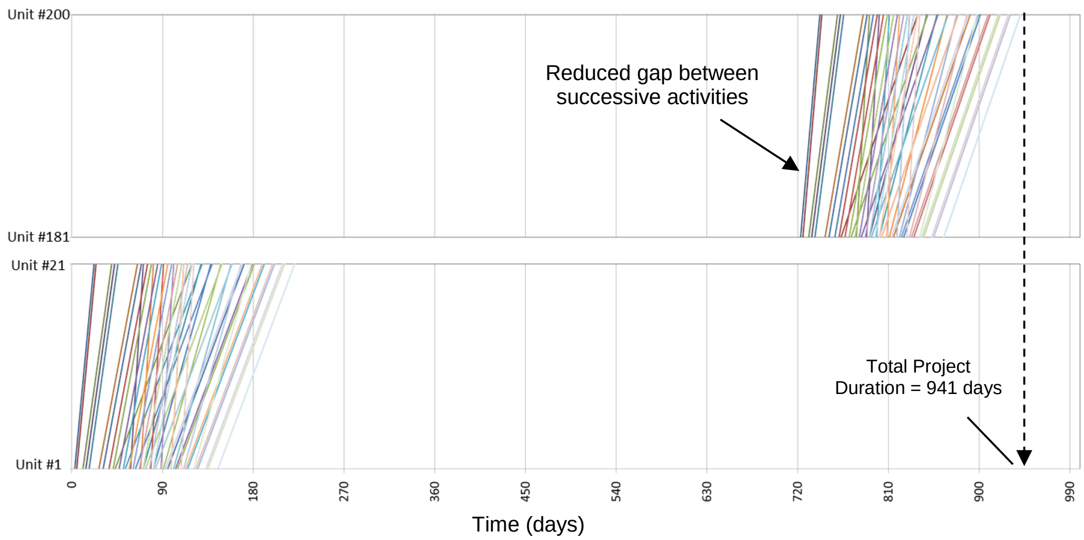

Figure 8: LOB chart for first and last batch using Pull-Batch-based scheduling method (PBSM)

To highlight the impact of pull scheduling on the WIP, Figure 9 shows the WIP using the aforementioned methodologies with and without pull scheduling. It should be noted that the finish time of any unit is the same using both methods, accordingly, they share same LOB. Using the Pull-Batch-based scheduling technique (PBSM), the construction cycle time has greatly decreased in comparison to scheduling using batching only. For example in Figure 9(a), unit number 60 has a cycle time of 100 working days using the Pull-Batch-based scheduling technique and a cycle time of 300 working days using the Batch-based scheduling technique on its own. Also the number of units in progress at any point in time has reduced greatly. For instance at the 250th working day in Figure 9(b), the number of unfinished units in progress are 40 units using the PBSM method as opposed to 160 units using the BSM method.

Table 1 provides a summary of the results using the Conventional, Batch-based, and Pull-Batch-based scheduling techniques. The results include: total project duration, total cost, maximum WIP in terms of construction cycle time, and maximum WIP in terms of number of unfinished units. The last two columns in the table shows the maximum number of unfinished units working in progress, and the time period which they have occupied, respectively. For example, using the CSM, the maximum number of unfinished units are 200 over a time period of 161 days. From Table 1, the optimum schedule is achieved using the PBSM method which combines the batching and pull concepts, as it has the least cost, duration, and WIP inventory. Accordingly, applying this scheduling technique helps deliver discrete repetitive buildings in less duration, minimal waste, and in a cost-effective manner, thus meeting the goals of low-income housing.

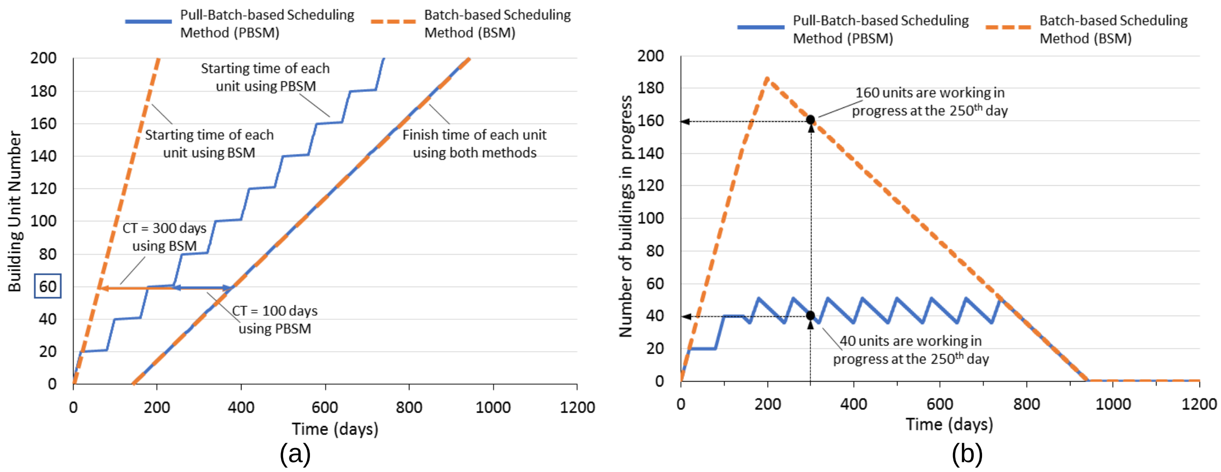

Figure 9: WIP charts using Pull-Batch-based Scheduling method in terms of: (a) Unit's construction cycle time, (b) Number of unfinished units at any point in time

