

PROJECT CONTROLS EXPO 2018
Technical Paper

BENEFITS OF PLANNING WITH LINE OF BALANCE

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Abstract

Roads, pipelines, multi-family housing complexes and high-rise buildings are examples of projects with an intrinsic characteristic of repeatability, i.e., in which a group of activities are performed successive times. Network scheduling methods such as PERT-CPM have proven successful in the planning and control of projects, but are not as suitable for projects of a repetitive nature. Line of balance (LOB) is a planning technique developed for this type of project. A repetitive operation can be represented by a straight line on a time-location graph. Its slope is the production rate at which the activity advances. In this paper, the author intends to show how to calculate and plot lines of balance and demonstrate the relevance of planning with LOB and its advantages for project controls. Two case studies are addressed.

Introduction

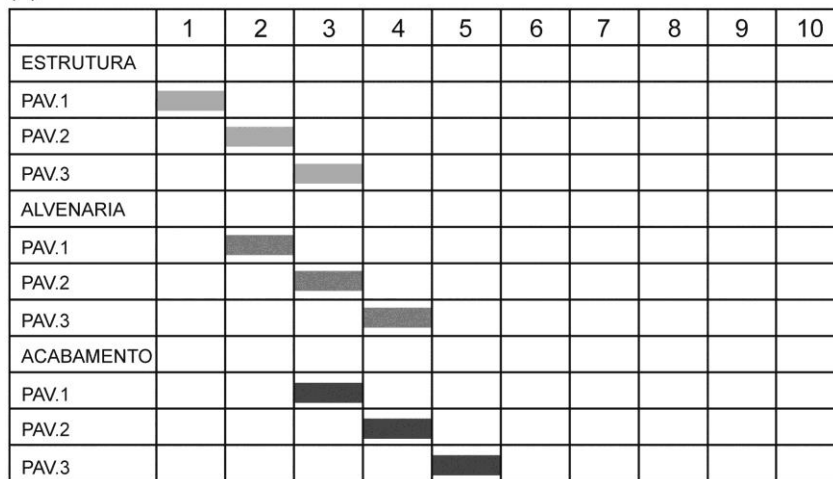
In the construction industry, many projects are comprised of activities with a linear and/or repetitive nature. Roads, pipelines, multi-family housing complexes and high-rise buildings are examples of projects with an intrinsic characteristic of repeatability, i.e., in which a group of activities are performed successive times. Although network scheduling methods, such as PERT-CPM, have proven successful in the planning and control of most projects, they are not as suitable for projects of a repetitive nature because the resulting schedule frequently contains unwanted gaps. The line of balance (LOB) technique, also known as time-location diagram or space-time diagram, is a planning technique developed for repetitive projects. Since a crew performs the same service multiple times throughout construction, the project progress can be represented as a straight line plotted in a time-location chart where the slope of the line shows the production rate at which the activity is performed. The objective of this paper is to demonstrate the relevance of planning with LOB and its advantages for project controls purpose.

AACE Recommended Practice 10S-90, "*Cost Engineering Terminology*," defines line of balance (LOB) as "a graphical display of scheduled units versus actual units over a given set of critical schedule control points on a particular day. The line of balance technique is oriented towards the control of production activities" [1]. Originally developed in the US in 1941 by the Goodyear Tire & Rubber Company under George E. Fouch's guidance, the LOB technique was also applied successfully to the planning and control of the US Navy production during the 1950's. Later, the line of balance methodology was adapted for use in civil construction, in manufacturing, and to control the flow of industrial operations. The increasing popularity of PERT/CPM helped to enhance the LOB methodology as a planning and control tool.

Graphical Display

In order to illustrate the LOB technique, consider the very simple schedule displayed in Figure 1(a). This bar chart schedule can be redrawn with a distinct work breakdown structure by gathering the activities that are performed successive times. The resulting schedule, shown as Figure 1(b), provides a visual representation of the activities which enables the reader to have a better understanding of the overall project sequence. As an improvement, the planner may draw a line connecting the repetitive activities; the slope of each line represents the production rate of the service.

(a)



(b)

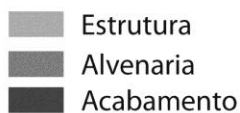
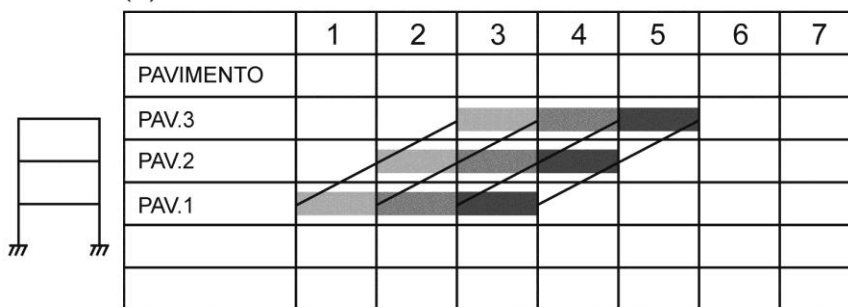


Figure 1 – Schedule: (a) conventional bar chart; (b) rearranged bar chart and LOB

As seen above, the line of balance summarizes of the activity production rates by grouping similar activities along a single line, thus condensing the schedule into a shorter document where time is

plotted against produced units. The slope for each trade defines the production rate in time; the steeper the line the greater its production rate. Unlike the traditional bar graph schedule where the major concern is the duration of the individual activities, the LOB philosophy focuses on the rhythm (production rate) of the service, and it assumes that each crew will achieve a particular *uniform* production rate for each service, i.e., its progress will be linear. Because the slope of the line defines the production rate, by using LOB the planner clearly reveals when the service will be performed in each work unit.

Example One: Suppose a contractor intends to build a 7-km linear sewage system whose work cycle consists of two consecutive operations performed sequentially in 1-km sections of trench excavation and pipelaying [2]. This cycle will happen seven times. Suppose that the excavation of each trench section takes 2 days and the pipelaying takes 1 day, with an interval of 1 day between the operations as seen in Figure 2.

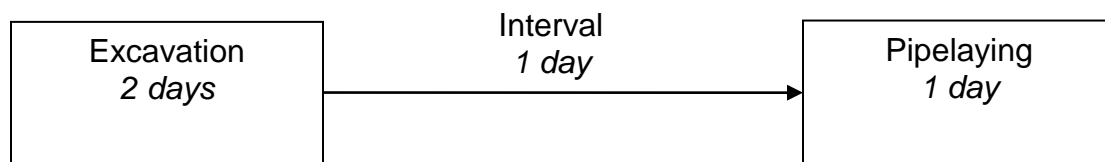


Figure 2 – Cycle of trench excavation and pipelaying

Assuming the project has an overall duration of 10 days, the lines of balance are shown in Figure 3. The slope of each shaded bar represents the required work rate (to finish the job within the overall duration), and its thickness is equivalent to the duration of each activity. The time of occurrence of each service is easily derived: the excavation of the fourth kilometer must take place between days 4 and 5; pipelaying of the sixth kilometer will occur on day 9 and so on.

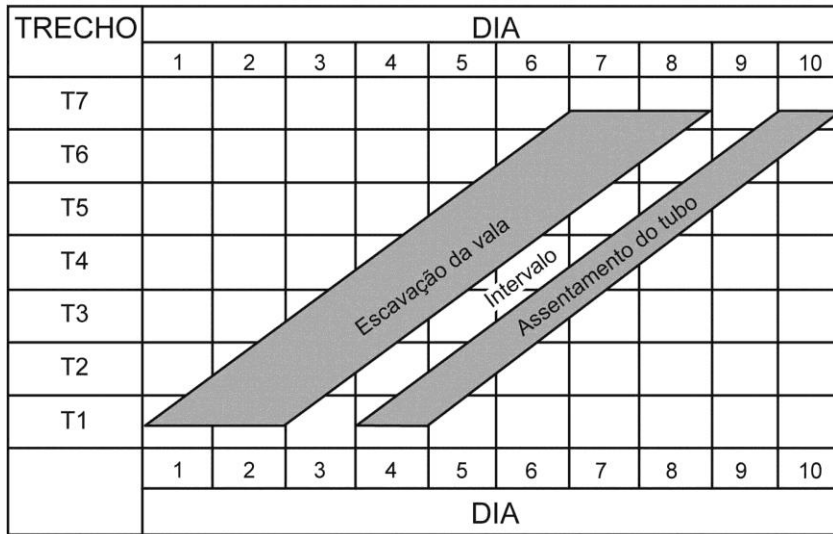


Figure 3 – LOB with a total duration of 10 days

The next step is to allocate resources to complete the work within the desired timeframe. If one excavation crew takes 2 days to dig 1 kilometer of ditch, at the end of the 10 days the excavation would be on the fifth kilometer. This represents an insufficient production rate, as shown in Figure 4.

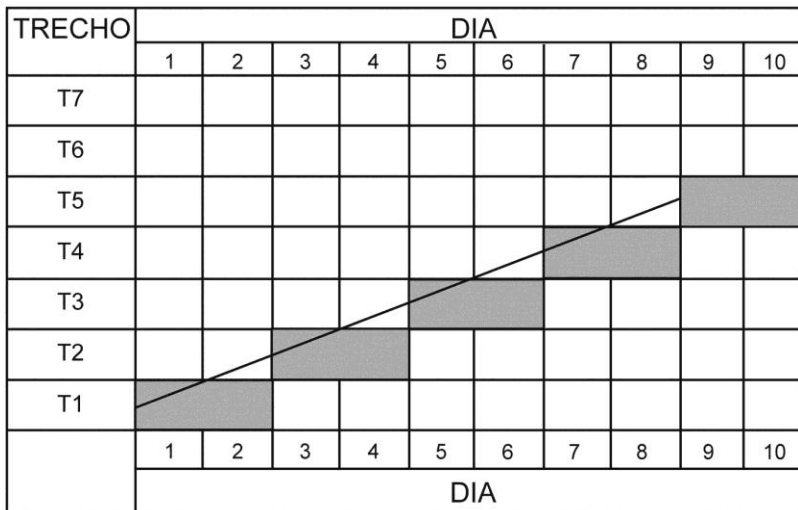


Figure 4 – LOB with a single excavation team

Figure 5 shows the progress that could be achieved by employing two excavation crews: every two days, 2 km of trench would be excavated. Furthermore, at the end of the sixth kilometer the contractor could demobilize the second crew because the remaining crew would be sufficient to finish the job by day 8, which correlates with the deadline for excavation established in Figure 3.

TRECHO	DIA									
	1	2	3	4	5	6	7	8	9	10
T7							Equipe 1			
T6					Equipe 2					
T5					Equipe 1					
T4			Equipe 2							
T3			Equipe 1							
T2	Equipe 2									
T1	Equipe 1									
	1	2	3	4	5	6	7	8	9	10
	DIA									

Figure 5 – LOB with two excavation teams

Example Two: When constructing a multi-story building, there are ascending services (carried out in a bottom-up direction) such as masonry and structure, and there can be descending services (carried out in a top-down direction) such as external painting. A line of balance graphic for these three activities is shown in Figure 6. The masonry productivity is clearly higher than that of the structure because its line of slope is steeper. Therefore, masonry should not start immediately after the structure is completed on the first floor because the crews would soon run out of work. Remember that masonry has a higher rate of production and therefore a shorter cycle. The way to solve this problem is to calculate a “backward pass,” by planning the topmost floor masonry to start immediately after the structure is completed and then to schedule the lower levels accordingly, as shown in Figure 6. This establishes a delayed starting point for the masonry crews.