Table 1: Summary of results using batching and pull scheduling techniques

Scheduling Technique	Total Project Duration (days)	Total Cost (million EGP)	Maximum WIP (Cycle time in days)	Maximum WIP (Number of unfinished units)	
				Number	Time Period (days)*
Conventional	1156	1,167	957	200	161
Batch-based schedule	941	1,112	742	186	2
Pull-Batch-based schedule	941	1,112	202	51	2

4 SUMMARY AND CONCLUDING REMARKS

This paper presented a critical scheduling problem to deliver housing units in minimal duration and cost to meet the demand of low-income earners in Egypt. CFS framing systems are used in these housing units as a more cost-effective and faster alternative to traditional concrete structural systems. Due to the repetitive process of constructing these CFS buildings, and the fact that the low-income housing are often provided in the form of a development of typical units located very close to each other, repetitive scheduling is needed to maintain the continuous work flow of resources. Due to the analogy between the manufacturing process of repetitive units of given product and the construction process of repetitive units, the lean manufacturing concepts of batching and pull production have been utilized in this research. Using a case study of 200 low-income housing units, two LOB scheduling techniques have been examined, with respect to the total duration, cost and WIP inventory, against the conventional LOB technique which maintains the flow of resources continuously across the entire 200 units. The first technique uses the batching concept by delivering the 200 units in batches of 20 units maintaining the workflow within each batch. The second technique uses a combination of the batching and pull-production concepts to pull upstream activities towards the downstream activities. Results demonstrate that the first scheduling technique outperforms the conventional method by completing the project in less cost, duration, and WIP inventory. On the other hand, the second technique resulted in same duration and cost as the first technique, yet it achieved less WIP inventory by reducing construction cycle time, eliminating any unnecessary overproduction, and avoiding having unfinished units in idle. In essence, this paper proves that applying lean manufacturing concepts in construction has tangible benefits which encourages further investigation of other potential lean concepts.

5 REFERENCES

Abu-Hamd, M. 2015. Implementation of BIM into cold-formed steel residential buildings. *WIT Transactions on The Built Environment*, **149**, WIT Press.

Bakry, I., Moselhi, O., and Zayed, T. 2014. Optimized acceleration of repetitive construction projects. *Automation in Construction*, 39, 141-151.

Ballard, G. 2001. Cycle Time Reduction in Home Building. Proceedings of 9th annual conference of the International Group for Lean Construction, National University of Singapore.

Colliers. 2015. Greater Cairo Real Estate Market Overview, Colliers International Service Lines.

Construction Industry Institute (CII). 2004. *Application of Lean Manufacturing Principles to Construction*. University of Texas, Austin: Diekmann, J.E., Krewedl M., Balonick, J., Stewart, T., and Won, S.

Harris, R.B., and Ioannou, P.G. 1998. *Repetitive Scheduling Method*. Center for Construction Engineering and Management, University of Michigan, Ann Arbor, Michigan.

Hegazy, T., and Kamarah, E. 2008. Efficient Repetitive Scheduling for High-Rise Construction. *Journal of Construction Engineering and Management*, **134(4)**: 253 - 264.

Sacks, R. and Goldin, M. 2007. Lean Management Model for Construction of High-Rise Apartment Buildings, *Journal of Computing in Civil Engineering*, **133(5)**: 374-384.

Sacks, R., and Partouche, R. 2009. Production Flow in the Construction of Tall Buildings. *Proceedings of Construction Research Congress Conference*, ASCE, Seattle, Washington, April 5-7.

Santos, A., Powell, J.A., Sarshar, M. 2000. Reduction of Work-In-Progress In The Construction Environment. *Proceedings of 8th Annual Conference of the International Group for Lean Construction*. Brigthon, UK, 17-19 July.

Steel Framing Industry Association (SFIA). 2017. *Advantages of Cold-Formed Steel Framing*. http://www.cfsteel.org/advantages-of-cold-formed-steel-framing [Last accessed, 07-02-2017].

Shim, E. 2011. Impacts of Matched Batch Sizes on Time Reduction in Construction Projects. *Proceedings of the 28th International Association for Automation and Robotics in Construction (ISARC)*, Seoul, Korea, 929 – 934.

Sivaraman, A., and Varghese, K. 2016. Pull Planning System to Coordinate the Engineering Procurement and Construction on Process Plant Projects. *Proceedings of Construction Research Congress*, ASCE, May 31–June 2, 2016, San Juan, Puerto Rico, 1720 – 1730.

Tommelein, I.D. 1998. Pull-Driven Scheduling for Pipe-Spool Installation: Simulation of a Lean Construction Technique. *Journal of Construction Engineering and Management*, ASCE, **124 (4):** 279-288.

Ward, S.A., and McElwee, A. 2007. Application of the Principle of Batch Size Reduction in Construction. *Proceedings of Annual Conference of the International Group for Lean Construction (IGLC-15), July 2007, Michigan, USA*, 539-548.

Yang, T., and Ioannou, P.G. 2001. Resource-Driven Scheduling for Repetitive Projects: A Pull-System Approach. *Proceedings of 9th Annual Conference of the International Group for Lean Construction (IGLC)*, Ballard, G. & Chua, D., Singapore, Singapore, 6-8 Aug.