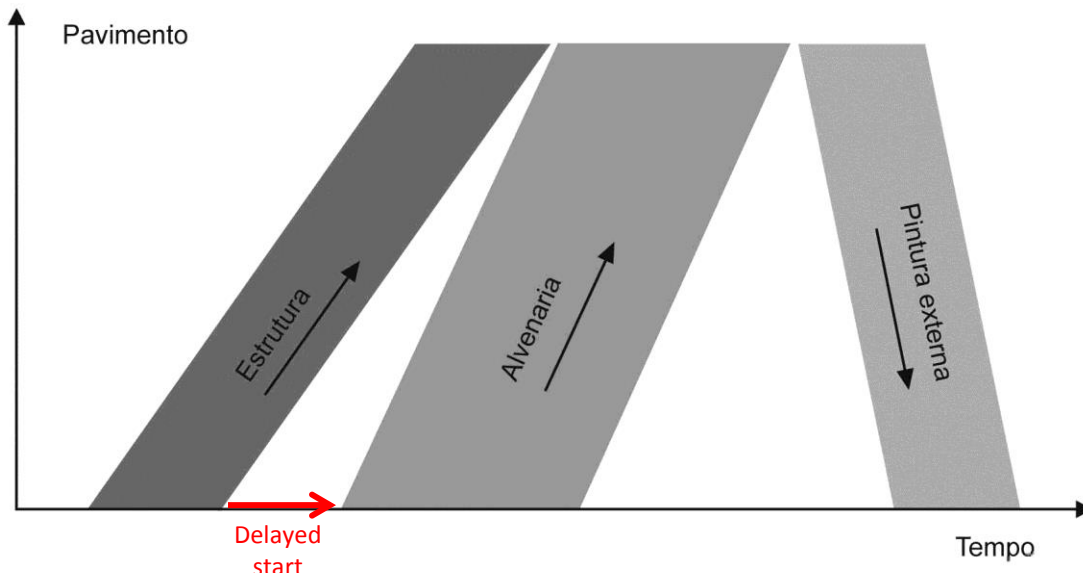


Figure 6 –

LOB for bottom-up and top-down services

The graph below (Figure 7) illustrates a similar LOB example; the difference being that it shows only the start line for each of the activities in order to produce a simpler diagram. This is how LOB is plotted by some commercial scheduling software.

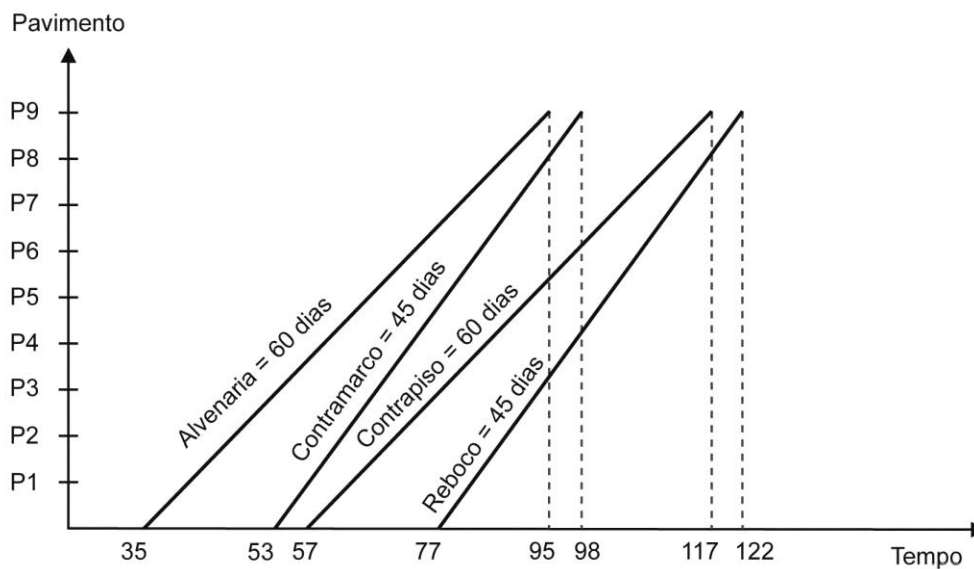


Figure 7 – LOB with the start date of the operations

Figure 8 shows how to establish the individual LOB relationships and the possible relationships between predecessor and successor:

- If the production rate of an activity is higher than that of its successor, the successor may start immediately the first unit (level, section) of the first activity. The lines of balance are therefore “linked by the base” as shown in Figure 8(a);
- If the production rate of an activity is lower than that of its successor, then the successor may *not* start immediately after the first unit of the first activity because a conflict becomes inevitable. To avoid such conflict, it is necessary to allow some lead time to the first activity by delaying the start of the successor. In this case, the lines of balance are “linked by the top” as shown in Figure 8(b). [3]

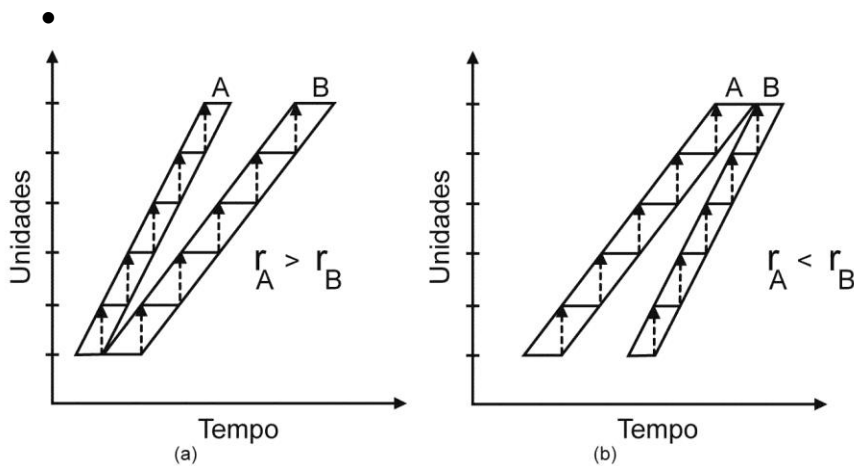


Figure 8 – Plotting LOB: (a) $r_A > r_B$ “linked by the base”; (b) $r_A < r_B$ “linked by the top”

Optimizing LOB

In a project where many services have a repetitive pattern the planner may feel tempted to assign the same productivity to all of them; this is known as *parallel planning*. This, however, is not always feasible from an operational point of view. For instance, in the construction of a multi-story building, a one-week cycle per floor may be established for the primary trades. However, some quick (high production rate) services would look unrealistic if scheduled to last one week per floor. Similarly, other slower services would require an excessive number of workers in order to complete their work on a floor in one week. This is the rationale behind LOB optimization, a process that consists of finding the proper production rate (balance) for each individual service or trade.

The following simplified example is for the construction of a pier, represented by three operations: drive piles; build pile caps; and install concrete deck (Figure 9). This three-activity sequence must be performed ten times in order to complete the entire pier. [4]

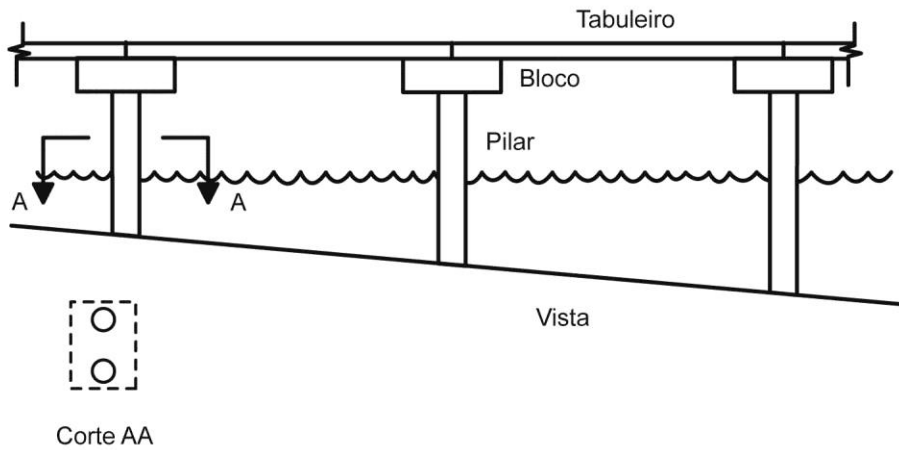


Figure 9 – Pier elevation

For each section of the pier, the construction sequence is linear; pile caps must follow piles, and deck must follow pile caps. Figure 10 shows the projected time for each pier sequence, with the required durations. To provide a margin of error in the completion of each operation, or perhaps to allow for relocation of equipment, a time buffer of 5 days is inserted between activities. This plan shows that a total time of 50 days is needed to complete the first section of the pier.

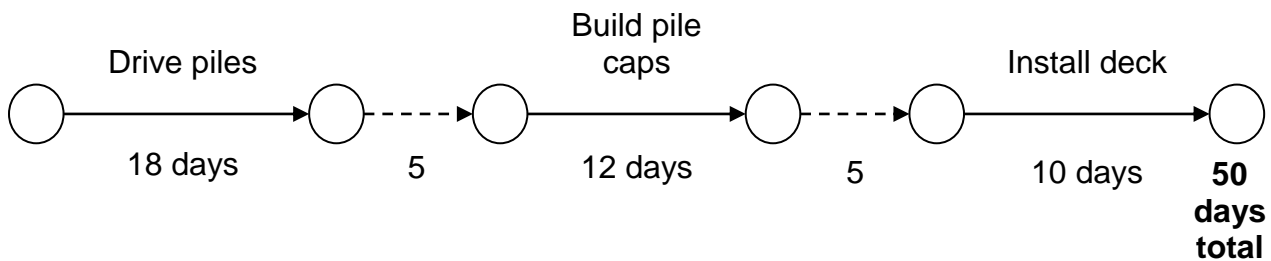


Figure 10 – First pier section: Logic diagram with buffers

If a production of one additional pier section per week is established as a goal, the total time required to complete the entire 10 sections would be calculated as 95 days (50 days to complete the first section, plus 9 additional sections @ 1 section/week). Figure 11 shows this graphically both as a classic bar chart and as LOB. Note that this production goal requires the crews and equipment to be able to work on four piers concurrently throughout the project.

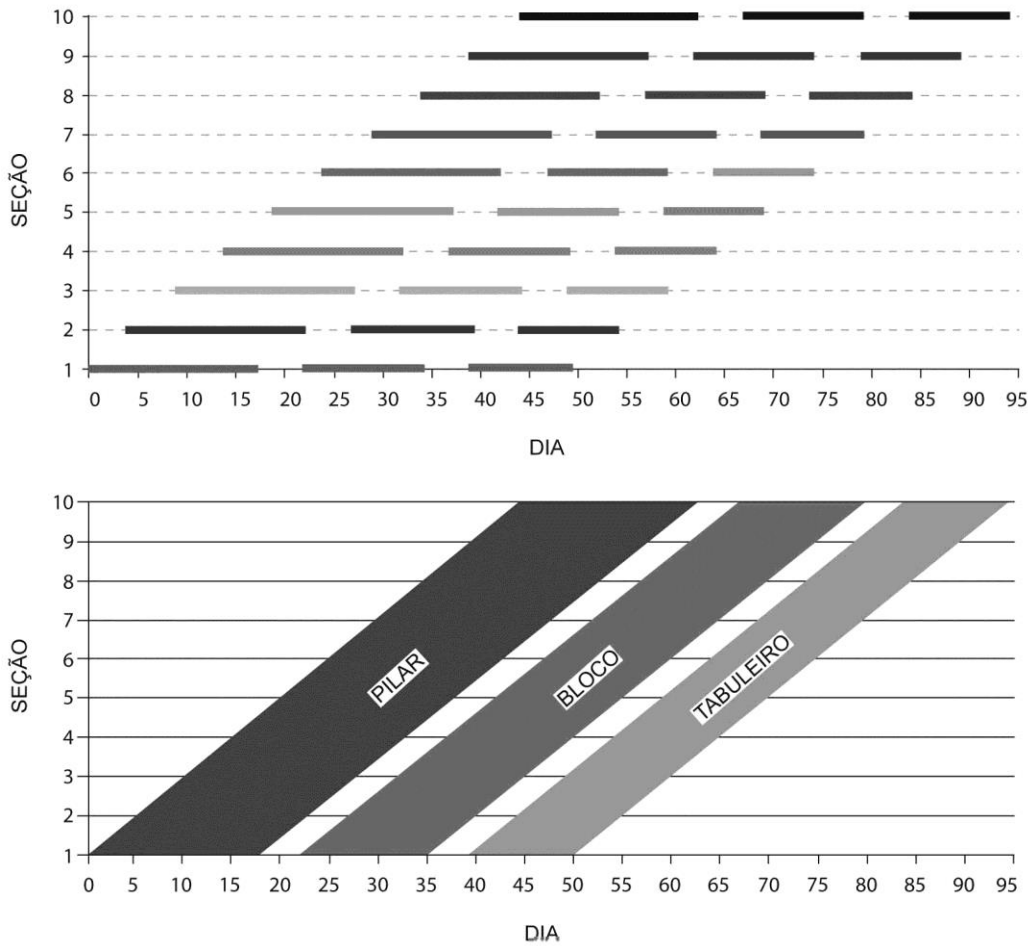


Figure 11 – Time for completion of 10 sections at a rate of 1 section/week

If planning ceased at this point, the schedule (and possibly the contract performance period) would be established as 95 work days for this project. However, it is essential to recognize that this plan is based upon identical production rates for all three trades/crews. While it might be possible to adjust crew sizes and equipment to achieve identical production rates, this is not what happens in the real world. Different operations seldom have identical production rates with parallel lines of balance. Such planning expectations are unfeasible and impractical because in order for every activity to perform at the same “speed,” might require either too large (or too short) crews, entailing conflicts for space, require impossible equipment logistics (e.g. 1.75 pile rigs) and add complexity to field supervision. The logical solution is to adopt variable rhythms, based on the optimum crew and equipment size for each service and their respective production rates.

In the example of the pier, assume that a standard pile cap crew requires one team of six men (and associated equipment) to build it in 12 days. If two crews are allocated, each cap will be completed

in 6 days, which represents a production rate of $(5/6 \text{ section/week} = \underline{0.83 \text{ section/week}})$. The revised LOB diagram is shown in Figure 12. Note that this lower production rate requires an overall duration greater than the original 95 days planned.

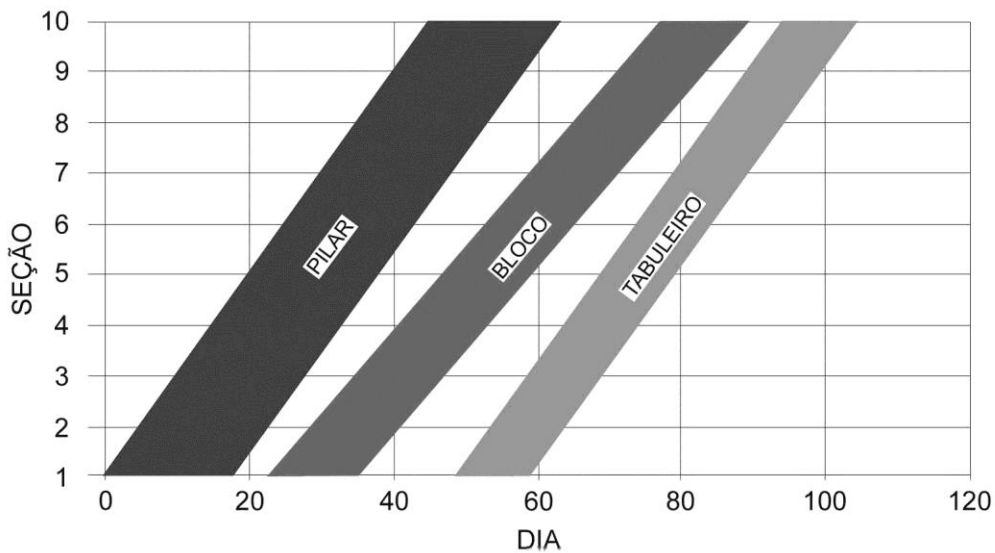


Figure 12 – LOB with two pile cap crews

If three pile cap crews were allocated in the project, the production rate of this service would increase and the crew would be able to complete a section every 4 days ($5/4 \text{ section/week} = \underline{1.25 \text{ section/week}}$) as shown in Figure 13. Note that accelerating the pile cap operation does not improve the overall time performance of the project. This is because, due to its faster pace, the pile cap operation is “linked by the top” and would therefore need to start later in order not to “collide” against the pile driving operation. The successor deck operation (linked by the bottom) would have to be accelerated as well in order to achieve any overall time savings for this sequence.

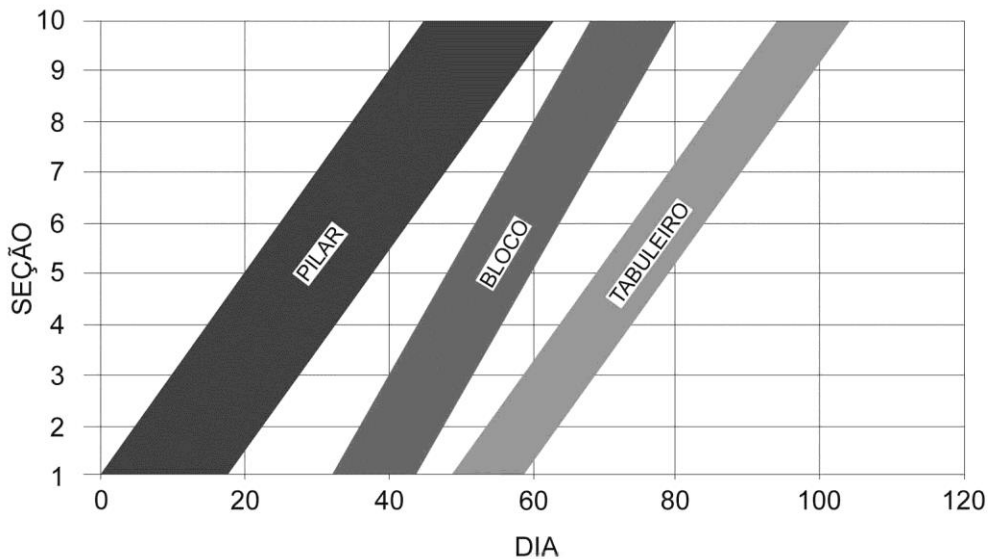


Figure 13 – LOB with three pile cap crews

Note that the gap between the start of first piling and the start of caps reflects the delayed start of pile cap operations to avoid “colliding” with the tenth pier piling.

The following two case studies show examples for preparing LOB schedule information.

Case Study 1

Calculated LOB (Tabular & Graphic) for Sequential Operations

The case study presented below shows how to prepare the lines of balance in tabular and graphic form. The project is for the construction of 20 identical houses (n) with a delivery target (R_o) of three houses per week (assuming a week of 5 days x 8 hours = 40 man-hours) The production cycle is composed of five sequential operations as shown in Figure 14:

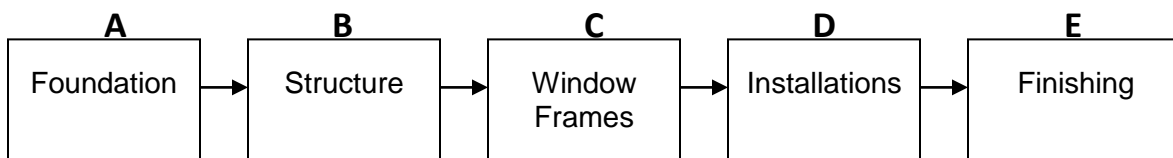


Figure 14 – Sequence of operations

Table 1 shows the total required man-hours (Mh) per service and the “base crew” size (theoretical crew size) for each operation per house [3].

<i>Operation</i>	<i>Mh/house</i>	<i>Base crew size (workers)</i>
A	110	3
B	320	8
C	365	9
D	35	2
E	210	5

Table 1 – Production rate data and crew size per operation

With respect to Operation **A** (Foundations), in order to reach the desired delivery target of 3 houses/week, it is necessary to assign a **Calculated Crew Size** (C_c) with the following calculated number of workers according to **Equation 1** below:

$$C_c = \frac{\text{Man-hours per house} \times \text{Desired Production Rate}}{\text{Hours per week per worker}} \quad \text{Eq. 1}$$

Using the data given in Table 1, $C_c = (110 \times 3)/40 = \mathbf{8.25 \text{ workers for Operation A}}$. That figure is rounded up to **9**, the closest multiple of the base crew (3 men). By rounding up the crews, the weekly **Adjusted Production Rate** (R_r) is derived using **Equation 2**:

$$R_r = \frac{\text{Desired Production Rate} \times \text{Actual Crew Size}}{\text{Calculated Crew Size}} \quad \text{Eq. 2}$$

Thus for Operation A, the **Adjusted Production Rate** $R_r = (3 \times 9)/8.25 = \mathbf{3.27 \text{ houses/week}}$. This rate is greater than our desired delivery target rate, and can therefore be accepted as calculated.

The **duration** (t) of Operation A for each house is given by **Equation 3**:

$$t = \frac{\text{Man-hours per house}}{\text{Number of men in one crew} \times \text{Hours per day per worker}} \quad \text{Eq. 3}$$

Thus for Operation A, the duration per house $t = 110/(3 \times 8) = 4.58$ days.

The time elapsed between the start of first house and the start of the twentieth house (T) is calculated using Equation 4:

$$T = \frac{(n - 1) \times \text{Working Days per Week}}{\text{Adjusted Production Rate}} \quad \text{Eq. 4}$$

Thus for operation A, $T = (20-1) \times 5/3.27$ the time elapsed = **29.05 days**.

Therefore, for **Operation A** the LOB is depicted in Figure 15.

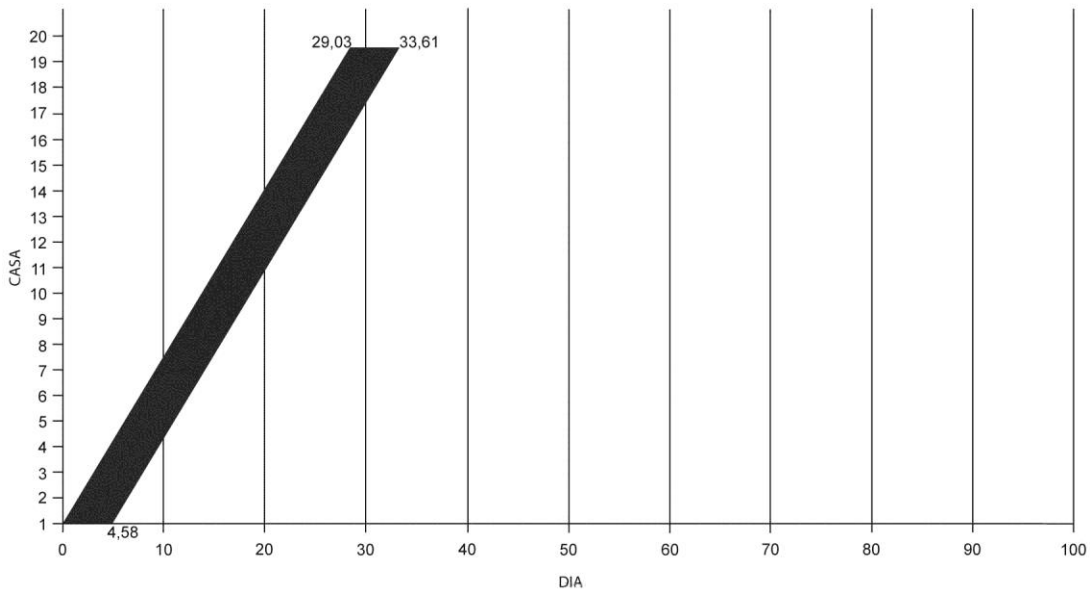


Figure 15 – LOB of Operation A

The completion point of the twentieth house is calculated by adding (T + t) or in this example, $(29.03 + 4.58) = 33.61$

Table 2 shows this exercise extended to all five operations:

Oper.	Mh per house H	Base crew (workers) C_b	Calculated crew (workers) C_c	Actual crew size C_a	Adjusted production rate (houses/week) R_r	Time per house (days) t	Time from start on 1st to start on last house (days) T
A	110	3	8.25	9	3.27	4.58	29.05

B	320	8	24.00	24	3.00	5.00	31.67
C	365	9	27.38	27	2.96	5.07	32.09
D	35	2	2.63	4	4.57	2.19	20.83
E	210	5	15.75	15	2.86	5.25	33.22

Table 2 – Calculation of the line of balance schedule information (tabular form)

Formulas used to generate Table 2:

$$C_c = \text{Desired Production Rate} \times \text{Mh per unit} / \text{Working hours per week} = (R_o \times H) / 40$$

$$C_a = \text{Rounding of } C_c \text{ to the closest multiple of } C_b \text{ (the Base Crew)}$$

$$R_r = \text{Desired Production Rate} \times \text{Adjusted Crew} / \text{Calculated Crew} = (R_o \times C_a) / C_c$$

$$t = \text{Mh per unit} / (\text{Base Crew} \times \text{hours per day}) = H / (C_b \times 8)$$

$$T = (\text{Total Number of units} - 1) \times \text{days per week} / \text{Adjusted Production Rate} = (n-1) \times 5 / R_r$$

After introducing a 5-day buffer between sequential operations to account for staging, relocation of equipment (cranes, hoists) and eventual inefficiency, the planner is able to plot the five lines of balance in the same graph, shown here as Figure 16. The higher production rate (R_r) for Operation D is reflected in the greater slope of that line. The total length of the project reaches **86.67 days**.

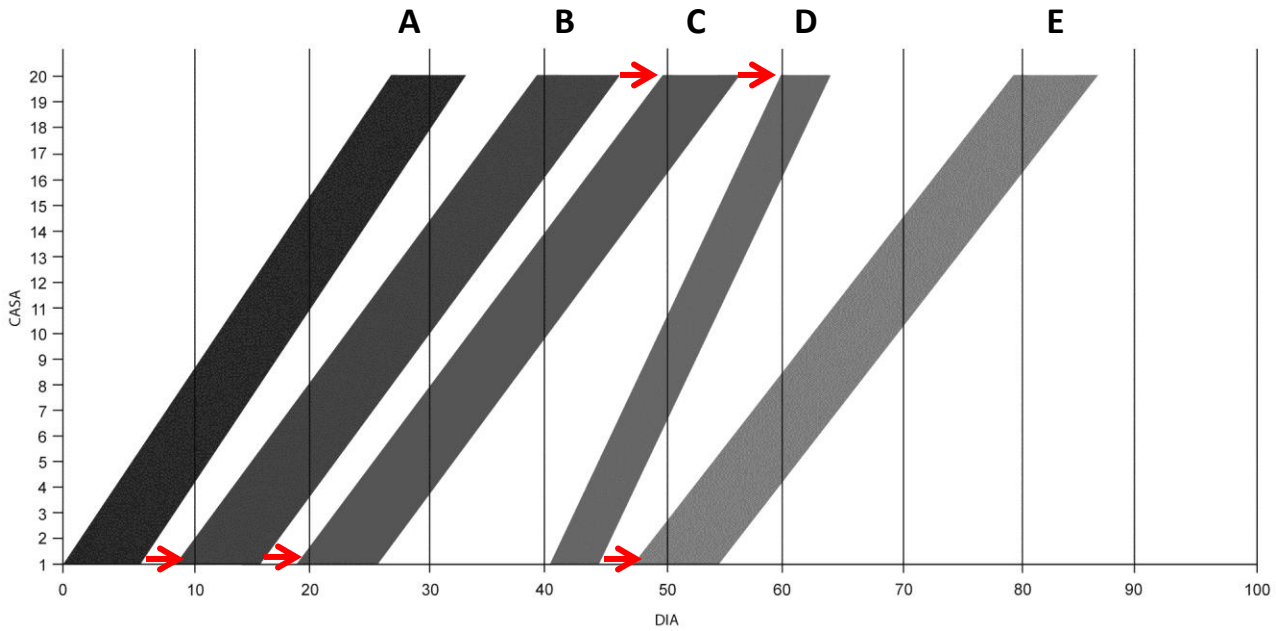


Figure 16 – Lines of balance for Case Study 1 (20 houses)

For project controls purposes, Table 3 shows the time of start and finish of each of the operations for each house. Because Operation **D** has a faster pace than Operation **C**, the start date for House 20 was the first to be calculated (“linked by the top”), and the other start dates were derived by successive subtractions.

HOUSE	A		B		C		D		E	
	START	FINISH	START	FINISH	START	FINISH	START	FINISH	START	FINISH
1	0	4.58	9.58	14.58	19.58	24.65	40.98	43.17	48.17	53.42
2	1.53	6.11	11.25	16.25	21.27	26.34	42.07	44.26	49.92	55.17
3	3.06	7.64	12.92	17.92	22.96	28.03	43.17	45.35	51.67	56.92
4	4.58	9.17	14.58	19.58	24.65	29.72	44.26	46.45	53.42	58.67
5	6.11	10.69	16.25	21.25	26.34	31.41	45.35	47.54	55.17	60.42
6	7.64	12.22	17.92	22.92	28.03	33.10	46.45	48.63	56.92	62.17
7	9.17	13.75	19.58	24.58	29.72	34.79	47.54	49.73	58.67	63.92
8	10.69	15.28	21.25	26.25	31.41	36.48	48.63	50.82	60.42	65.67
9	12.22	16.81	22.92	27.92	33.10	38.17	49.73	51.92	62.17	67.42
10	13.75	18.33	24.58	29.58	34.79	39.86	50.82	53.01	63.92	69.17
11	15.28	19.86	26.25	31.25	36.48	41.55	51.92	54.10	65.67	70.92
12	16.81	21.39	27.92	32.92	38.17	43.24	53.01	55.20	67.42	72.67

HOUSE	A		B		C		D		E	
	START	FINISH	START	FINISH	START	FINISH	START	FINISH	START	FINISH
13	18.33	22.92	29.58	34.58	39.86	44.93	54.10	56.29	69.17	74.42
14	19.86	24.44	31.25	36.25	41.55	46.62	55.20	57.38	70.92	76.17
15	21.39	25.97	32.92	37.92	43.24	48.31	56.29	58.48	72.67	77.92
16	22.92	27.50	34.58	39.58	44.93	50.00	57.38	59.57	74.42	79.67
17	24.44	29.03	36.25	41.25	46.62	51.69	58.48	60.67	76.17	81.42
18	25.97	30.56	37.92	42.92	48.31	53.38	59.57	61.76	77.92	83.17
19	27.50	32.08	39.58	44.58	50.00	55.07	60.67	62.85	79.67	84.92
20	29.03	33.61	41.25	46.25	51.69	56.76	61.76	63.95	81.42	86.67

Table 3 – Lines of balance calculated analytically

Case Study 2 Calculated LOB for Non-Sequential Operations

As outlined in Table 4, the second case study refers to the execution of a 20-story building according to the sequence and the hours (Mh) of each activity per floor. The basis for planning is to finish 1 floor every 2 weeks, or 0.5 floor/week (considering a week as 5 days of 8.8 hours per day), and allowing a 3 day buffer between operations on the same floor.

Fig. 17 shows the logic diagram for this Case Study.

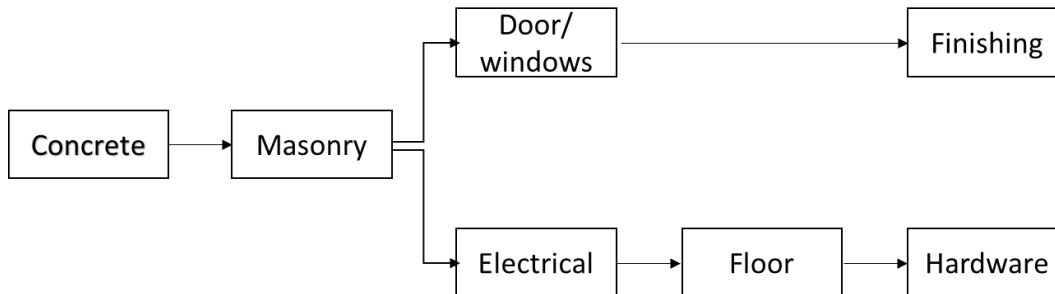


Figure 17 – Logic for Case Study 2 (Building)

Operation	Mh/floor H	Base Crew Size (workers) C_b	Predecessor Operation
A. Concrete Structure	250	3	–
B. Masonry	300	4	Concrete Structure
C. Doors/Windows	300	3	Masonry
D. Electrical Installation	200	3	Masonry
E. Floor Tile	200	5	Electrical
F. Hardware	50	2	Floor Tile
G. Finishing	200	5	Doors/Windows

Table 4 – Man-hours, base crew size and sequence

Using the desired production rate of **0.5 floor/week**, Table 5 shows the LOB scheduling according to the calculated production rates (using the identical formulas from Case Study 1):

Operation	Mh per floor H	Base crew size (workers) C_b	Calculated crew size (workers) C_c	Actual crew size C_a	Adjusted production rate (floors/week) R_r	Time per floor (days) t	Time from start on 1st to start on last floor (days) T
A. Concrete	250	3	2.84	3	0.53	9.47	85.23
B. Masonry	300	4	3.41	4	0.59	8.52	76.70
C. Doors/Windows	300	3	3.41	3	0.44	11.36	102.27
D. Electrical	200	3	2.27	3	0.66	7.58	68.18
E. Floor Tile	200	5	2.27	5	1.10	4.55	40.91
F. Hardware	50	2	0.57	2	1.76	2.84	25.57
G. Finishing	200	5	2.27	5	1.10	4.55	40.91

Table 5 – Calculation of the line of balance schedule information (tabular form)

Figure 18 is the final line of balance for the Case Study 2 schedule. When operations may occur concurrently (windows may happen simultaneously with electrical installation, floor tile placement may happen simultaneously with hardware, etc.), there will be overlapping lines of balance, as seen

in Figure 18. A careful analysis of the LOB schedule reveals that doors/windows installation (Operation C) begins before the tiles are placed in the lower floors of the building, but after they are placed in the higher floors. This reflects the outworking of the initially defined sequence of predecessor and successor operations (right-most column of Table 4).

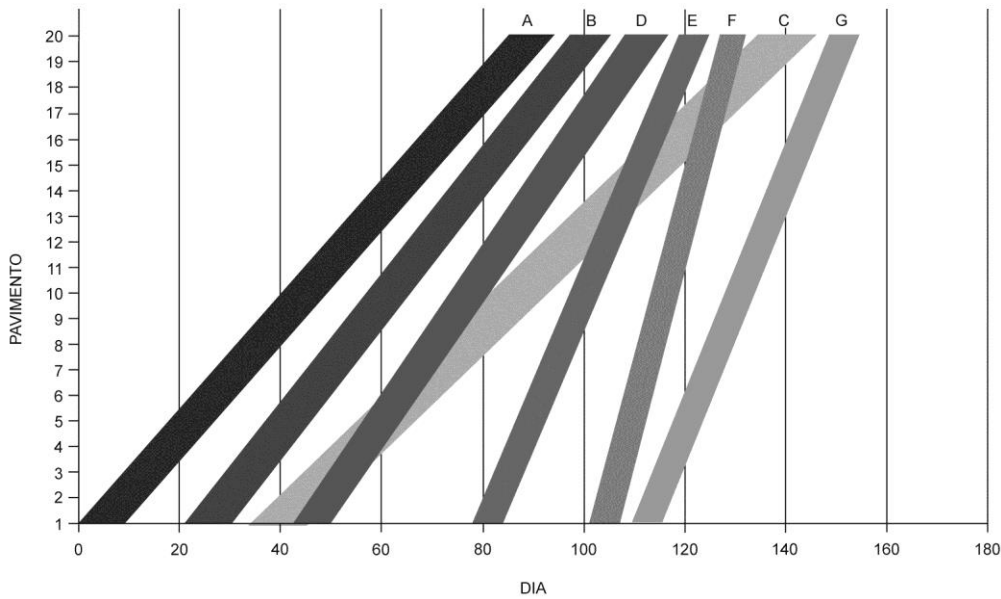


Figure 18 – Lines of balance for Case Study 2 (Building)

It is important to note that Figure 18 displays the projected trade sequence, with Operations A, B, D, E & F all linked by the top, reflecting their increasing adjusted production rates. Operations F & G are linked by the base (reflecting a lower production rate for the successor activity). Operation C is linked by the base due to a lower production rate than its predecessor, Operation B.

The management information graphically displayed in Figure 18 clearly shows the interrelationships of the trade crews as the project advances from floor to floor. Overall trade resource durations and dates are displayed, and adjustments to crew sizes can quickly show their effect on the overall project duration.

Summary and Conclusions

Line of Balance (LOB) is a scheduling method with proven results for linear projects as well as projects composed of repetitive operations such as roads, pipelines, housing projects and high-rise buildings. This article has shown the process for developing LOB schedules as well as addressed several issues associated with the technique. The basis of LOB is to graphically display and optimize the required resources for each stage or operation so that the project sequence is not impeded and the target result is achieved. Traditional CPM network methods and bar charts are not as well suited for repetitive projects because they can generate schedules with hidden gaps and inaccurate production cycles, and are not as quickly adjusted for alternate resource usages/crew sizes. The LOB method shows each operation as a line whose slope is determined by the production rate. The steeper the line, the faster the operation is performed. By plotting several lines onto the same chart, the overall project schedule can be depicted with improved visibility and provide the project team with a greater understanding of the resource interrelationships.

Defining the optimum production rate for each operation is the major challenge in LOB scheduling. The optimum production is based on the theoretical (or base) crew size and the number of man-hours required by each operation for each unit of production (floor, house, section, mile, etc.). [5] Using this initial data, the planner is able to generate the cycle for each operation and draw its corresponding line of balance. Since most operations do not have equal production rates, the lines will have different slopes. For operations with a lower production rate than its predecessor, the two lines will be "linked by the base." For operations with a production rate greater than its predecessor, the two lines will be "linked by the top." The latter situation indicates that the successor should not begin immediately (on the lowest floor or the earliest stage) but rather must wait a certain period in order to join the predecessor at the top (or end) of the graph. On occasions when sequential activities have an identical rate of production, a problem can arise on the LOB graphic; one line may hide another. The scheduler must pay careful attention to ensure the visibility of all activities/operations.

The graphical figures presented in the body of this paper highlight the inherent usefulness of LOB in the visualization of activity cycles and resources over a linear project. The LOB methodology is useful for schedule development, optimization and troubleshooting, and is strongly advocated for repetitive commercial construction projects. The scarcity of commercial LOB software is a concern, although this can be indirectly derived from popular scheduling software. All schedulers should consider adding LOB methodology to their tool box of techniques because of its great clarity and visual value to the construction management project team.

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